

# THÈSE DE DOCTORAT

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Contraindre la formation et l'évolution des plus gros astéroïdes  
de la ceinture principale

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# Résumé

Les astéroïdes de notre système solaire présentent une grande variété de tailles, de formes, de compositions et de propriétés orbitales. En raison de leur grand nombre, et même s'ils ne représentent qu'une fraction infime de la masse totale des planètes, ils fournissent des contraintes puissantes pour les modèles de formation des systèmes planétaires. A cet égard, l'étude des propriétés physiques des astéroïdes (taille, forme, spin, densité, masse, structures interne) est primordiale pour tenter ensuite de remonter le temps et mieux comprendre comment le Système solaire s'est formé et a évolué depuis l'accrétion des premiers planétésimaux. Cependant, on sait peu de choses sur leurs densités et leurs structures internes alors qu'il s'agit de propriétés fondamentales qui découlent des conditions de formation et de l'évolution collisionnelle.

Afin de progresser dans notre compréhension de la structure interne des astéroïdes, un large programme de l'ESO a été mené pour imager un échantillon significatif des plus grands ( $D \geq 100$  km) astéroïdes de la ceinture principale, couvrant les principales classes de composition. L'instrument à optique adaptative dans le visible VLT/SPHERE/ZIMPOL a fourni des observations à haute résolution pour 42 astéroïdes. Les images détaillées ont permis de calculer leurs volumes via des modèles de forme 3D, et donc leurs densités grâce à des estimations de la masse.

Cette thèse a pour but d'apporter de nouvelles contraintes sur la formation et l'évolution des plus grands astéroïdes de la ceinture principale, en particulier via la modélisation de la forme des cibles du programme ESO. Des modèles de forme 3D détaillés ont été produits en utilisant la méthode de reconstruction de forme 3D MPCD, laquelle a été précédemment développée pour la mission ESA/Rosetta. Des courbes de lumière optique ont également été acquises avec les télescopes TRAPPIST. Les résultats englobent les études dédiées de deux astéroïdes en particulier, (16) Psyché et (22) Calliope ainsi que l'analyse quantitative de l'échantillon complet de modèles de forme.

Psyché et Calliope sont deux astéroïdes riches en métaux dont les densités sont parmi les plus élevées connues pour les petits corps. La forme 3D obtenue de Psyché, qui est la cible d'une prochaine mission Discovery de la NASA, implique une forme primordiale proche de celle d'un ellipsoïde de Jacobi. La densité apparente de Calliope a été déterminée à partir de son modèle de forme et de l'orbite de son satellite. Sa densité élevée, associée aux déterminations précédentes de sa composition de surface riche en silicate, suggère fortement un intérieur différencié. L'analyse de tous les modèles de forme a montré une division en deux familles d'objets, les sphériques et les allongés. Enfin, la grande différence entre les densités obtenues a fourni des indices sur les origines des principales classes de composition.

Mots clés: astéroïdes, formes 3D, Système solaire

# Abstract

Asteroids in our Solar System exhibit a wide variety of sizes, shapes, compositions, and orbital properties. Because of their large numbers, and even if they only represent a tiny fraction of the total mass of the planets, they provide powerful constraints for planetary system formation models. In this regard, the study of the physical properties of asteroids (size, shape, spin, density, mass, internal structure) is of prime importance to then try to turn back the clock and better understand how the Solar System formed and evolved since the accretion of the early planetesimals. However, little is known regarding their densities and internal structure although these are fundamental properties that derive from the formation conditions and collisional evolution.

To make progress in our understanding of the internal structure of asteroids, an ESO large program was conducted to image a significant sample of the largest ( $D \geq 100$  km) main belt asteroids, covering the main compositional classes. The VLT/SPHERE/ZIMPOL adaptive-optics-fed instrument working in the visible provided high-resolution observations for 42 of these bodies. The detailed disk-resolved images allowed to derive their volumes via 3D shape modeling, thus their densities when combined with mass estimates.

This thesis aims to bring new constraints on the formation and evolution of the largest main belt asteroids, mainly through the shape modeling of the ESO large program targets. Detailed 3D shape models were produced using the 3D shape reconstruction procedure MPCD, that was previously developed for the ESA/Rosetta mission. Optical lightcurves were also acquired with the TRAPPIST telescopes. The results encompass the dedicated studies of two particular asteroids, (16) Psyche and (22) Kalliope and the quantitative analysis of the complete sample of shape models.

Psyche and Kalliope are both metallic rich asteroids whose densities were found to be among the highest known for small bodies. The obtained 3D shape of Psyche, which is the target of a forthcoming NASA discovery mission, implies a primordial shape close to that of a Jacobi ellipsoid. The bulk density of Kalliope was determined from its shape model and from the dynamics of its satellite. Its high density, coupled with previous determinations of its silicate-rich surface composition, strongly suggests a differentiated interior. The analysis of the 42 reconstructed shape showed a division in two families of objects, the spherical and the elongated. Finally, the large difference in the derived densities provided clues about the origins of the main compositional classes.

Keywords: asteroids, 3D shapes, Solar System

# Résumé étendu en français

## Introduction

Les astéroïdes de notre système solaire présentent une grande variété de tailles, de formes, de compositions et de propriétés orbitales. En raison de leur grand nombre, et même s'ils ne représentent qu'une fraction infime de la masse totale des planètes, ils fournissent des contraintes puissantes pour les modèles de formation des systèmes planétaires. A cet égard, l'étude des propriétés physiques des astéroïdes (taille, forme, spin, densité, masse, structures interne) est primordiale pour ensuite tenter de remonter le temps et ainsi mieux comprendre comment le Système solaire s'est formé et a évolué depuis l'accrétion des premiers planétésimaux. Cependant, on sait peu de choses sur leurs densités et leurs structures internes alors qu'il s'agit de propriétés fondamentales qui découlent des conditions de formation et de leur histoire collisionnelle.

Afin de progresser dans notre compréhension de la structure interne des astéroïdes, un large programme de l'ESO a été mené par P. Vernazza pour imager un échantillon significatif des plus grands ( $D \geq 100$  km) astéroïdes de la ceinture principale, couvrant les principales classes de composition. Le *Very Large Telescope* (VLT), un télescope de 8 m installé au Chili a été utilisé à cet effet. SPHERE est un instrument installé au VLT qui permet d'obtenir des images en optique adaptative, c'est à dire corrigé des perturbations de l'atmosphère. En particulier, sa caméra ZIMPOL est la première capable de produire une correction en optique adaptative dans le domaine visible, ce qui permet d'obtenir des résolutions sans précédents pour des installations au sol. L'observation par SPHERE/ZIMPOL de grand astéroïdes de la ceinture principale fournit des images détaillées de leurs surfaces qui actuellement ne peuvent être surpassées que par des missions spatiales dédiées (Fig. 0.1).

La campagne d'observation SPHERE a observé 42 astéroïdes au total (Fig. 0.2). Plusieurs visites ont été effectuées pour chaque cibles, parfois lors de plusieurs oppositions. Le but principal était de reconstruire la forme tridimensionnelle (3D) de ces objets, ce qui donne accès au volume et donc et à la densité une fois combiné avec des estimations existantes de la masse.

Le but de ma thèse était donc de participer à la reconstruction des modèles de forme en appliquant une méthode déjà existante, MPCD. Ensuite, l'analyse des formes obtenues devait permettre d'obtenir de nouvelles contraintes sur la formation et l'évolution de ces astéroïdes ainsi que sur leurs classes de composition par extension.

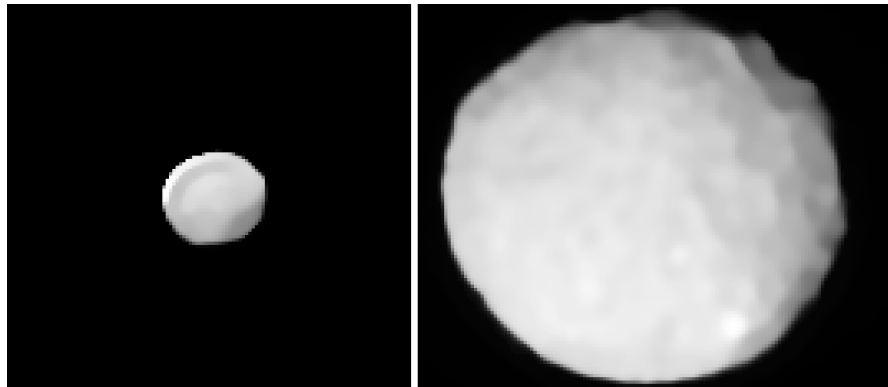


Figure 0.1.: Comparaison entre deux images du même objet, ici l'astéroïde Pallas, obtenues avec l'instrument NACO à gauche et avec SPHERE/ZIMPOL à droite qui a une bien meilleur résolution.



Figure 0.2.: Images des 42 astéroïdes observés par SPHERE durant la campagne d'observation triées par taille. Illustration provenant d'un communiqué de presse ESO: <https://www.eso.org/public/france/news/eso2114/>

## Courbe de lumières

En raison de leurs formes irrégulières, la luminosité des astéroïdes change avec le temps lorsqu'ils tournent autour de leur axe de rotation. La mesure du flux apparent ou de la magnitude d'un astéroïde en fonction du temps permet de construire sa courbe de lumière (Fig. 0.3).

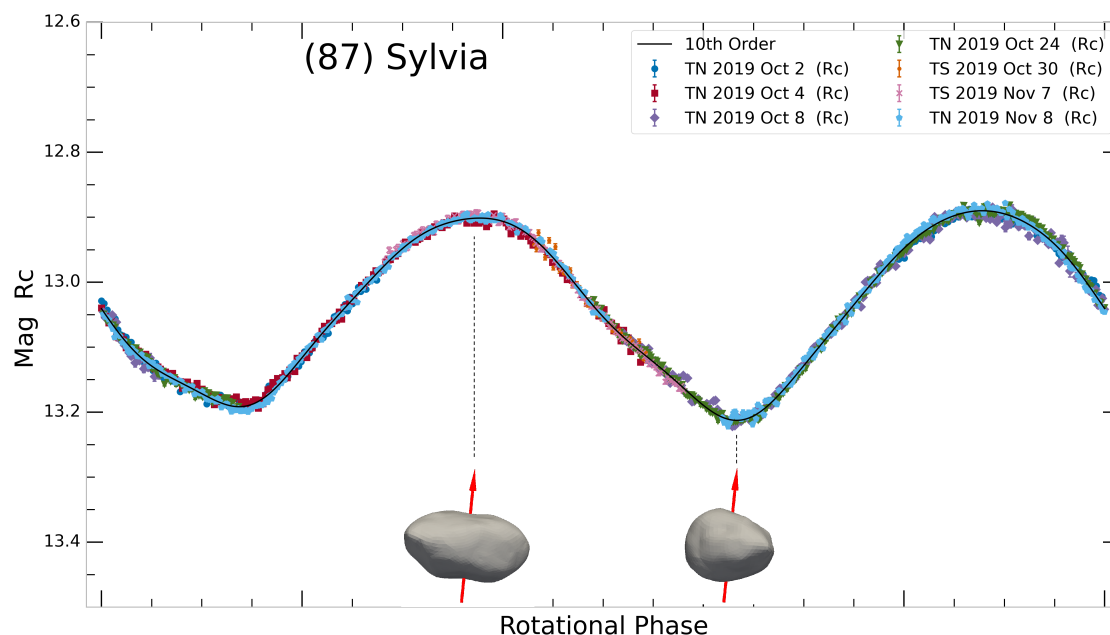


Figure 0.3.: Courbe de lumière de l'astéroïde (87) Sylvia. Son modèle de forme au moment d'un maximum et d'un minimum montre la variation correspondante de la surface présentée par l'astéroïde.

Les courbes de lumières permettent de déterminer les paramètres de rotation d'un astéroïde (période de rotation et orientation de son axe de rotation), ainsi que sa forme globale. Elles sont aussi utilisées en combinaison d'autres type de données, tel que les images d'optique adaptative, par certaines méthodes de reconstruction 3D. J'ai utilisé les télescopes TRAPPIST-Nord et -Sud de l'université de Liège pour reconstruire les courbes de lumières de nombreuses cibles observées avec SPHERE afin d'aider à la reconstruction de leurs formes 3D par la méthode ADAM.

J'ai également utilisé les courbes de lumières pour étudier d'autres phénomènes. Par exemple, le passage du satellite de l'astéroïde Kalliope devant celui-ci a pu être détecter en comparant sa courbe de lumière pendant et hors transit (Fig. 0.4).

## La méthode de reconstruction 3D MPCD

Pour reconstruire la forme 3D des cibles du large programme ESO, j'ai utilisé la méthode MPCD développée par C. Capanna et L. Jorda ([Capanna, 2013](#)) pour étudier les

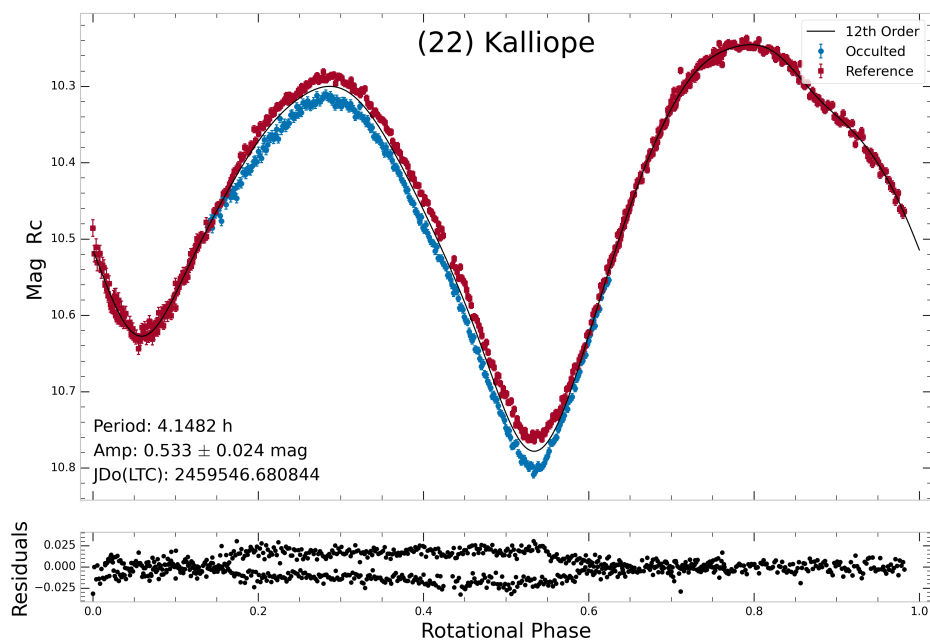


Figure 0.4.: Courbe de lumière de l'astéroïde Kalliope lors d'un transit de son satellite Linus (en bleu). Une courbe de référence obtenue hors transit (en rouge) permet de visualiser l'atténuation causée par le passage du satellite.

cibles de la mission spatiale Rosetta de l'ESA ([Capanna et al., 2013](#); [Jorda et al., 2016](#)).

Contrairement à la méthode ADAM utilisée par une autre équipe avec qui nous collaborons, MPCD a la particularité de ne pas utiliser de courbe de lumières mais uniquement des images résolues. Pour reconstruire une forme 3D, MPCD déforme graduellement un modèle initial jusqu'à ce que les images synthétiques produites par ce modèle correspondent aux images observées.

Nous sommes partis des modèles de forme ADAM pour essayer d'améliorer leurs formes. Certaines adaptations furent nécessaires pour permettre l'usage d'images provenant d'instrument d'optique adaptative, mais MPCD a pu être utilisé pour reconstruire la forme de nos astéroïdes avec succès.

## (16) Psyché

L'astéroïde (16) Psyché est le plus grand astéroïde de type M de la ceinture principale. Il a été défini par le passé comme un monde métallique à cause de sa surface riche en métaux ([Elkins-Tanton et al., 2017](#)). Le caractère unique des caractéristiques de Psyché en a fait une cible de choix pour l'exploration spatiale, ce qui a conduit à sa sélection comme cible d'une mission Discovery de la NASA.

Cependant, la vraie nature de Psyché reste énigmatique ce qui a conduit à la formulation de plusieurs scénarios de formation distincts. On ne sait notamment pas si son

intérieur est intact ou est de type "tas de gravats", ni s'il est différencié ou homogène.

Une meilleure compréhension de l'histoire de Psyché nécessitait une caractérisation plus poussée de sa taille et de sa forme, ce qui en faisait une cible particulièrement intéressante à observer avec SPHERE. Nous avons donc décidé au début de la thèse de porter une attention particulière à cet astéroïde.

Psyché a été observé par SPHERE en 2018 et 2019 pour un total de 60 images en 12 époques. Psyché offrait une vue de son pôle nord en 2018, tandis qu'en 2019 on le voyait le long de son équateur. Cela a permis de couvrir toute sa surface en plus de bien contraindre ses dimensions sur ses trois axes.

La forme 3D de Psyché a été reconstruite en utilisant la méthode MPCD. La Figure 0.5 montre une comparaison entre certaines images SPHERE et les images synthétiques correspondantes produites à partir du modèle ADAM. Le volume obtenu permet de calculer une densité élevée  $\rho = 3.89 \pm 0.52 \text{ g}\cdot\text{cm}^{-3}$ .

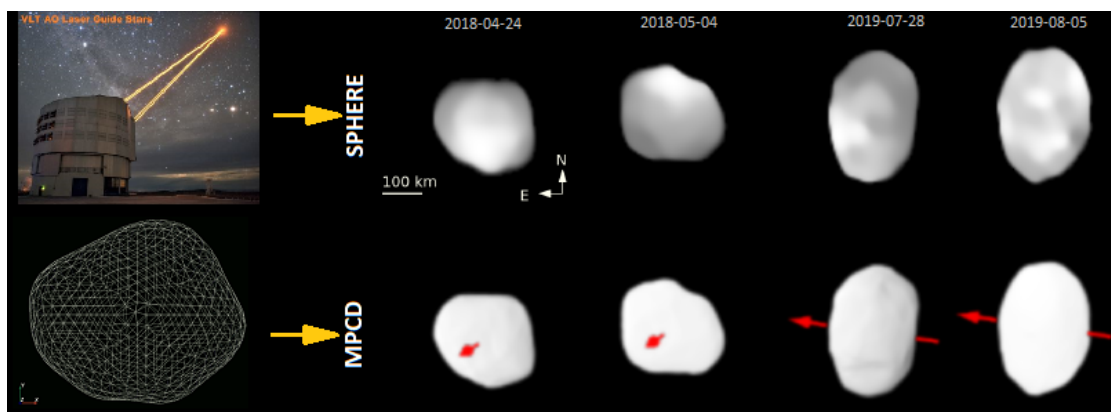


Figure 0.5.: Comparaison entre des images SPHERE de Psyché et les images synthétiques correspondantes produites à partir du modèle ADAM, montrant que notre modèle reproduit bien les observations. Les flèches rouges indiquent l'axe de rotation.

La forme de Psyché apparaît comme proche d'un ellipsoïde le long de son équateur et aplatie à ses pôles. Cependant, trois grandes dépressions ont été identifiées le long de l'équateur et pourraient avoir été causées par des impacts violents. Elles sont notées A, B, et C sur la Figure 0.6. Un ellipsoïde triaxial a été ajusté sur le modèle de forme après avoir supprimé les facettes correspondant aux dépressions observées, et ce de manière à mesurer la forme primordiale de Psyché.

Finalement, nous avons testé l'hypothèse que Psyché ait pu se former à l'équilibre hydrostatique. Il en résulte que la forme et la densité de Psyché est compatible avec celle d'un ellipsoïde de Jacobi, une des figures d'équilibre possibles, à condition de supposer une période de rotation initiale plus courte ( $\sim 3 \text{ h}$  au lieu de  $4.2 \text{ h}$ ). Ce résultat suggère que Psyché pourrait s'être formé alors que son intérieur avait toujours un comportement fluide tandis que des collisions ultérieures auraient ralenti sa rotation tout en créant les dépressions observées.



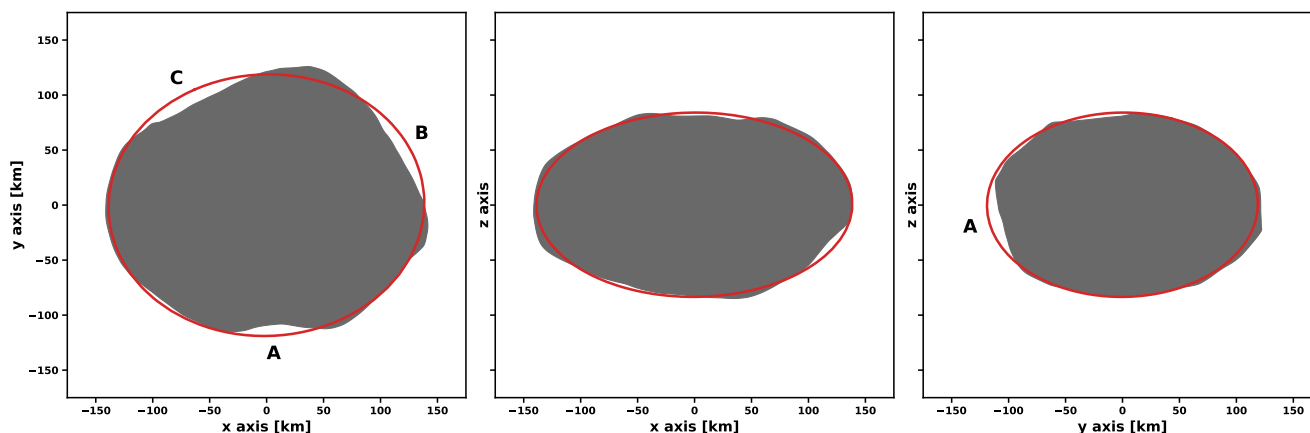


Figure 0.6.: Profils du modèle MPCD et de son ellipsoïde triaxial correspondant, avec une vue sur le pôle (gauche) et deux vues équatoriales (centre et droite). Les axes x, y et z sont alignés sur les principaux axes d'inertie (en supposant un intérieur homogène).

## (22) Calliope

L'astéroïde (22) Calliope est le deuxième plus gros astéroïde de type M de la ceinture principale après Psyché. Calliope possède un satellite, Linus, qui permet de contraindre précisément sa masse via la détermination de l'orbite de Linus. Cette cible représentait donc une bonne opportunité pour obtenir une détermination précise de la densité d'un autre astéroïde de type M en plus de Psyché. Contrairement à Psyché, Calliope ne possède pas une surface riche en métaux.

Calliope a été observé à sept époques entre mars et mai 2018 et en juin 2019 avec SPHERE, pour un total de 35 images. Les deux apparitions ont eu lieu à des géométries d'observation différentes, comme dans le cas de Psyché. En plus d'ADAM, une autre équipe a utilisé sa méthode de reconstruction 3D, SAGE, pour également fournir un modèle de forme. A partir de ses deux modèles, nous avons appliqué MPCD et produit deux modèles supplémentaires qui peuvent être comparés sur la Figure 0.7. Nous avons ensuite pu déterminer le diamètre de Calliope en prenant la moyenne des quatre modèles.

En second lieu, la détermination de l'orbite de Linus devait nous permettre d'obtenir une valeur plus précise de la masse de Calliope. Nous avons complété les données SPHERE avec des images provenant d'autres grands télescopes terrestres équipés d'instruments d'optique adaptative : Gemini-Nord, Keck II, et le VLT avec les caméras NACO et SPHERE/IRDIS (Fig. 0.8). Cela nous a permis d'augmenter le nombre de mesures à 94, couvrant 48 époques sur 17,5 ans (2001-2019). Les images ont été récupérées dans différentes archives et réduites de manière homogène. Deux équipes différentes ont ensuite utilisées ces mesures pour modéliser l'orbite de Linus et dériver une masse de  $M = 7.78 \cdot 10^{18}$  kg.

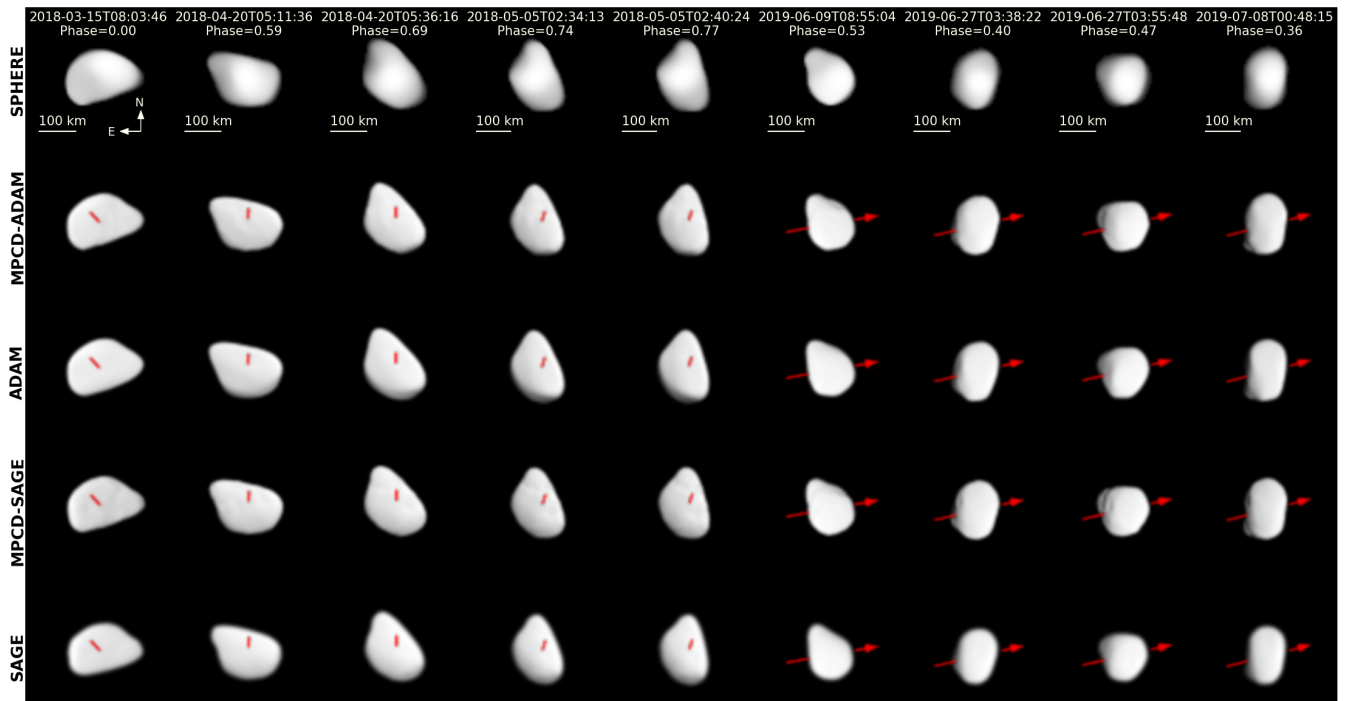


Figure 0.7.: Comparaison entre les images SPHERE de Calliope (une par époque) et les images synthétiques correspondantes produite à partir des modèles ADAM, SAGE et des deux modèles MPCD.

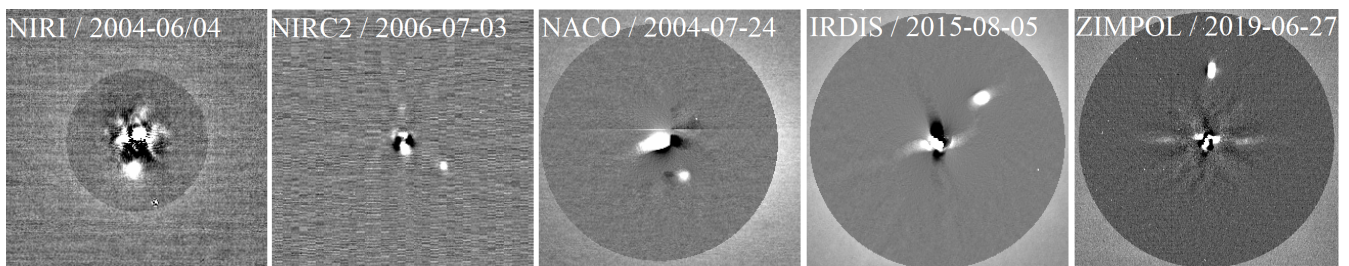


Figure 0.8.: Exemple d'images en optique adaptative de Calliope prises avec différents télescopes et révélant son satellite Linus. Les images ont été traitées pour enlever le halo brillant autour de Kalliope, améliorant ainsi la détectabilité de Linus.

En combinant nos nouvelles valeurs de la masse et du volume, nous avons pu déterminer la densité de Calliope,  $\rho = 4.40 \pm 0.46 \text{ g}\cdot\text{cm}^{-3}$ . Cette valeur est la plus importante densité connue à ce jour pour un petit corps du Système Solaire.

Nous avons ensuite estimé que la teneur en métal de Calliope était de l'ordre de 40 à 60%. Une telle teneur en métaux, associée à une surface pauvre en métaux, rappelle la structure interne de la planète Mercure et suggère un intérieur différencié.

## Analyse de forme

L'analyse de forme a été réalisée tout d'abord en calculant l'écart par rapport à un ellipsoïde ainsi que l'asphéricité de chaque modèle. Ces deux paramètres permettent de quantifier respectivement la proximité de la forme d'un astéroïde avec un ellipsoïde triaxial ou avec une sphère. Nous remarquons en premier lieu la forte corrélation entre ces deux paramètres et la taille, et donc la masse, de l'astéroïde (Fig. 0.9). En effet, plus un astéroïde est massif, plus il devient ellipsoïdal ou sphérique en raison de sa propre gravité. Ensuite, nous avons également remarqué que la distribution de l'asphéricité de notre échantillon semble être bimodale au premier ordre. Nous avons donc séparé notre échantillon en deux groupes composés de corps plus sphériques d'une part, et de corps plus allongés d'autre part. Les ajustements linéaires de ces deux groupes séparément ont montré des corrélations encore plus fortes. Un test DIP a de plus rejeté l'unimodalité de notre distribution globale.

## Densité

Les densités de tous nos astéroïdes ont été calculées en combinant une moyenne des estimations de masse disponibles avec nos diamètres dérivés des modèles de forme. La distribution de la densité pour toutes nos cibles révèle une forte bimodalité entre les corps pauvres en volatils et les corps riches en volatils (Fig. 0.10). La grande disparité entre les densités des différentes classes de compositions conforte l'idée de différentes compositions internes et suggère des origines multiples pour les astéroïdes maintenant présent dans la ceinture principale.

## Conclusions et perspectives

Le but de la thèse portait sur la reconstruction des formes 3D d'un échantillon des plus gros astéroïdes de la ceinture principale. Dans un premier temps, des courbes de lumière ont été produites avec les télescopes TRAPPIST pour être utilisées par les modélisations 3D effectuées avec la méthode ADAM par une autre équipe. Ensuite, la méthode MPCD a été appliquée à chaque cible ayant été suffisamment observée par SPHERE (40 cibles sur 42), permettant d'obtenir de nouveaux modèles de formes. Nos

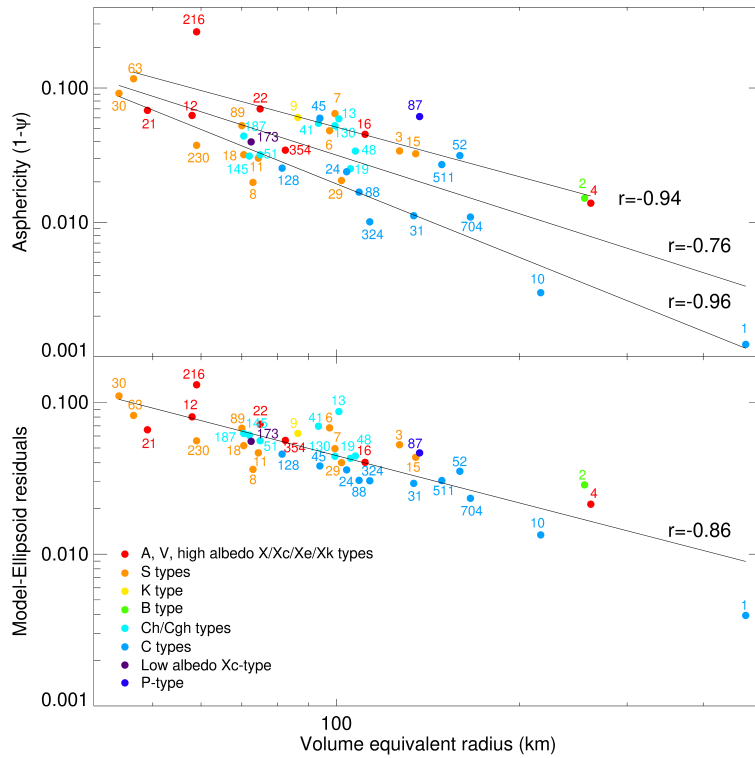


Figure 0.9.: *Panneau supérieur* : Asphéricité de nos cibles en fonction de leurs tailles. *Panneau inférieur* : Écart par rapport à un ellipsoïde de nos cibles en fonction de leurs tailles. Les deux quantités apparaissent fortement corrélées avec la taille. Dans le cas de l'asphéricité, l'ajustement séparé de sous-échantillons augmente encore les coefficients de corrélation.

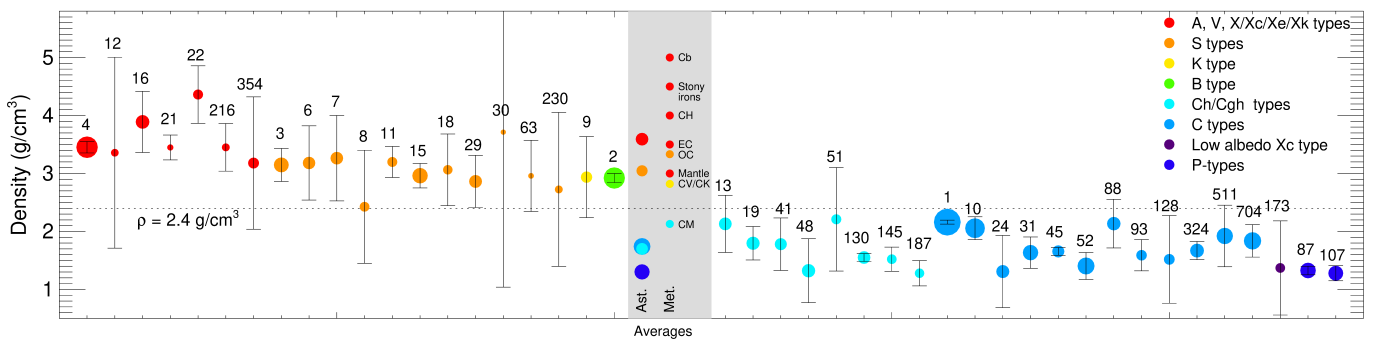


Figure 0.10.: Distribution de la densité de nos astéroïdes. Les astéroïdes sont regroupés selon leur classification spectrale, et leur densité moyenne est comparée à leurs analogues météoritiques potentiel au centre de la figure. Les barres d'erreur correspondent à des valeurs de 1 sigma.

modèles montrent un meilleur ajustement avec les images observées et des volumes proches de ceux des modèles ADAM.

En parallèle à la modélisation de chaque cible, je me suis également concentré sur deux objets particulièrement intéressants, Psyché et Calliope. Ces deux astéroïdes de type M ont révélés des densités très importantes, les plus élevées connues à ce jour pour des petits corps du Système Solaire. La forme 3D de Psyché, qui est la cible d'une prochaine mission Discovery de la NASA, implique une forme primordiale proche de celle d'un ellipsoïde de Jacobi. La densité apparente de Calliope a été déterminée à partir de son modèle de forme et de la dynamique de son satellite. Sa densité élevée, associée aux déterminations précédentes de sa composition de surface riche en silicate, suggère fortement un intérieur différencié.

L'analyse de tous les modèles de forme a montré une division en deux familles d'objets, les sphériques et les allongés. Enfin, la grande différence entre les densités obtenues a fourni des indices sur les origines des principales classes de composition.

À l'avenir, la méthode MPCD deviendra de plus en plus pertinente avec l'arrivée des télescopes géants tels que l'ELT. La résolution améliorée entre 3 et 5 fois par rapport à SPHERE permettra d'étudier la surface de nos cibles de façon beaucoup plus détaillée, ainsi que de viser des astéroïdes plus petits ou plus lointains, notamment en dehors de la ceinture principale.

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# 1. Introduction

The main topic of this thesis is the study of the small bodies of the Solar System, in particular the largest main belt asteroids. This first chapter starts by introducing general knowledge on the small bodies of the Solar System (Sect. 1.1). The nature of the asteroids is discussed, along with their composition, their formation and subsequent evolution in the context of the Solar System history. The next section present an overview of the methods used to study the physical properties of asteroids, focusing on the most relevant to this thesis (Sect. 1.2). The last section of this chapter is devoted to the description of an ESO imaging survey of the largest main belt asteroids in which this thesis take place (Sect. 1.3).

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## 1.1. The small bodies of the Solar System

### 1.1.1. What are they ?

The small bodies of the Solar System are the leftovers of the material that accreted to form the planets at the beginning of the Solar System. These airless bodies can be found almost everywhere in the Solar system, ranging in size from meters to hundreds of kilometers and in composition from rocky to icy. With more than one million known asteroids, they are by far the dominating component, not in mass but in number, of the Solar System. Asteroids are with the comets and the *Trans-Neptunian Objects* (TNOs) among the most pristine objects formed in the initial solar nebula, some 4.6 billion years ago. Since their formation, they have experienced many collisions as well as thermal and dynamical evolution processes that shaped their present day properties. As such, studying their compositions, orbital distributions, and physical properties is fundamental to better understand the initial conditions that existed in the solar nebula and the subsequent evolution of our planetary system.

### 1.1.2. Where are they in the Solar System ?

The small bodies of the Solar System exhibit an incredible diversity in compositions and orbital properties. Their location and distribution are not random, they are thus separated in several populations called *Near-Earth Asteroids* (NEAs), *Main-Belt Asteroids* (MBAs), giant planet Trojans, irregular satellites, Centaurs, TNOs and comets.

The MBAs, by far the most numerous group, are found in a region called the main belt located between the orbits of Mars and Jupiter, between 1.5 and 4 *Astronomical Unit* (AU). The gravitational influence of Jupiter prevented the formation of a planet in this region of the Solar System. The distribution of objects inside the main belt is not homogeneous. Some groups, thought to be fragments of past asteroid collisions, share similar proper orbital elements (semimajor axis  $a$ , eccentricity  $e$ , and orbital inclination  $i$ ) and are called asteroid families. They appear as local concentrations in the distribution of the orbital elements (Fig. 1.1). On the contrary, there are also gaps in these distributions. They are called the Kirkwood gaps and correspond to the 3:1, 5:2, and 2:1 mean motion resonances with Jupiter. The orbits at these peculiar locations are unstable. Objects found there are gradually excited dynamically by the gravitational interactions with Jupiter which increase the eccentricity of their elliptical orbit.

The ejected asteroids can sometimes arrive in the vicinity of the Earth and become NEAs. They are defined by a semi-major axis  $a < 1.3$  AU. They can sometimes closely approach the Earth, which is a great opportunity to study these small objects coming from the main belt that are usually too faint to do so. However, they can also pose a threat to Earth in case of impacts. They are thus very important to study in order to discover them, characterize their orbit and assess impact probabilities, characterize their composition and structure, which plays a very important role to determine the

## 1. Introduction – 1.1. The small bodies of the Solar System

consequences of an eventual impact.

On the other side of the main belt, the Trojan asteroids can be found at the L4 and L5 Jupiter Lagrange points, following or preceding by  $60^\circ$  the giant planet on its orbit. Further away from the Sun are found the Centaurs which are a transient population on unstable orbits, and the TNOs, which are found below the orbit of Neptune as indicated by their name. Because they formed further away from the Sun, these objects possess more volatile-rich compositions and densities than objects that formed inward the snowline. The region in which they are found is referred to as the Kuiper belt. Almost all known dwarf planets are found there.

Comets are icy objects that present a coma and a tail due to outgassing of their volatile elements when passing close the Sun because of their highly eccentric orbits. They originate from the Kuiper or the Oort cloud, a spherical region outside the Kuiper belt. Finally, some asteroids referred to as active asteroids have been found to display cometary-like activities.

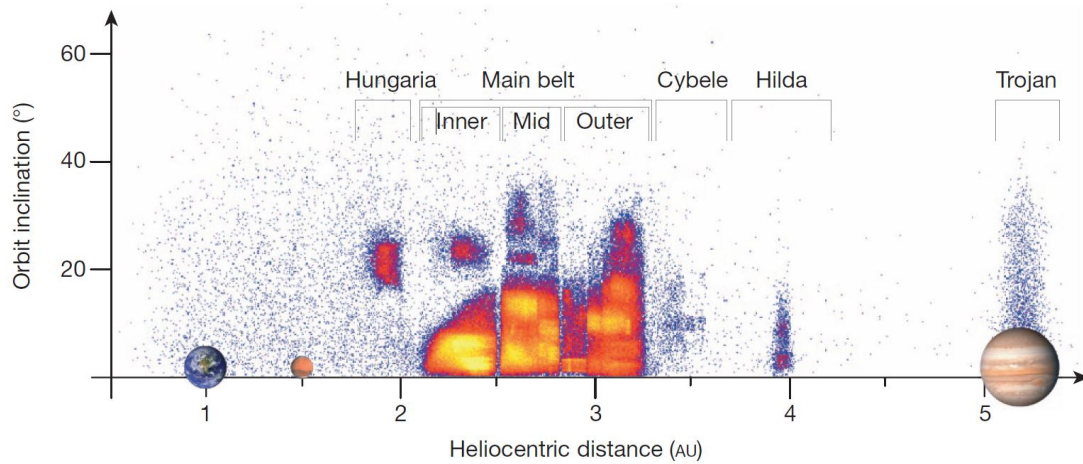


Figure 1.1.: Distribution of the MBAs as a function of their semi-major axis and orbital inclination (DeMeo and Carry, 2014).

### 1.1.3. Composition and classification

The composition of the small bodies evolves with their distance of formation to the Sun. The amount of volatile elements (ices) increases with the distance to the Sun and thus with lower temperatures. The densest materials formed in the inner Solar System, while the most distant regions are composed of ice dominated bodies. As such, knowing the current distribution of the elements is highly important to go back to the conditions at the beginning of the Solar System.

With the first reflectance spectra of asteroids obtained in the 1970s, the first proposition of a classifications of the asteroid population in distinct groups were proposed (Chapman et al., 1971, 1975). There were initially three categories: the S class regrouping the "stony" asteroids; the C class, that includes the "carbonaceous" asteroids; and

## 1. Introduction – 1.1. The small bodies of the Solar System

the U class, for objects that could not be categorized in the other two. S asteroids are generally bright, dense, and mostly composed of silicates. The C asteroids are darker, less dense, and are composed of carbonaceous material. These classifications, or taxonomies, were later refined by using the visible and Near-InfraRed (NIR) spectral properties, as well as albedos, of asteroids. There are three main taxonomical classification used today: Tholen (Tholen, 1984), SMASS (Bus and Binzel, 2002), and Bus-DeMeo (DeMeo et al., 2009).

The Tholen (Tholen, 1984) taxonomy was developed from photometric measurements obtained from the ultraviolet to the visible in the framework of the Eight-Color-Asteroid Survey (ECAS), along with albedos measurements. It consists in 14 different classes, most of which are grouped into three main classes C, S and X, the later including the metallic asteroids.

The Small Main-belt Asteroid Spectroscopic Survey (SMASS) survey gathered a set of 1477 reflectance spectra in the visible (from 0.44 to 0.92  $\mu\text{m}$ ), which are at the base of the classification of same name (Bus and Binzel, 2002). This survey provided a much better resolution than ECAS, allowing resolve much subtle features. This taxonomy defines 24 asteroid types that are grouped in three main complexes, homonyms to those of the Tholen classification.

The SMASS taxonomy was later extended to the NIR region by adding spectra covering wavelengths from 0.82  $\mu\text{m}$  to 2.45  $\mu\text{m}$  (DeMeo et al., 2009). The Bus-DeMeo taxonomy also defines three major groups: C, S, and X, plus end members that do not fall in another category (Fig. 1.2). Subcategories denoted with a second lowercase letter corresponds to transition between the main type and a second type designed by the lowercase letter.

These observations and classification efforts allowed to reach a preliminary understanding of the compositional distribution across the different populations. It was notably found that the composition of the main belt is partially structured. Fig. 1.3 illustrates this by showing the contributions of different taxonomic types across the main belt. While the inner main belt is mostly composed of stony asteroids, a majority of carbonaceous asteroids is found in the outer belt. However, there are also significant composition overlap, which suggests that the main belt must have experienced mixing after its formation. This observation, along with others, indicates that the history of the Solar System was not a static one, but is instead an history of dynamic changes (DeMeo and Carry, 2014; Nesvorný et al., 2018).

### 1.1.4. Internal structure and link with the meteorites

Asteroids can have a variety of internal structures, from homogeneous to fully differentiated, and from coherent to loose aggregates called rubble piles. It mainly results of (i) the initial heating the body experienced after its accretion due to the presence of short-lived radionuclides; and (ii) violent impacts that could fracture and heat the asteroid, or even completely fragment it. The different outcomes for the internal structures are illustrated in Fig. 1.4. In this figure, different material that experienced

## 1. Introduction – 1.1. The small bodies of the Solar System

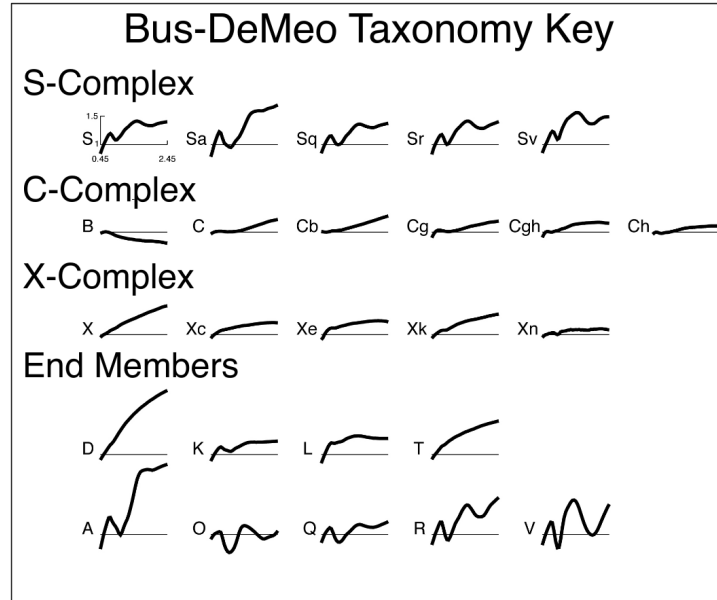


Figure 1.2.: Mean spectra of the 24 asteroid types defined by the Bus-DeMeo taxonomy (DeMeo et al., 2009).

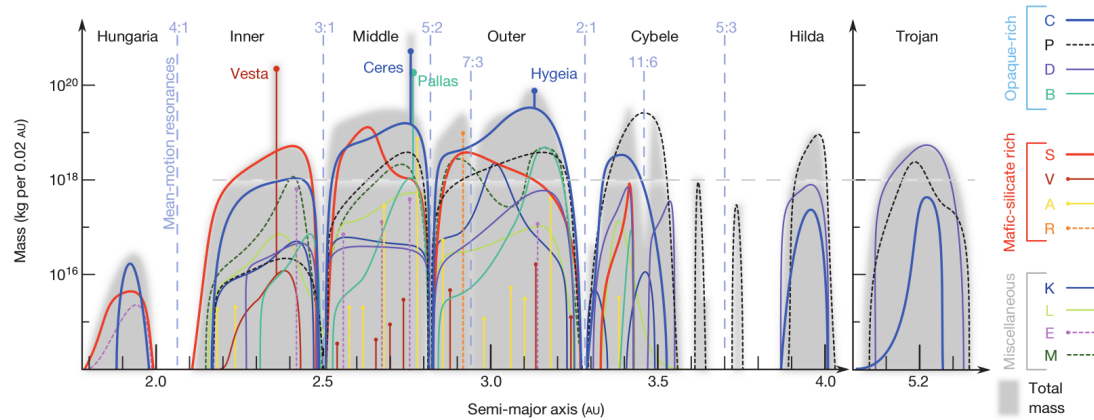


Figure 1.3.: Compositional mass distribution of the main belt as a function of the semi-major axis (DeMeo and Carry, 2014).

## 1. Introduction – 1.1. The small bodies of the Solar System

different metamorphism are represented by different colors.

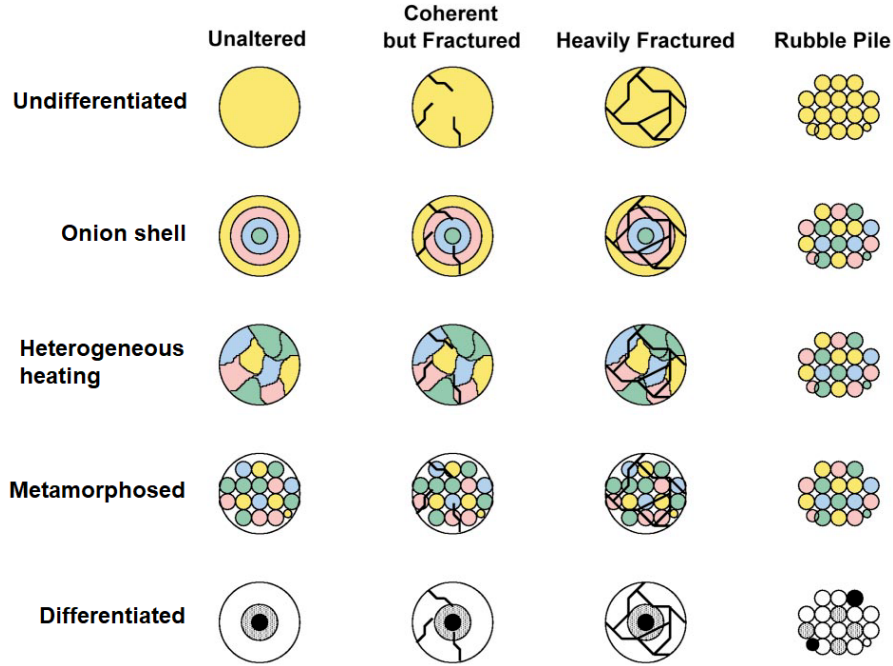


Figure 1.4.: Schematic summarizing the different internal structures of asteroids for different level of fracturation and heating. Adapted from (Wilkison et al., 2002).

The interior properties of asteroids are not easily accessible because the surface composition determined by spectroscopic measurements are not necessarily representative of the internal composition and structure. Meteorites are fragment of asteroids that have fallen on Earth. Hence meteorites are considered as reflection of the compositional diversity of MBAs, with some limitations.

There are two main groups of meteorites, those resulting from planetary differentiation (achondrites and iron meteorites), and the more primitive chondrite meteorites. Achondrites and iron meteorites show signs of melting and metamorphism due to differentiation processes that also separated metals from silicates. Their origin in the parent body determines the composition and density: metal-poor for the external layers and metal-rich for the core. The chondritic meteorites are composed of chondrules embedded in a matrix. Chondrules are round inclusions with size up to a more than a centimeter that formed at high temperature during the formation of the Solar System. Meteorites can be analyzed in laboratory to precisely determined their composition. Then, linking asteroids classes with meteorite types allows to constrain the compositional distribution of the main belt (Fig. 1.5). This is not an easy task and not all asteroids possess a meteoritic analogue. Moreover spectra of different parent bodies can sometimes corresponds to the same meteorite group (Vernazza et al., 2016, 2014).

## 1. Introduction – 1.1. The small bodies of the Solar System

If the density of an asteroid can be estimated, and that its spectral type can be linked with a meteorite type, then it is possible to deduce some information on its internal structures by comparing the asteroid density with the corresponding material density (e.g. [Scheeres et al., 2015](#)). Asteroid can be fractured, which results in the presence of internal void called macroporosity. In the case of an homogeneous body, the porosity  $\Psi$  can be derived from the bulk density  $\rho_{bulk}$  and the density of the material it is composed of  $\rho_{material}$  as:

$$\Psi = 1 - \frac{\rho_{bulk}}{\rho_{material}}. \quad (1.1)$$

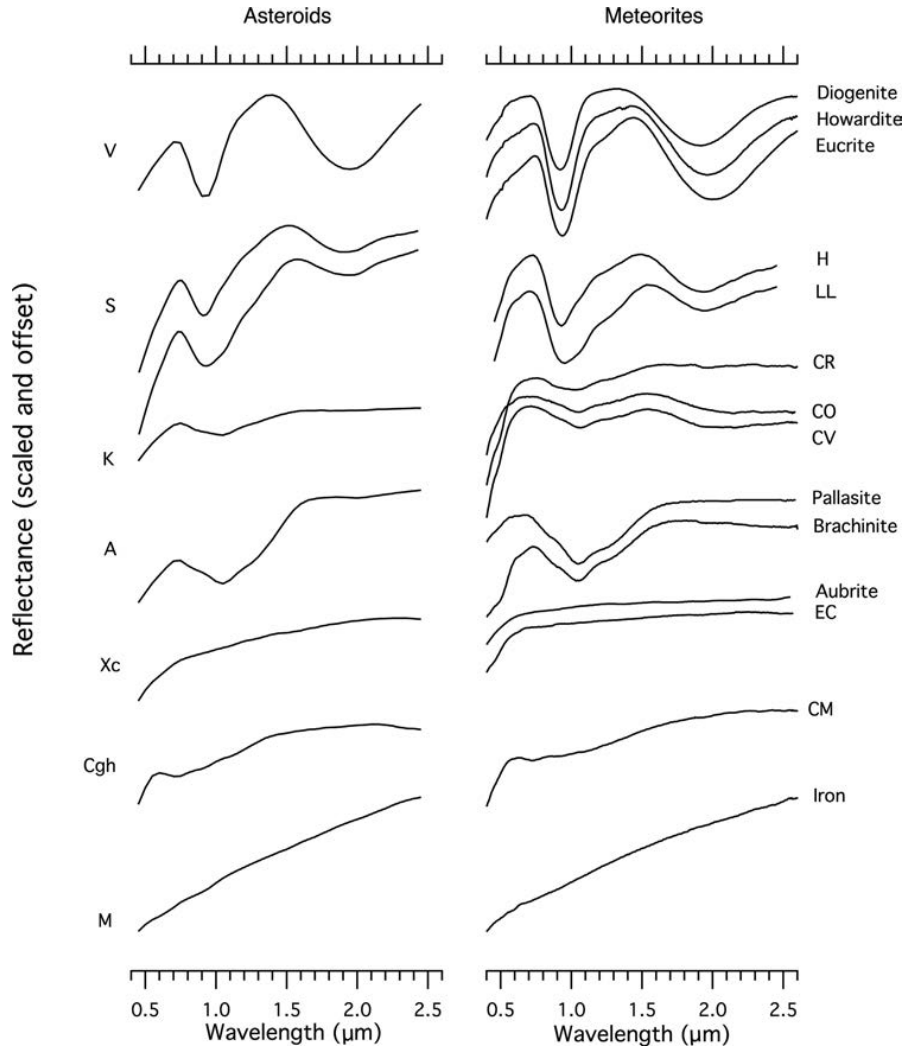


Figure 1.5.: Association between several classes of MBAs and their associated meteorites via their visible and NIR spectra ([Vernazza and Beck, 2017](#)).



### 1.1.5. Formation and dynamical evolution

The formation of the Solar System began some 4.56 billion years ago with contraction of a protosolar nebula, giving birth to a proto-Sun surrounded by a protoplanetary accretion disk. Then, the dust present in the disk condensed and accreted into  $\mu\text{m}$  particles, grains, and then pebbles, helped by concentration mechanisms in turbulent structures present in the disk (Cuzzi et al., 2008; Johansen et al., 2007). This process led to the formation of the planetesimals of 100 to 1000 km in size (Johansen and Klahr, 2011). The inner region of the Solar System was too hot to allow volatile elements to condense. Thus, the planetesimals that formed inward the snowline should have been composed only of refractory material such as silicates and metals. On the contrary, volatile-rich planetesimals should have formed beyond the snowline (Fig. 1.6, panel b).

However, the Solar System we observe today is much less ordered than what should have been the primordial architecture of the planetesimal belt (for a review on the composition of the small bodies, see Vernazza and Beck, 2017). Observations of the visible and NIR spectral properties, from albedos, and from meteorites associations revealed that the main belt has undergone substantial mixing and constitutes a sample of compositions coming from all regions of the Solar System (Fig. 1.6, panel a). Moreover, the high inclination and eccentricities of the giant planet Trojans, the peculiar orbital properties of the TNOs or the discovery of "hot Jupiters" orbiting close to their stars are other evidences of a dynamic history for the Solar System.

By comparing the present architecture of the Solar System with the primordial compositional gradient, the required migration of material for different compositional classes can be deduced (Fig. 1.6, panel c). Important transfers from the outer Solar System to the main belt are notably necessary. Several numerical migration models have been developed to try to reproduce these observations. These dynamical models, such as the Nice model (Levison et al., 2009; Morbidelli et al., 2005; Tsiganis et al., 2005) and the Grand Tack model (Walsh et al., 2011) postulates that planetary migrations are at the origins of the gravitational perturbations that disperse the small bodies. However, they are all subject to debates.

Therefore, deciphering the main belt collisional and dynamical evolution is very important to decode the Solar System's past due to its high diversity as it allows to provide constraints on planetesimal and planet formation models (e.g. Bottke and Morbidelli, 2017; Vernazza and Beck, 2017).

## 1.2. Physical properties

Along with the characterization of the orbital and surface properties of asteroids, the study of their physical properties is as much essential to better understand our Solar System and its small bodies. The physical parameters of asteroids comprise the mass, the size, the spin (rotation period and orientation), and the shape. These parameters can all reveal different new facts about the nature of asteroids and the mechanisms of

## 1. Introduction – 1.2. Physical properties

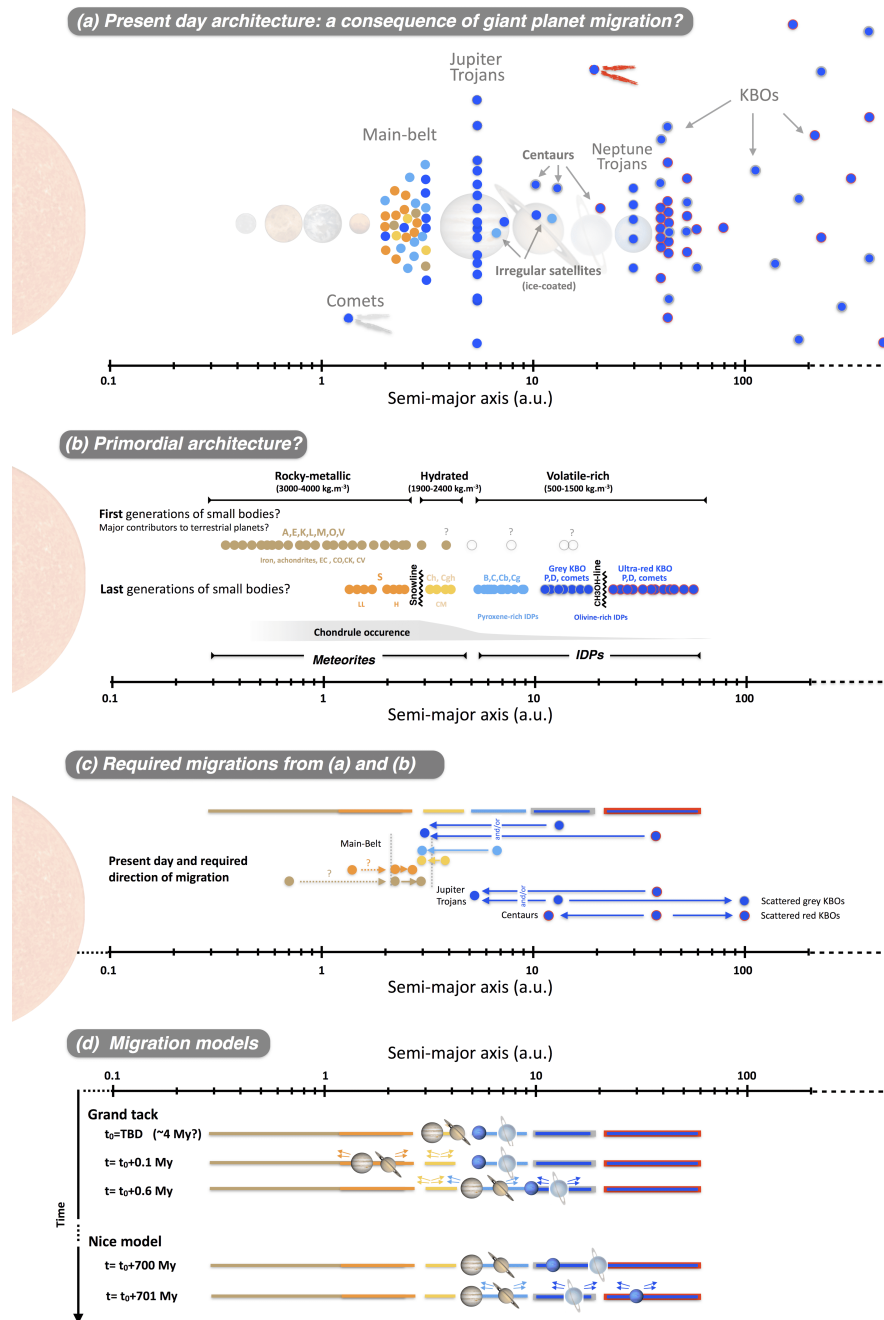


Figure 1.6.: Diagrams of the dynamical evolution of small bodies from [Vernazza and Beck \(2017\)](#). The architecture of populations of small bodies observed today (a) is compared to a the possible primordial compositional gradient (b). Then, panel (c) present the migrations required to obtain the present day structures which can be compared with the predictions from different migration models (d).

their evolution.

All bodies of the Solar System mutually perturb each other gravitationally. Therefore, mass estimations of asteroids are valuable to the ephemeris models that can be used to plan, for instance, spacecraft flybys or stellar occultations.

Studying the asteroids spin rates with respect to their diameters has brought to light a so called spin-barrier at a period of rotation of about 2.2 h for asteroids of  $D \geq 0.15$  km (Harris, 1996; Pravec and Harris, 2000). This barrier suggests that objects spinning faster than 2.2 h must have a monolithic structure in order not to fly apart. Larger asteroid, however, are thought to be rubble piles which are loose aggregations held together by gravity but with no assumed internal cohesion. Therefore, they cannot rotate exceedingly fast, otherwise they would break because of the centrifugal force overcoming the gravity.

Studying the spin axis distribution has brought to light a size dependency, with pole latitudes of smaller objects clustering towards values of  $\pm 90^\circ$  (Hanuš et al., 2011). This was explained by the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect<sup>1</sup>, which is more effective on smaller asteroids.

Sizes and 3D shapes provide volume estimations which, when combined with the mass, yields bulk densities. Density is one of the most fundamental properties to constrain the bulk composition and internal structure of asteroids, and thus their formation and evolution (Scheeres et al., 2015).

Many more examples could be cited, but one thing to note is the importance of the shape models. Indeed, producing a shape model always come with a determination of the rotation period and the spin axis orientation. If the model is scaled, it also provides the dimensions and the volume of the body. There are two main strategies in shape model reconstruction. The first one is to produce many low resolutions models using an abundant data source, usually photometry. The large number of models provide statistically significant samples of asteroid populations that can be used to study their physical properties. The second strategy is to produce the most detailed model possible for selected targets using the best data from different sources. These well described targets can then be used to extrapolate on the whole class they belong to. In this thesis, we combined the two strategies. Indeed, a representative sample of the largest MBAs was selected and observed during an ESO large program (see Sect. 1.3). For each target, the best shape model possible were produced. Then, some particularly interesting objects were subject to detailed study (in my case, the dense M-type asteroids Psyche and Kalliope, presented in Chapter 4). Finally, the sample was studied as a whole to try to derive conclusions on the different classes (Chapter 5).

We review in this section the different data types and the associated methods used to characterize the physical properties of asteroids that are relevant to this work.

---

<sup>1</sup>A non-gravitational effect due to thermal radiations modifying the rotational properties of  $D \leq 30$  km asteroids.

### 1.2.1. Photometry

Photometry is the measure of the brightness variation of an object with time. It is the most abundant data source as it is easily obtainable for many asteroids even with small equipment.

#### Lightcurves

Because of their irregular shapes, the brightness of asteroids changes with time as they rotate around their spin axis. The variation of the projected area on the plane of the sky presented by an asteroid modifies the amount of disk-integrated solar light that is reflected. Measuring the apparent flux or magnitude of an asteroid as a function of time allows to construct its so-called rotational lightcurve. Fig. 1.7 shows an example of a lightcurve and the relation with the shape of the asteroid.

Lightcurves can be of two kinds: dense or sparse-in-time. Dense lightcurves are the result of dedicated observation sampling densely the rotation of an asteroid during several hours and for one or several nights close in time. The sparse lightcurves consist in individual measurements spanning months or years and are usually the by-product of sky surveys.

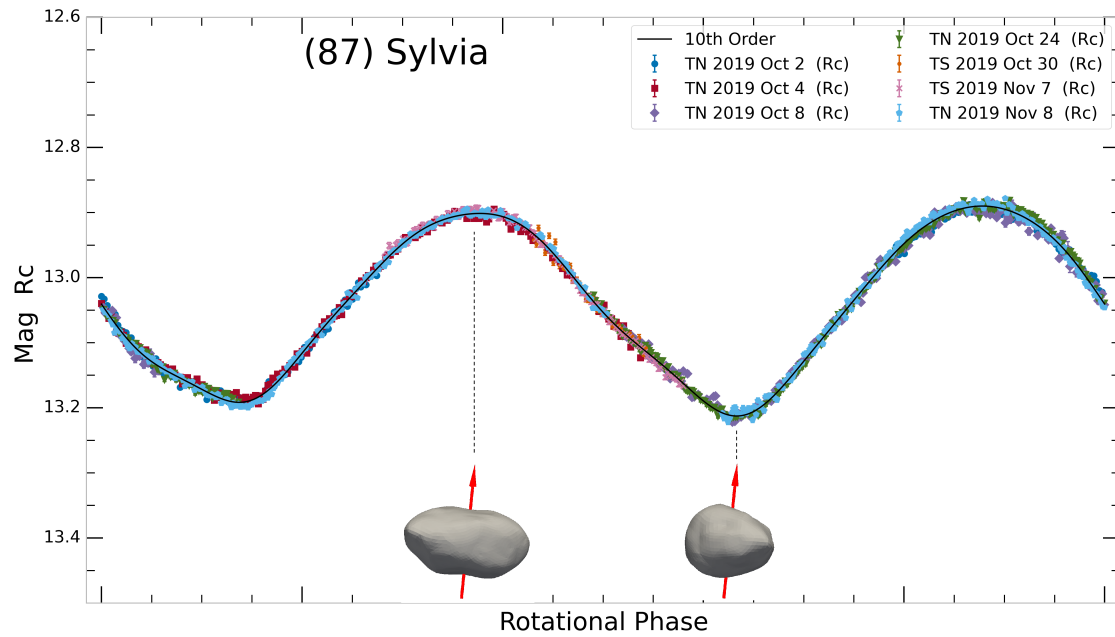


Figure 1.7.: Lightcurve of the asteroid (87) Sylvia. Its shape model at the time of a maximum and a minimum shows the corresponding variation of the projected area presented by the asteroid.

#### Rotation periods

The most direct parameters that can be derived from lightcurves is the synodic rotation

period from mathematical analysis (such as Fourier, see Fig. 1.8) of the periodicity. Most asteroids have rotation periods between 4 and 10 h. However, some rotate much slower in tens of days while some small monolithic bodies can rotate much faster, in only a few minutes. A single lightcurve covering a full rotation is in principle sufficient to determine the spin rate, but the accuracy will be greatly improved by increasing the time span of the observations.

Asteroid spins can be either in a relaxed or an excited state. A relaxed rotation corresponds to a spin vector aligned with the maximum moment of inertia and thus to the minimal energy state. This is not the case for asteroids in excited rotational state for which the rotation period and spin axis orientation change with time. This induces stresses on the asteroid interior, dissipating energy and modifying the inertia tensor over time. Asteroids in excited states tend to relax after a period of time, called the damping time, proportionate to the inverse square power of the diameter (Harris, 1994). Consequently, all large asteroids are found to be in a relaxed rotational state.

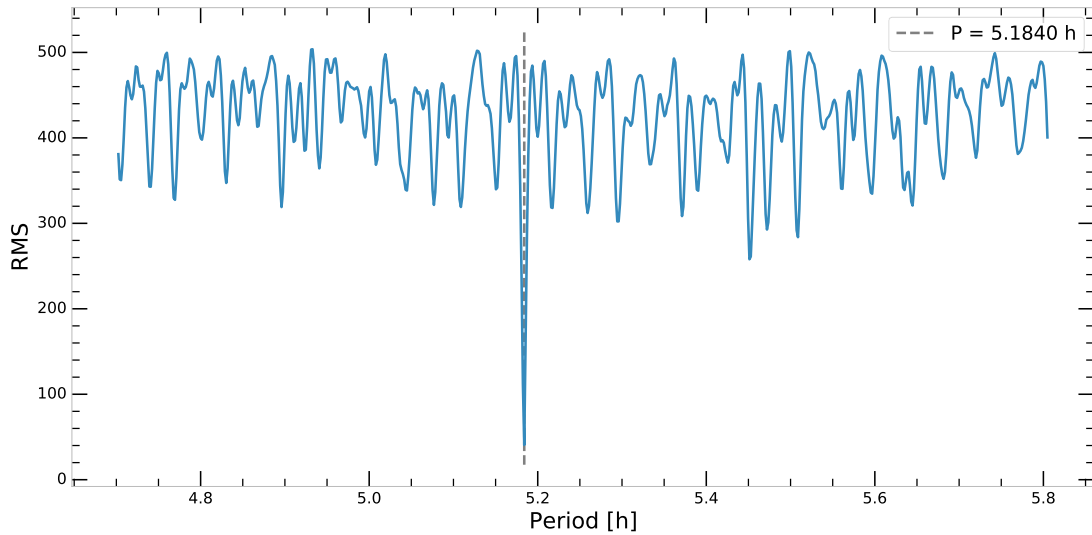


Figure 1.8.: Example of a periodogram of the asteroid (87) Sylvia obtained with the FALC method (Harris et al., 1989). A range of periods are tested and the lightcurve is fitted with Fourier series up to a given order. The best period corresponds to the lowest root mean square (RMS) residual.

### Spin axis orientations

The spin axis coordinates can also be determined by analyzing lightcurves from multiple apparitions (Magnusson et al., 1989). Usually, two ambiguous solutions separated a longitude difference of  $\sim 180^\circ$  are obtained. While small asteroids tend to cluster to extreme values of spin obliquity ( $\pm 90^\circ$ ) because of the YORP effect, an excess of prograde rotators is observed for larger asteroids that better retained their primordial rotational states.

### Shape models

Finally, the ultimate goal of lightcurve acquisitions is to determine the 3D shape of the observed asteroids. A basic shape representation is the triaxial ellipsoid model, parameterized by the length of three axis  $a \leq b \leq c$ . The lightcurves amplitudes provide information on the relative dimensions of the asteroid, given as the axis ratios  $b/a$  and  $c/b$ , and thus on its elongation.

However, asteroids are usually very irregular and are not well represented by the ellipsoid model. A new framework of asteroid shape modeling was thus needed to address this limitation. In 2001, [Kaasalainen and Torppa \(2001\)](#); [Kaasalainen et al. \(2001\)](#) presented a new lightcurve inversion technique modeling them by a convex shape model. This method requires observations covering a wide range of viewing and illumination geometries to produce unique solutions for the spin pole and the shape. It became a very popular method and had since been applied to derive hundreds of asteroids shapes. They are freely available at the [Database of Asteroid Models from Inversion Techniques \(DAMIT\)](#)<sup>2</sup>.

The lightcurves do not provide information on the size or on any small-scale details and concavities. Fortunately, this lack is notably filled by the techniques described in the following sections. From disk-integrated photometry alone, only convex global shape can be produced. To ensure unique solutions of the inverse problem, MBAs need to be observe during several apparitions in order to gather data at sufficiently different geometries (Sun-asteroid-Earth relative positions). For NEAs that closely approach the Earth, a single flyby can sometimes be sufficient. However, Centaurs and TNOs are too far away and thus can never be observed at significantly different geometry than opposition.

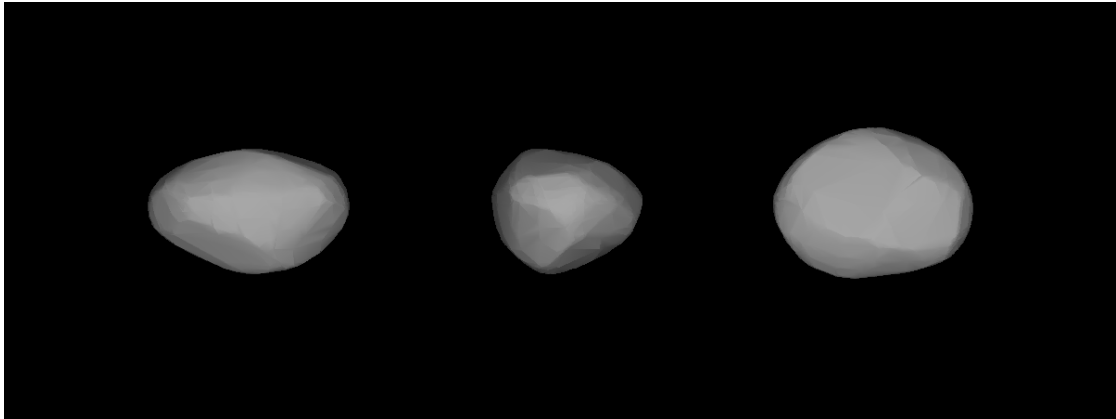


Figure 1.9.: Shape model of (22) Kalliope derived by the lightcurve inversion method ([Hanuš et al., 2011](#)).

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<sup>2</sup><https://astro.troja.mff.cuni.cz/projects/damit/>

### 1.2.2. Stellar occultation

When an asteroid passes in front of a star as seen from Earth, it temporarily blocks the light of the star during a few seconds, depending on the size of the asteroid. With the apparent velocity of the asteroid on the plane of the sky, a physical length can be derived from the duration of the event and fitted on the asteroid **Two-Dimensional (2D)** disk. This length is called a chord. Stellar occultations are a good complement to the lightcurves as they provide a measurement of the size that can be used to scale shape models from lightcurves inversion. They also provide direct information on the **Three-Dimensional (3D)** shape if multiple chords are acquired by observers dispersed on the occultation path (Fig. 1.10). Stellar occultations can also be further combined with other data type, like high-resolution images, to bring additional information on the size and the shape (see Sect. 1.2.5 below).

Stellar occultations can be observed even with small telescopes if the star is bright enough and an active community of amateur observers equipped with small portable instruments provide the majority of the occultation data. Even targets with very small angular sizes such as the TNOs can be studied. Indeed, the accuracy of a chord measurement depends mainly on the accuracy of the timing of the star disappearance and reappearance. To constrain the shape, many observers covering a large geographical area are needed to record multiple chords spaced out on the asteroid disk. Then, the accuracy on the sky position of the chords is determined by the accuracy on the absolute timing between chords from different observers when merging them together.

However, such an event is rare for a given asteroids and the accuracy of the available ephemeris prevent accurate predictions for small asteroids. This situation is rapidly evolving thanks to the **European Space Agency (ESA)** Gaia space observatory, a spacecraft launched in 2013 and designed to obtain astrometric measurements with unprecedented precision. The Gaia Data Release 3 (Gaia DR3), recently made available in June 2022, contains astrometric solutions for around  $1.46 \times 10^9$  stars and more than 150 000 asteroids (Tanga et al., 2022). This will drastically increase the number of occultation predictions for a given object, facilitate the observations by reducing the uncertainties on the shadow path, and allowing the accurate predictions for much smaller objects.

### 1.2.3. Radar

Radar observation of asteroids is one of the few active methods in astronomy. The principle is to emit radio waves and then measure the distribution of the echo power that bounces back on the asteroid surface (Ostro et al., 2002). The time delay between the emission and the reception of the signal provides information on the range while the Doppler frequency informs on the radial velocity. It produces two-dimensional images, called delay-Doppler images, that directly provides information on the size, with up to decimeter spatial resolution, and on the rotation velocity (Fig. 1.11). These



## 1. Introduction – 1.2. Physical properties

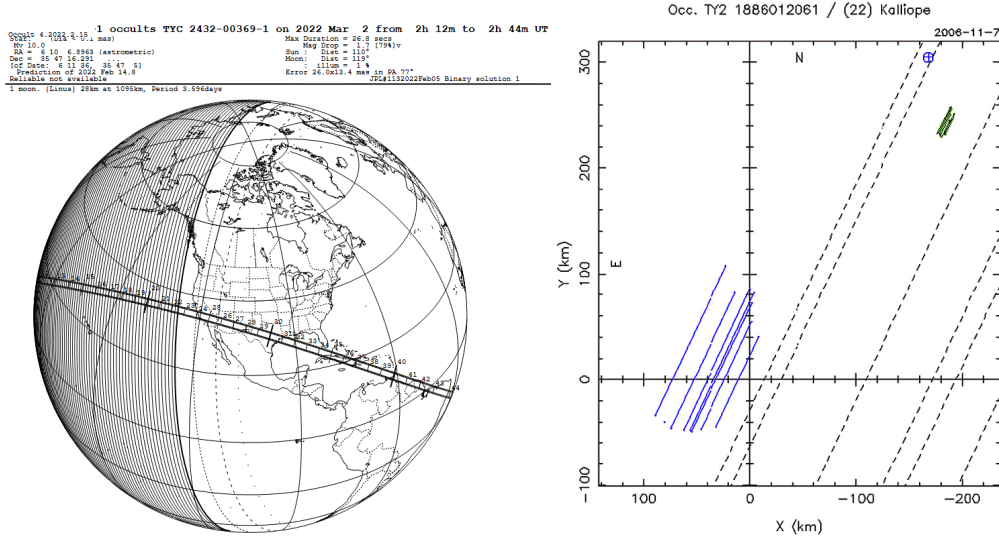


Figure 1.10.: *Left:* Example of a stellar occultation prediction by the asteroid (22) Kalliope on 2022 Mars 2, visible for observers located between the two parallel black lines that indicate the shadow path. The occulted star has a visual magnitude of 10.0 and the expected magnitude drop is 1.7, for a maximum duration of 26.8 s (Source: [S. Preston's website](#)). *Right:* Stellar occultation by (22) Kalliope observed in 2006. The blue chords correspond to Kalliope itself while the smaller green chords correspond to the occultation of the same star but by its satellite Linus. The dotted lines are negative chords for which no flux drop was recorded ([Descamps et al., 2008](#)).



images are characterized by an hemispherical degeneracy because of points of the asteroids being at the same distances and the same radial velocities.

Thanks to the microsecond accuracy on the time delay, radar observations strongly constrain the orbit determination. This is particularly important to drastically reduce uncertainties for newly-discovered NEAs and to expand accurate orbit-prediction intervals to decades or centuries for those previously observed (Benner et al., 2015).

Multiple Delay-Doppler images can be combined to constrain detailed shape models with concavities and rotation states. Because the echo power is proportional to the inverse fourth power of the distance, radar is limited to study NEAs during their close approaches and the largest MBAs. With the two main radar observatories studying Solar System bodies, the Goldstone telescope and the Arecibo telescope that sadly collapsed in December 2020, hundreds of NEAs and MBAs have been observed in radar. These observations revealed a large array of rotation states (complex and principal-axis), surfaces (smooth or rough) and shapes (spherical, highly elongated, contact binaries) along with binary and ternary systems. Moreover, radar albedo can reveal different surface compositions. For instance, the mean radar albedo of 0.37 which is the largest known so far, of the M-type asteroid (16) Psyche indicates a very metal rich surface (Shepard et al., 2017).

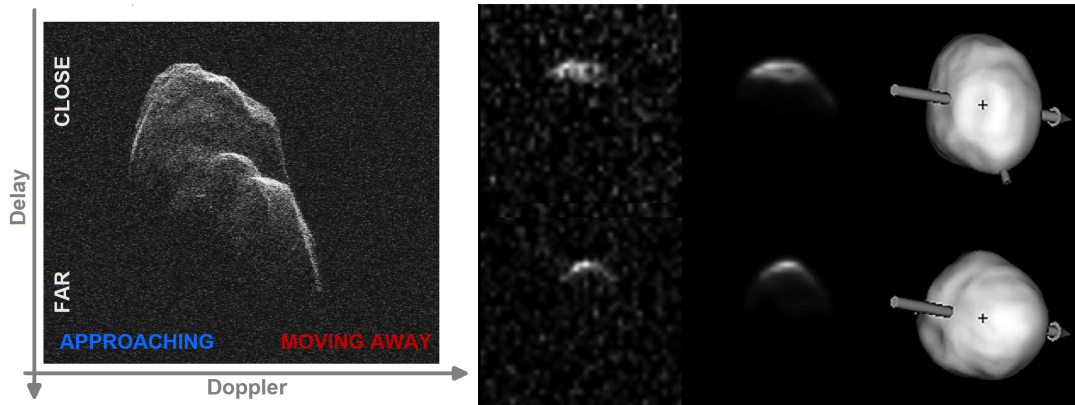


Figure 1.11.: *Left*: Example of a Delay-Doppler image of the NEA Toutatis obtained at the Goldstone Observatory in 2012. *Right*: Radar observations of the large MBA (16) Psyche (Shepard et al., 2017). The Delay-Doppler images are on the left and the corresponding shape model fits are on the right. On the center it is the simulated images from the shape model.

#### 1.2.4. High angular-resolution imaging

Disk-resolved images provide the most direct way to measure the size and shape of an asteroid. The apparent shape projected on the plane of the sky provide is given by the contour of the object delimited by the limb and the terminator. Obtaining multiple views during the course of the asteroid's rotation allows to determine the 3D shape.

Asteroids have small angular diameters ( $< 0.5''$ ), thus large telescope as well as special instrumentation and processing methods are required.

#### 1.2.4.1. Adaptive Optics

Even without the atmosphere, the image of a point-like source is not punctual because of the diffraction. The core of the diffraction pattern has an angular size  $\Theta$  given by:

$$\Theta = \frac{\lambda}{D}, \quad (1.2)$$

where  $\lambda$  is the wavelength of the received light and  $D$  is the diameter of the telescope. A diameter of 8 m observing in the visible at 500 nm translates in a diffraction limited resolution of  $\Theta \sim 0.013''$  (13 mas). However, ground-based telescopes are affected by the atmospheric turbulence of the air above it that is caused by layers of different temperatures and different wind speeds. The light rays coming from astronomical sources are deviated and distorted, causing a blurring of the image and a dramatic loss of resolution. Even if the large observatories on Earth are located in places with very favorable meteorological and atmospheric conditions, a typical value of the angular size of a star, the so-called atmospheric seeing, is of around one arcsecond which is  $\sim 100$  times larger than the diffraction limited resolution.

To improve the performance of optical systems, the **Adaptive optics (AO)** technique aims to correct in real time the incoming wavefront by deforming a mirror in order to compensate for the distortions (Fig. 1.12, left). To measure the shape of the distorted wavefront, a fraction of the incoming light is sent to a wavefront sensor. A reference source is used to measure the impulse response of the telescope and the atmosphere combined. This source can be a nearby star, and it is then called a Natural Guide Star (NGS) or an artificial source called a Laser Guide Star (LGS) that is created with a laser that excites sodium atoms in the mesosphere. There are several types of sensors used to reconstruct the wavefront. One of them is the Shack–Hartmann wavefront sensor that is notably used for the SPHERE instrument at the VLT. It consists in an array of lenses that sample the wavefront. A distortion of the wavefront introduces a displacement of the image centroid produced by each lens on a detector proportional to the gradient. This displacement is measured and used to reconstruct the whole wavefront (Fig. 1.12, right). The next step is to flatten the wavefront by introducing opposite deformations with a deformable mirror that consists in a mirror placed on an array of actuators that can contract or extend to deform the mirror. Wavefront corrections are harder to achieve for shorter wavelengths which is why AO instrument were first working in the infrared before being adapted to the visible.

#### 1.2.4.2. Observatories and instruments

Following the intense development of the AO in the last 30 years, every large observatories are now equipped with AO instruments in order to take full advantage of the

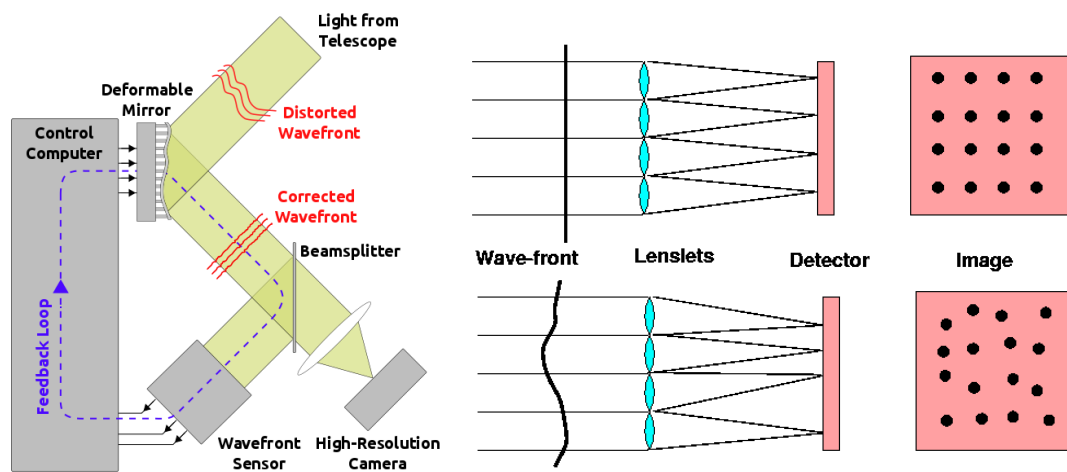


Figure 1.12.: *Left:* Schematic of an AO system. A beam splitter is used to deviate a small part of the flux toward the wavefront sensor while the rest reach the camera. The wavefront is measured and the data collected with a computer which then control the deformable mirror to correct the wavefront, closing the loop. *Right:* Schematic of a Shack-Hartmann wavefront sensor. An array of small lenses is slicing the wavefront and each lenses produces an image on a detector. The distortion of the wavefront induces displacements of the images with respect to their reference positions that can be measured and the whole wavefront reconstructed.

diameter of their telescopes. I present here the instruments and the observatories hosting them from which data related to this thesis come from. The ESO/SPHERE/ZIMPOL instrument was used to obtain the high-resolution images used for the asteroid shape modeling. For all the other instruments, archival data were gathered for the orbit determinations of the satellites of the multiple systems.

**The W. M. Keck Observatory** consists in two twin 10-m telescopes located on the Mauna Kea summit in Hawaii. They started operating in 1993 and 1996 and were the largest telescopes ever built until 2007. Their mirrors are composed of 36 hexagonal segments. The Mauna Kea site is an interesting location because of its high altitude of 4200 m and the good atmospheric conditions thanks to the ocean that provide temperature stability and an absence of relief that could create turbulent winds. The second telescope, Keck II, hosts the Near InfraRed Camera 2 (NIRC2) camera, a spectro-imager in the NIR at 1-5  $\mu\text{m}$  (van Dam et al., 2004; Wizinowich et al., 2000). With the smallest field of view available, the pixel scale is 9.94 mas/pixel.

**The Gemini Observatory** is composed of two 8-m telescopes, one in each hemisphere, that started observing in 2000. Gemini-North is located on the Mauna Kea summit in Hawaii and Gemini-South is on the Cerro Pachón in Chile. The Near Infra-Red Imager and Spectrometer (NIRI) instrument is mounted on Gemini-North (Hodapp et al., 2003). It is a spectro-imager operating in the NIR (1-5  $\mu\text{m}$ ). The smallest pixel scale available is 22 mas/pixel.

**The Very Large Telescope (VLT)** is the European Southern Observatory (ESO) flagship observatory, located on the Cerro Paranal at 2635 m in the Atacama Desert in Chile. The dry climate of the desert makes the location very favorable for observations, with more than 300 clear nights per year and a mean seeing of 0.8". The VLT is composed of four identical 8.2-m telescopes, or Unit Telescopes (UT), inaugurated between 1998 and 2001 and since equipped with several AO instruments.

- **NACO:** Adaptive optics was introduced to the VLT on 2001 with the instrument NAOS-CONICA (NACO) that couple the Nasmyth Adaptive Optics System (NAOS) AO system to the scientific camera Near-Infrared Imager and Spectro-graph (CONICA) (Lenzen et al., 2004; Rousset et al., 2003). It comprises a spectrometer, a polarimeter and an imager working in the NIR (1-5  $\mu\text{m}$ ). The AO system is adapted to point-like sources but also to slightly extended objects, making it suitable for asteroids observation that can be used as natural guide stars. The smallest pixel scale available is 13.22 mas/pixel and the diffraction limited resolution in the K band is 50 mas.

- **SPHERE:** Later on, a second generation instrument of extreme AO was developed and achieved first light in 2014. Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) has been thought as a planet finder instrument. SPHERE provides direct imaging complemented by spectroscopic and polarimetric capability in the NIR and the visible (Beuzit et al., 2008). It is installed on the UT3 of the VLT (Fig. 1.13). Several subsystems are available.



Figure 1.13.: *Left*: The telescope of the UT3 (*Melipal*) of the VLT. The SPHERE instrument is visible in the bottom right corner (Credit: ESO, J. Girard). *Right*: One of the four 8.2-m telescopes of the VLT, here the UT4 *Yepun* observing with its laser guide star.

The Infra-Red Dual Imaging and Spectrograph (IRDIS) can provide NIR classical imaging with a pixel scale of 12.25 mas/pixel.

The Zurich IMaging POLarimeter (ZIMPOL) is a high contrast imaging polarimeter operating in the NIR and the visible (Beuzit et al., 2019). It also has a diffraction limited classical imaging mode and is the first instrument to bring AO capability in the visible. The shorter wavelengths of the visible spectra imply higher spatial resolution than in the NIR. Indeed, combined with the diameter of 8.2 m of the telescope, the diffraction limited resolution of ZIMPOL is  $\sim 15$  MilliArcSecond (mas) which is  $\sim 3.5$  times better than the Hubble Space Telescope. It represents a major improvement compared to the previous AO system such as NACO. This is well illustrated by the Fig. 1.14 with a comparison of the MBA Pallas ( $D \sim 515$  km) as seen from both instruments. ZIMPOL can indeed also be used to observe Solar System objects, notably providing spectacular images of large MBAs that can reveal their detailed shapes, the presence of eventual small companions, and surface features larger than  $\sim 30$  km such as impact craters.

#### 1.2.4.3. The deconvolution

The correction provided by the AO is never perfect and a post-processing step is required to restore the optimal angular resolution of the images. This processing is called the deconvolution and it aims at minimizing the blurring of the image by the Point Spread Function (PSF). The PSF is the response of the optical path which, in an ideal case, would be a simple Airy pattern caused by the diffraction. Instead, the remaining PSF is only partially corrected by the AO and it is necessary to estimate it to deconvolute and extract the details on the observed object. The deconvolution process is called myopic if the PSF is partially known or blind if it is completely unknown. An estimation of the PSF can be obtained by measuring a star (i.e., a point-like source)

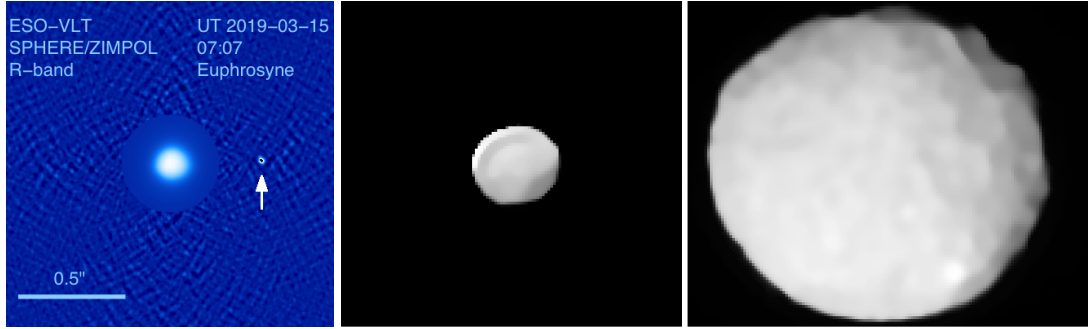


Figure 1.14.: *Left:* Discovery of a moon of the asteroid (31) Euphrosyne in SPHERE/ZIMPOL images in 2019 (Yang et al., 2020). The moon is the faint, non-resolved, source indicated by the white arrow. *Center and right:* Comparison of (4) Pallas ( $D \sim 515$  km) as seen by NACO (center) and by SPHERE/ZIMPOL (right). These images illustrate the large progress in resolution achieved by the ZIMPOL instrument. Craters are clearly identifiable which was not the case with previous AO systems.

in the field of view. When no stars are present in the image, a reference star close in angular separation can be observed shortly before or after the scientific image acquisition. The deconvolution is an ill-posed problem, but robust algorithm such as Myopic Iterative STEP preserving Restoration ALgorithm (MISTRAL) can be used to simultaneously determine the object and the PSF (Fusco et al., 2003; Mugnier et al., 2004). MISTRAL is particularly adapted to restore the sharp edges and planar regions of asteroid disks. The deconvolution is a critical part of the post-processing. Indeed, improper deconvolution can introduce systematic errors on the apparent size and contour determination as well as artifacts that will perturb the shape modeling.

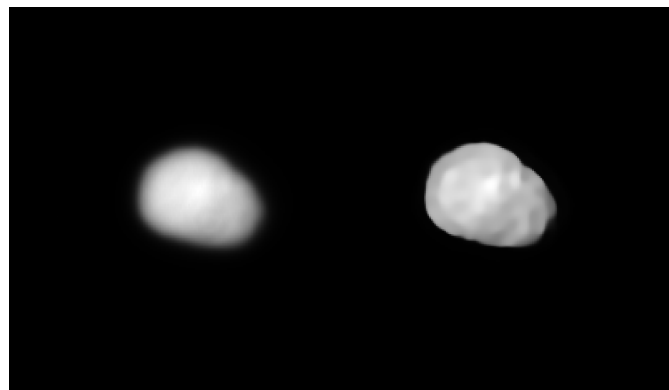


Figure 1.15.: Image of the MBA (15) Eunomia ( $D \sim 270$  km) with SPHERE/ZIMPOL before and after deconvolution by the MISTRAL algorithm.



### 1.2.5. Multi-data modeling

Multi-data modeling combines widely different data sources and modeling techniques in a single and coherent inversion to combine the advantages of each technique and alleviate their drawbacks. Such data sources include optical lightcurves, disk-resolved images, stellar occultation timings, mid-infrared thermal radiometry, optical interferometry, and radar delay-Doppler data (for a complete review, see [Durech et al., 2015](#)).

The work of [Kaasalainen and Lamberg \(2006\)](#) on the combination of disk-integrated and disk-resolved data triggered the development of the first multi-data shape inversion software, *Knitted Occultation, Adaptive optics and Light-curve Approach* (KOALA). KOALA is based on the convex shape inversion using optical lightcurves, to which it can add the informations given by 2D profiles of disk-resolved data and by stellar occultations data ([Carry et al., 2010](#); [Kaasalainen, 2011](#)). The addition of mid-infrared photometry was also included, allowing to constrain the surface properties ([Durech et al., 2012](#)). The reliability of this new multi-data technique was demonstrated with the flyby of (21) Lutetia by the ESA Rosetta mission in 2010 (Fig. 1.16). The comparison between the images taken by the camera on-board Rosetta and the KOALA pre-flyby model showed a good agreement of the shape as well as an accuracy of the spin axis orientation of two degrees and of a couple of percent for the diameter ([Carry et al., 2012](#)).

Further development of the method led to the new software *All-Data Asteroid Modeling* (ADAM) that also includes the possibility to use radar delay-Doppler data and thermal infrared interferometry ([Viikinkoski, 2016](#); [Viikinkoski et al., 2015a,b](#)). ADAM has since been extensively used to produce tens of asteroid shape models (e.g. [Hanuš et al., 2017a,b](#); [Vernazza et al., 2018, 2021](#); [Viikinkoski et al., 2018](#)).

More recently, a new method called *Shaping Asteroid models using Genetic Evolution* (SAGE) was developed. It relies on a genetic evolution algorithm that iteratively produces populations of random shapes and spin axis orientations by mutating the previous generations until convergence to a stable global minimum is reached ([Bartczak and Dudziński, 2018](#)). It was first developed for lightcurve inversion solely, and later extended to include disk-resolved data as well ([Dudziński et al., 2020](#)).

### 1.2.6. Space missions

In-situ measurements are observations of Solar System objects by a spacecraft in orbit around the body or during a flyby of the body. They provide images of very high spatial resolution that are unachievable from the ground, which notably allows for very precise 3D shape determinations. The mass can also be determined from the spacecraft orbit or from its deflection during the flyby. In-situ missions are thus able of accurate density determination as well as the topology and the craters sizes, shapes, and distributions. The counterpart to obtain such exquisite data is the very high cost in time and money required, which strongly limit the number of objects

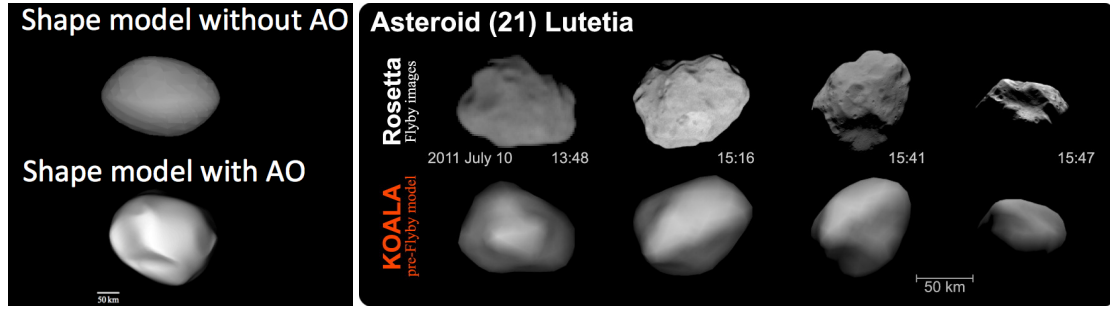


Figure 1.16.: *Left*: Comparison of shape models of (3) Juno with lightcurves only (top) and when AO images obtained with SPHERE are added (bottom, [Viikinkoski et al., 2015b](#)). The addition of AO data allows to move from a convex shape to a more detailed model with concavities. *Right*: Comparison between the KOALA shape model produced before the Rosetta flyby (top) and the images of Lutetia taken by the OSIRIS camera on-board the Rosetta spacecraft during its close approach ([Carry et al., 2012](#)).

visited. However, they are also essential to provide a ground-truth that can be used to calibrate and validate the remote sensing data and methods that can be applied on many more targets.

In 1991, (951) Ida became the first asteroid visited by a spacecraft during the flyby of Galileo while on its way to Jupiter. Since then, fourteen asteroids ranging from small NEAs to large MBAs have been imaged during eight flybys and six rendezvous missions as illustrated by Fig. 1.17. Space missions to asteroids revealed a large collection of shapes, cratering records, surface topology and internal structures. To date, three large MBAs have been visited by a spacecraft: (21) Lutetia, during its flyby by the Rosetta probe ([Pätzold et al., 2011](#)), and the two largest asteroids of the main belt, (4) Vesta and the dwarf planet (1) Ceres, orbited successively by the DAWN spacecraft ([Russell et al., 2015](#)). In the future, the large metallic MBA (16) Psyche will also be the target of a rendezvous mission ([Elkins-Tanton et al., 2017](#)).



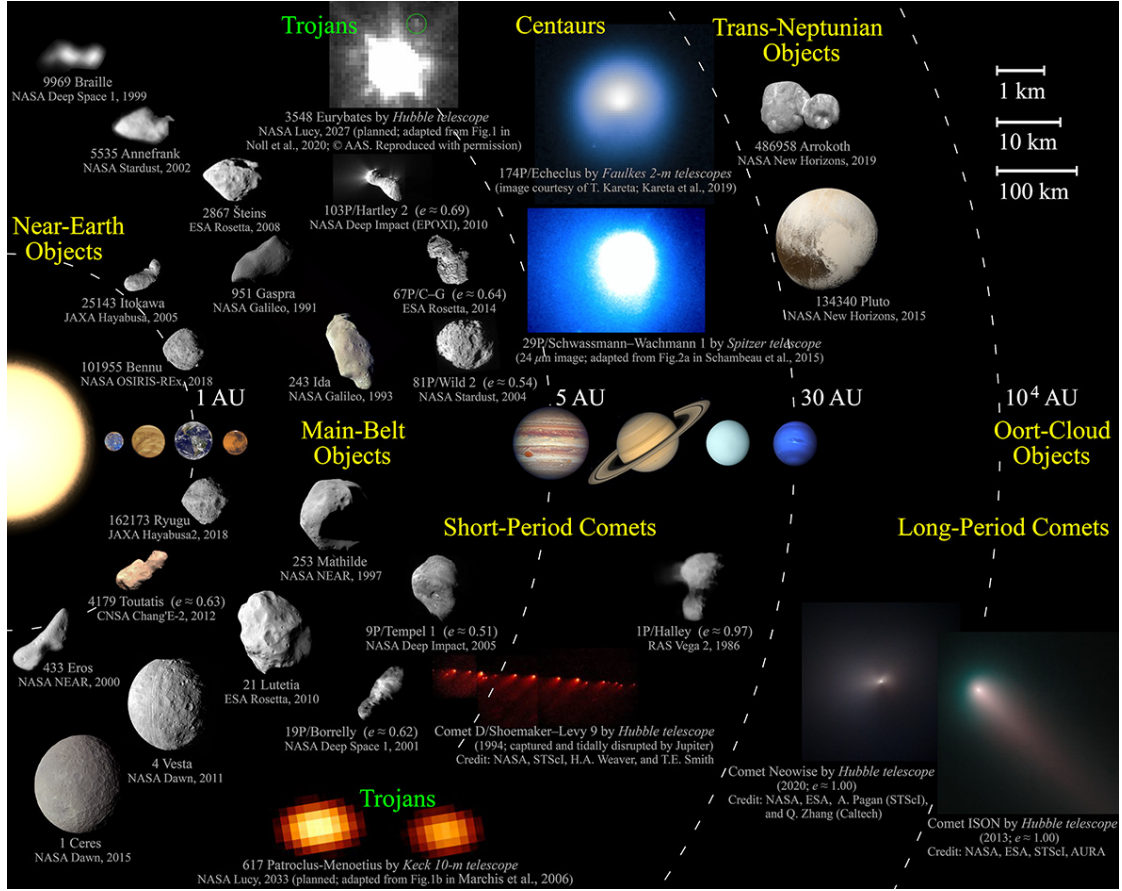


Figure 1.17.: Populations and distribution of small bodies in the Solar System represented by images of the bodies who have been visited by a spacecraft or with images from ground-based telescopes (Zhang and Michel, 2021). The size of the objects follows a logarithmic scale shown on the top right corner.

### 1.2.7. Mass estimates

In the previous section, we discussed some of the main methods to determine asteroid sizes and shapes, thus their volumes. An overview of the methods used to obtain the mass estimates that are necessary to derive bulk densities when combined with volumes is given here. The principle of every asteroid mass estimation is to analyze its gravitational effects on other objects (Carry, 2012). They can be divided in four categories.

**Spacecraft measurements:** In-situ ranging measurements of an asteroid by a spacecraft during a rendezvous mission or a flyby allows to accurately determine its orbit or the deflection of its trajectory, respectively. This technique provides by far the most precise masses, with a typical accuracy of a couple percent. For instance,

the NASA DAWN mission determined the mass of Vesta with an accuracy of nearly 1 part in  $10^6$  (Russell et al., 2012). However, it is limited to a handful of asteroids: six rendezvous and eight flybys to date. This number will increase in the coming years thanks to several missions like the NASA mission Lucy launched in 2021 that will fly by one MBA and six Jupiter trojans (Marchi and Olkin, 2021).

**Orbit of a satellite:** The mutual movement of the components of a multiple system can be imaged by radar or AO imaging. From multiple measurements, the mutual orbits can be determined and the mass derived using Kepler's third law (e.g., Vachier et al., 2012). It is the second most precise method with a typical accuracy of  $\sim 10\%$ , but it is available to a larger number of objects as a few hundreds of binaries are already known.

**Orbit deflection:** During a close encounter between a small asteroid and a larger one, the orbit of the small asteroid will be influenced by the gravitational attraction of the larger body, depending of its mass. Astrometric measurements before and after the event allow to measure the deflection of the smaller asteroid and then to determine the mass of the larger one. For the most massive asteroids, an accuracy of a few percent can be achieved but the accuracy deteriorates rapidly for smaller objects for which it can be larger than 100%. It is the first method used to estimate the mass of an asteroid (Hertz, 1966) and it has since been the source of several hundred mass values (e.g., Goffin, 2014; Siltala and Granvik, 2021).

**Planetary ephemeris:** This method use numerical models that predict the positions of the planets and minor bodies around the Sun. The models take into account the gravitational influences of the Sun and the planets but also of the most massive asteroids. Astrometric analysis of a small body with respect to the numerical model then leads to the mass estimation. As for the orbit deflection method, the best accuracy is achieved for largest asteroids. It is to be noted than for this technique as well as for orbit deflections, the recently released astrometric measurements by the ESA Gaia mission for more than 150 000 asteroids (Tanga et al., 2022) will greatly improve the results. About 100 asteroids will have their mass estimated with a relative accuracy better than 50%, and better than 10% for about 50 (Mouret et al., 2008). Moreover, masses derived using Gaia data will not suffer of as many biases and systematic errors thanks to the unprecedented completeness of the Gaia catalog.

### 1.2.8. The density and asteroid interiors

The surface composition of asteroids can be inferred from the analysis of the surface properties given by albedo or reflectance spectra. However, the surface composition is not necessarily representative of the bulk composition (Elkins-Tanton et al., 2011). Instead, the bulk density is the physical property that best constrains the interiors of

asteroids, but the only accurate measurements come from a handful of space missions and a few multiple asteroids. Because of this, little is known on the bulk composition and internal structure of asteroids. Yet, the bulk density is a fundamental physical property that contains critical information. The bulk density of an asteroid results directly from:

- Its formation location, that determines the composition of the building blocks from which it formed. A formation in the inner Solar System resulted in a rocky composition whereas the bodies that accreted far from the Sun contain volatiles and are less dense.
- Its time of formation, that determines its early thermal evolution. The presence in different amount of short-lived radionuclides (mainly  $^{26}\text{Al}$ ) resulted in different heating level of the interior, and thus in its differentiation or not.
- Its collisional history, that determines the amount of fractures created by violent collisions resulting in the presence of internal voids.

Consequently, the early stages of planetesimals formation and their following dynamical and collisional evolution can be constrained by the internal structures of the asteroids today.

The measurement of the density requires the measurements of the volume and of the mass. Both observables can be determined with much better accuracy for the larger asteroids than for the smaller ones. Moreover, the presence of internal voids in the interior of an object also needs to be taken into considerations to interpret the bulk density in term of composition. Smaller asteroids ( $D \leq 100$  km) are considered as collisionally evolved (Morbidelli et al., 2009) and their macroporosity can reach up to 50-60% (Carry, 2012; Scheeres et al., 2015). Fortunately, larger asteroids ( $D \geq 100$  km) are seen as primordial objects whose interior remained much more intact since their formation. Their interior are characterized by minimal macroporosities of typically less than 20% (Carry, 2012). For these reasons, the bulk density of large asteroids can be considered as an excellent tracer of their initial bulk compositions.

### 1.3. An imaging survey of the largest main belt asteroids with VLT/SPHERE

This thesis is taking place in the framework of an ESO Large Program (LP) lead by P. Vernazza (ID 199.C-0074). It consists in an high-angular-resolution imaging survey of a representative fraction of the largest MBAs with VLT/SPHERE aiming to constrain their formation and evolution. The sample comprises 42 asteroids in total, 39 with  $D \geq 100$  km and almost all of the  $D \geq 200$  km (20/23). It was carefully chosen to reflect the compositional diversity of the main belt, all the main taxonomic classes (S, Ch/Cgh, B/C and P/D) are represented. The choice to target the largest asteroids

of the main belt was done not only because they are the most suitable to image with SPHERE due to their higher angular diameters, but also because they are the best preserved bodies in the main belt and thus better reflect the conditions of the early Solar System.

One of the main science objectives of this campaign was to constrain the density of the largest asteroids with unprecedented accuracy ( $<10\%$ ) via their 3D shape. Because the largest asteroids have minimal macroporosity (Carry, 2012), the bulk density allows to characterize their internal structure, which in turn yields crucial information on their time and location of formation, as well as on their thermal and collisional evolution. Other questions concerned the possibility of correlations between surface composition and density as well as the research of evidence of differentiation. These constraints are key inputs for thermal evolution models to predict the time and location formation of the main compositional classes (inward or outward of the snowline).

To try to shed some light on these questions, VLT/SPHERE observations were conducted between May 2017 and September 2019 for a total of 152 h. To best cover their surfaces, each asteroid was typically observed during at least five epochs spread in longitude, and during one or several apparitions near opposition (phase angle  $\leq 15^\circ$ ) to maximize the angular diameter and the illumination of the surface. For each epoch, a sequence of five images was acquired close in time and under good seeing conditions ( $\leq 0.8''$ ) and at airmass below 1.6. Two asteroids that were not comprised in the large program sample have also been observed with SPHERE from individual proposals that aimed to take advantages of particularly bright apparitions. These are (65) Cybele (P.I. M. Marsset) and (121) Hermione (P.I. P. Vernazza). Table 1.3 summarizes for each observed asteroid their principal characteristics (class, size and rotation period) and the number of observations (apparitions, epochs and images) as well as their angular diameter and resolution (in km per pixel) at the time of the observations.

The high angular resolution of SPHERE/ZIMPOL, the new generation AO instrument working in the visible ( $\sim 20$  mas at 600 nm; Schmid et al., 2017), means that sharp images of most of the  $D \geq 100$  km MBAs can now be obtained from the ground as these targets display an angular diameter larger than 100 mas around opposition. The fantastic images obtained by SPHERE can then be used to precisely constrain the shape of these bodies but also to study surface features, such as impact craters, of  $D \geq 30$  km. The survey revealed an amazing variety of shapes and surface topology as illustrated by a poster (Fig. 1.19) from an ESO press release at the occasion of the publication of the final results of the LP (Vernazza et al., 2021).

The data reduction were performed using the ESO pipeline and is described in Vernazza et al. (2018). The image were deconvolved with the myopic deconvolution algorithm MISTRAL, which is optimized for images with sharp boundaries (Fusco et al., 2003; Mugnier et al., 2004). At the beginning of the program, the deconvolution was using a stellar PSF acquired on the same night as the asteroid observations. However, the results were not always satisfactory because of the varying AO correction on the guide star due to its angular separation with the asteroid. Bright artifacts were appearing on the asteroids disk, rendering the data unusable. Another strategy was

1. Introduction – 1.3. An imaging survey of the largest main belt asteroids with VLT/SPHERE

then explored, based on a parametric 2D Moffat PSF. Not only deconvolution with a Moffat function always converged to satisfactory results, similar to deconvolution using stellar PSFs, but it also allowed to drop the stellar PSF acquisitions, resulting in a time gain of 20-30% for the science observations (Fétick et al., 2019).

The reliability of the data and the processing methods were tested on (4) Vesta. Vesta is the second largest body of the main belt and was orbited between 2011 and 2012 by the DAWN spacecraft. Using the shape model and albedo map obtained from the DAWN in-situ data (Preusker et al., 2016; Schröder et al., 2014), synthetic images of Vesta at the time of the observed SPHERE images were generated with the Optimized Astrophysical Simulator for Imaging Systems (OASIS) tool (Jorda et al., 2010). Then, the deconvolved SPHERE images were directly compared to the ground truth provided by the DAWN synthetic images (Fétick et al., 2019). The spectacular comparison is illustrated on Fig. 1.18. The contours are corresponding to the sub-pixel level. Craters larger than 20 km can be identified, as well as the main surface features: the giant impact basin at Vesta's south pole and its prominent central peak, scarps, and albedo variegation.

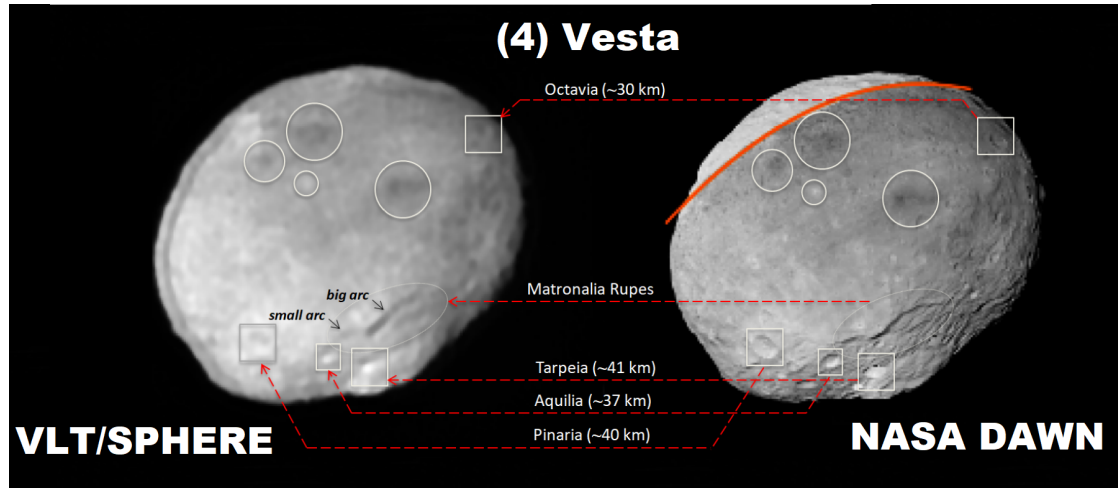


Figure 1.18.: Comparison between a SPHERE image of Vesta (left), and a synthetic view derived from in-situ data taken by DAWN. The corresponding shape and surface features convincingly assesses the reliability of the instrument and of the data processing (Fétick et al., 2019).

At the start of my thesis, in October 2019, the asteroid observations by SPHERE for the LP had just been completed. Several papers dedicated to particularly interesting individual targets had already been published.

Observations of the S-type asteroid (89) Julia, the parent body of a small collisional family, revealed a large impact crater (~75 km wide) that could be linked via numerical simulations to the impact at the origin of the Julia family (Vernazza et al., 2018).

Viikinkoski et al. (2018) presented observations and a shape model of (16) Psyche. Psyche is a metal rich asteroid considered as a possible exposed proto-planetary



metallic core, and the target of the NASA Psyche mission. The refinement of its density was incompatible with the density of any iron meteorites but consistent with that of stony-iron meteorites such as mesosiderites.

Carry et al. (2019) determined an homogeneous interior for the Ch-type asteroid (41) Daphne from detailed modeling of its shape and the orbit of its small satellite. This is in agreement with the proposed hypothesis that Ch- and Cgh-type asteroids comprise a population of undifferentiated bodies with an originally homogeneous internal structure.

(7) Iris presented a large angular size of  $0.33''$  during its 2017 apparition, making it an ideal target for a cratering record study. Iris's shape revealed eight surface features interpreted as impact craters as well as a large equatorial excavation (Hanuš et al., 2019).

Table 1.1.: List of the large main belt asteroids observed with SPHERE with the taxonomic type, volume equivalent diameter  $D$ , and rotation period  $P$ .  $N_a$ ,  $N_e$ ,  $N_i$  are the number of apparitions, epochs and images.  $D_{ang}$  and  $R$  are the approximate angular diameter and resolution in km per pixel for each apparition. The asteroids that were visited by a spacecraft are highlighted by a \*.

| Number | Name       | Class | $D$ [km] | $P$ [h] | $N_a$ | $N_e$ | $N_i$ | $D_{ang}$ ["]      | $R$ [km/px]     |
|--------|------------|-------|----------|---------|-------|-------|-------|--------------------|-----------------|
| 1      | Ceres*     | C     | 939      | 9.07    | 2     | 5     | 25    | 0.82 - 0.60        | 4.3 - 5.8       |
| 2      | Pallas     | B     | 511      | 7.81    | 2     | 11    | 53    | 0.43 - 0.48        | 4.6 - 4.2       |
| 3      | Juno       | S     | 254      | 7.21    | 1     | 6     | 30    | 0.33               | 2.7             |
| 4      | Vesta*     | V     | 523      | 5.34    | 1     | 6     | 30    | 0.67               | 3.1             |
| 6      | Hebe       | S     | 195      | 7.27    | 1     | 7     | 35    | 0.2                | 3.3             |
| 7      | Iris       | S     | 199      | 7.14    | 2     | 6     | 32    | 0.31 - 0.15        | 2.3 - 4.9       |
| 8      | Flora      | S     | 146      | 12.87   | 2     | 4     | 20    | 0.20 - 0.13        | 2.7 - 4.0       |
| 9      | Metis      | K     | 173      | 5.08    | 1     | 6     | 30    | 0.16               | 4.4             |
| 10     | Hygiea     | C     | 433      | 13.82   | 2     | 11    | 54    | 0.30 - 0.23        | 4.8 - 6.3       |
| 11     | Parthenope | S     | 149      | 13.72   | 2     | 5     | 25    | 0.11 - 0.14        | 4.5 - 3.8       |
| 12     | Victoria   | A     | 116      | 8.66    | 1     | 4     | 20    | 0.11               | 3.8             |
| 13     | Egeria     | Ch    | 202      | 7.05    | 1     | 6     | 30    | 0.17               | 4.4             |
| 15     | Eunomia    | S     | 270      | 6.08    | 2     | 14    | 80    | 0.13 - 0.23        | 6.4 - 3.7       |
| 16     | Psyche     | M/Xk  | 223      | 4.19    | 2     | 12    | 60    | 0.14 - 0.18        | 6.0 - 4.4       |
| 18     | Melpomene  | S     | 141      | 11.57   | 2     | 6     | 30    | 0.09 - 0.15        | 5.3 - 3.3       |
| 19     | Fortuna    | Ch    | 211      | 7.44    | 1     | 6     | 30    | 0.19               | 3.9             |
| 21     | Lutetia*   | M/Xc  | 98       | 8.17    | 1     | 10    | 36    | 0.15               | 3.1             |
| 22     | Kalliope   | M/X   | 150      | 4.15    | 2     | 7     | 35    | 0.10 - 0.11        | 5.9 - 5.6       |
| 24     | Themis     | C     | 208      | 8.37    | 1     | 6     | 30    | 0.15               | 4.8             |
| 29     | Amphitrite | S     | 204      | 5.39    | 3     | 12    | 60    | 0.11 - 0.15 - 0.14 | 6.0 - 4.5 - 4.8 |
| 30     | Urania     | S     | 88       | 13.69   | 1     | 4     | 20    | 0.11               | 2.9             |
| 31     | Euphrosyne | C     | 268      | 5.53    | 1     | 7     | 34    | 0.16               | 5.9             |

*Continued on next page*

Table 1.1 – *Continued from previous page*

| Number | Name       | Class | $D$ [km] | $P$ [h] | $N_a$ | $N_e$ | $N_i$ | $D_{ang}$ ["] | $R$ [km/px] |
|--------|------------|-------|----------|---------|-------|-------|-------|---------------|-------------|
| 41     | Daphne     | Ch    | 187      | 5.99    | 2     | 7     | 35    | 0.18 - 0.15   | 4.1 - 5.0   |
| 45     | Eugenia    | C     | 188      | 5.70    | 2     | 10    | 54    | 0.15 - 0.17   | 4.8 - 4.2   |
| 48     | Doris      | Ch    | 215      | 11.89   | 1     | 2     | 7     | 0.15          | 5.1         |
| 51     | Nemausa    | Cgh   | 150      | 7.78    | 1     | 6     | 30    | 0.13          | 4           |
| 52     | Europa     | C     | 319      | 5.63    | 2     | 13    | 53    | 0.17 - 0.16   | 6.3 - 6.9   |
| 63     | Ausonia    | S     | 93       | 9.30    | 1     | 5     | 25    | 0.11          | 3.7         |
| 65     | Cybele     | Xc    | 263      | 6.08    | 1     | 7     | 35    | 0.15          | 5.5         |
| 87     | Sylvia     | X/P   | 274      | 5.18    | 1     | 10    | 38    | 0.14          | 6.4         |
| 88     | Thisbe     | C     | 218      | 6.04    | 1     | 6     | 30    | 0.24          | 3.5         |
| 89     | Julia      | S     | 140      | 11.39   | 1     | 8     | 40    | 0.16          | 3.3         |
| 121    | Hermione   | C     | 181      | 5.55    | 1     | 6     | 30    | 0.14          | 5.4         |
| 128    | Nemesis    | C     | 163      | 38.93   | 1     | 5     | 25    | 0.14          | 4.1         |
| 130    | Elektra    | Ch    | 199      | 5.22    | 1     | 6     | 30    | 0.14          | 4.5         |
| 145    | Adeona     | Ch    | 144      | 15.07   | 1     | 3     | 15    | 0.13          | 3.5         |
| 173    | Ino        | Xc    | 145      | 6.11    | 1     | 5     | 25    | 0.14          | 3.2         |
| 187    | Lamberta   | Ch    | 141      | 10.67   | 1     | 5     | 25    | 0.18          | 2.9         |
| 216    | Kleopatra  | M/Xe  | 118      | 5.39    | 2     | 11    | 55    | 0.10 - 0.11   | 4.5 - 3.9   |
| 230    | Athamantis | S     | 118      | 23.98   | 1     | 3     | 13    | 0.11          | 3.7         |
| 324    | Bamberga   | C     | 227      | 29.44   | 2     | 15    | 38    | 0.20 - 0.18   | 3.9 - 4.4   |
| 354    | Eleonora   | A     | 165      | 4.28    | 1     | 6     | 35    | 0.12          | 4.6         |
| 511    | Davida     | C     | 298      | 5.13    | 1     | 6     | 33    | 0.23          | 5.5         |
| 704    | Interamnia | C     | 332      | 8.71    | 2     | 12    | 46    | 0.24 - 0.20   | 4.5 - 5.6   |

## 1.4. This thesis

I have been involved in the LP since my master's thesis conducted at the University of Liège under the supervision of Emmanuël Jehin. The topic was about the construction of lightcurves for the LP's targets using the TRAPPIST telescopes, in order to support the ongoing shape modeling of these objects.

I had the opportunity to meet with Pierre Vernazza, Laurent Jorda, and the rest of the LP's team during a workshop at the Observatoire de Haute Provence. This meeting triggered the start of the present thesis that aims to actively contribute to the shape reconstruction and analysis of the large MBAs targeted by SPHERE. These objects are among the most primordial remnants of the formation of the Solar System. As such, studying their internal structure allows to determine the nature of the initial building blocks of their formation (rock only or a mixture of rock and ice) and their subsequent evolution (differentiation or not, collisions). Finally, these constraints serve as direct inputs for models of the Solar System. This thesis represented for me a unique opportunity to contribute to a better understanding of the Solar System using

the amazing data provided by the SPHERE instrument.

In Chapter 2 and Chapter 3 we review the methods used for this work. Firstly, I present in Chapter 2 the observations with the TRAPPIST telescopes that I continued during my thesis, and the constructions of dense optical lightcurves that are used by combined-data modeling algorithms. Secondly, a description is given in Chapter 3 of the 3D reconstruction algorithm *Multiresolution PhotoClinometry by Deformation* (MPCD) used to produce detailed shape models for each of the LP targets.

In Chapter 4, I present the results of the shape modeling and analysis dedicated to two M-type asteroids: (16) Psyche and (22) Kalliope. They are both metal rich asteroids characterized by high bulk densities. Psyche is the target of the incoming NASA Psyche mission. Its shape is analyzed along with the implications on its formation conditions. Kalliope is a binary system, which allowed to accurately determine its density and explore the question of its differentiation.

Finally, Chapter 5 is devoted to quantitative analysis of the whole set of shape models and the derivation of topographic properties for each compositional class in order to reach broad conclusions regarding their early formation and evolution.



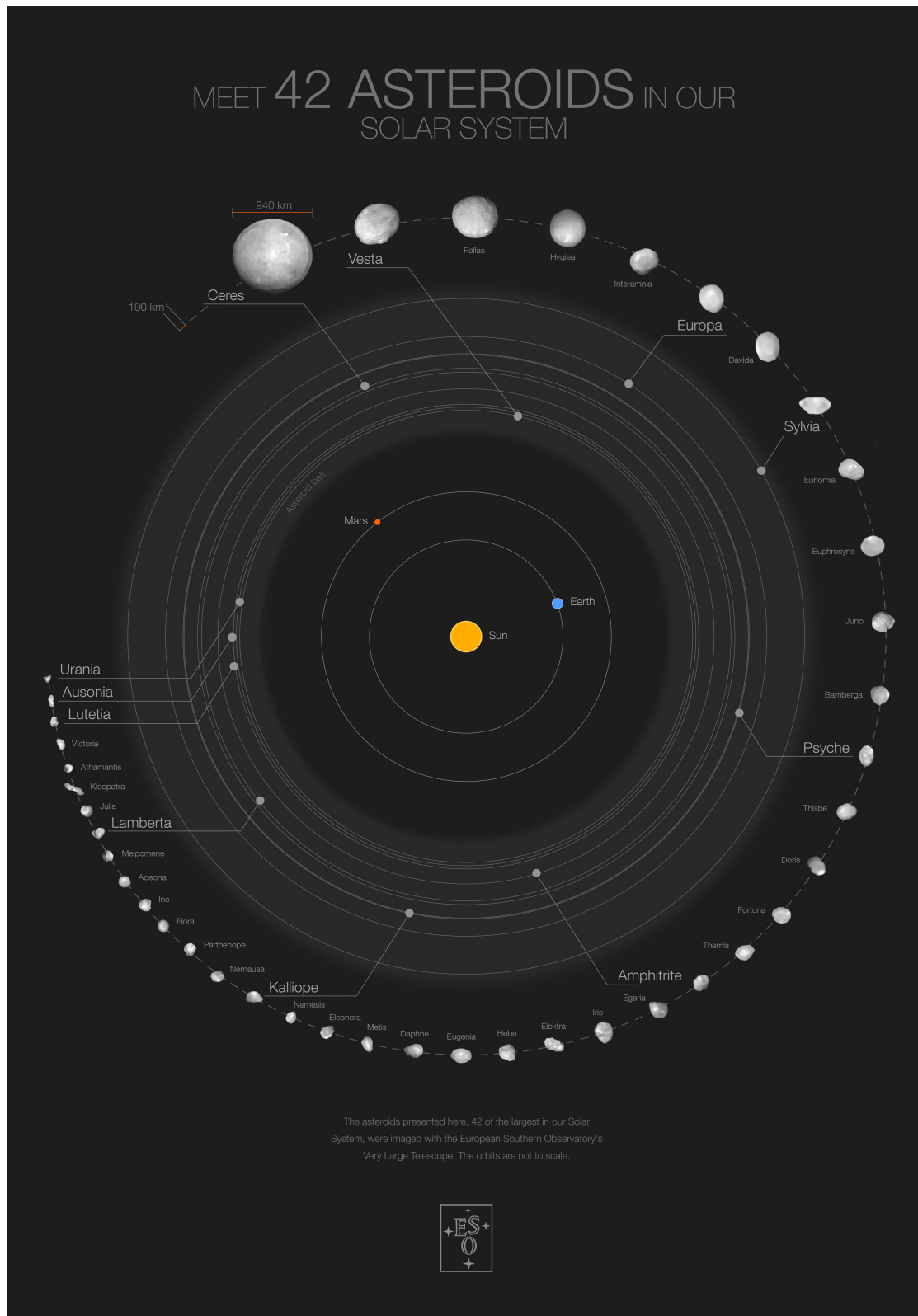


Figure 1.19.: Poster showing the 42 asteroids imaged by VLT/SPHERE during the program+, sorted and scaled by their volume equivalent diameter. Credit: ESO/M. Kornmesser/Vernazza et al./MISTRAL algorithm (ON-ERA/CNRS).

## 2. Optical lightcurves

This chapter is devoted to photometric observations of asteroids aiming to obtain their optical lightcurves. Lightcurves have been widely used since more than 20 years to determine the global shape of asteroids. We present here the lightcurves of several large MBAs that were acquired using the TRAPPIST telescopes.

Those lightcurves were then sent to two different teams that developed their own multi-data modeling algorithms: **ADAM** and **SAGE**. By combining lightcurves with other data types, most importantly the high-resolution images of SPHERE/ZIMPOL, they produced detailed shape models for all targets of the large program.

Finally, these models were used as inputs of the MPCD method described in Chapter 3.

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## 2.1. Why are lightcurves needed ?

With the advances in AO techniques and instrumentation, as shown by the high-resolution images produced by SPHERE/ZIMPOL, one can wonder why lightcurves would still be needed for asteroid shape reconstruction. Indeed, it can seem counter intuitive to use disk-integrated data when disk-resolved observations are available. First, lightcurves allow to produce convex, low resolution shape models that can be use as input of the multi-data reconstruction methods. Then, the disk-resolved data provides the fine-scale details and reveal the concavities of the asteroid topography. However, unlike the rendezvous space missions that can very densely image their target, our SPHERE observations consisted in series of images taken every  $\sim 60^\circ$  in planeto-centric longitudes, providing a limited number of silhouettes. The lightcurves are thus particularly important for the shape reconstruction to stabilize the optimization process and to provide information on regions not covered by the disk-resolved observations. Finally, lightcurves are essential for the rotation period determination which allows to properly phase the AO images, and to retrieve the spin axis. For these reasons, we used the TRAPPIST telescopes to obtain new lightcurves of the ESO large program targets at about the same time, and so at the same viewing angle and illumination, than the disk-resolved images.

## 2.2. The TRAPPIST telescopes

### 2.2.1. Scientific goals

The TRAnsiting Planets and PlanetesImals Small Telescope (TRAPPIST) telescopes<sup>1</sup> are two twin telescopes with a diameter of 60 cm (Jehin et al., 2011). TRAPPIST-South (TS) was the first to be installed in 2010 at the ESO La Silla observatory in Chile. TRAPPIST-North (TN) followed in 2016 and is located at the Oukaïmeden observatory in Morocco. Both telescopes are operated at the University of Liège in Belgium, by the Origins in Cosmology and Astrophysics group (OrCA) of the STAR institute. TRAPPIST-North is also a collaboration with the Cadi Ayyad University in Marrakesh. The two main focus of the project are concern photometric observations of exoplanet transits and small bodies of the solar system.

The exoplanet program performs follow-up observations of planetary candidates of transit surveys, like the NASA TESS mission. It aims at confirming the planetary nature of the candidates and at determining or refining the parameters of the known systems. Until 2020, another program was the photometric monitoring of a particular type of low-mass stars, the so-called ultra-cool dwarfs ( $T_{\text{eff}} \leq 2700$  K). The goal was to find Earth size planets transiting these stars. A new project, Search for habitable Planets EClipsing ULtra-cOOl Stars (SPECULOOS)<sup>2</sup>, now took over this monitoring.

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<sup>1</sup><https://www.trappist.uliege.be>

<sup>2</sup><https://www.speculoos.uliege.be>

## 2. Optical lightcurves – 2.2. The TRAPPIST telescopes

The TRAPPIST data, with the help of follow-up observations by the NASA Spitzer Space Telescope, led to the discovery of the famous TRAPPIST-1 system announced in 2016 (Gillon et al., 2016, 2017). This spectacular system of seven Earth-size temperate planets in orbital resonances will soon be a prime target for the NASA James Webb Space Telescope.

The second half of the observational time is dedicated to comets and asteroids. Bright comets are monitored along their orbit to follow their composition and activity as a function of their heliocentric distances (Jehin et al., 2014). Narrow-band cometary filters are used to measure the gas (OH, NH, CN, C<sub>2</sub>, ...) and dust production rates. Fainter comets are also monitored using broad-band filters.

The final category and the one that interest us in this manuscript is the observation of asteroids. Brightness measurements of MBAs and NEAs can be used among other things to search and refine their rotation periods and to determine their shapes and rotational states (e.g., Pravec et al., 2014). Although further away and much fainter, the TNOs and centaurs can also be studied with the stellar occultation method (see Section 1.2.2). Examples of such studies are the participation of TRAPPIST in the revision of size of the dwarf planet Eris (Sicardy et al., 2011) and the discovery of rings around the centaur Chariklo (Braga-Ribas et al., 2014).

Asteroid observations by TRAPPIST became more regular during my master's thesis in 2017. The main goal of this work was the observation of large MBAs in order to obtain dense rotation lightcurves and support the shape modeling of these objects. These asteroids in particular were part of the ESO large program described in Section 1.3, and in which this thesis also take place. I continued to observe more of them during my thesis, notably for objects with long or poorly known rotation periods, or with badly constrained spin axis orientation. These observations will be presented in Section 2.6.

Other MBAs are also observed in the framework of collaborations with different projects that make use of our data. Podlowska-Gaca et al. (2020) produced shape models of objects for which the Gaia mission will allow to determine the mass with very good precision, thus preparing for accurate densities determination. Marciniak et al. (2021) aimed at decreasing the observational biases for slow rotators and for asteroids with lightcurves of low amplitudes. In Vokrouhlický et al. (2021), the determination of a spin axis solution for (208) Lacrimosa helped to better understand the peculiar rotation state properties of the Koronis family. In 2018 December, the MBA (6478) Gault was found to display cometary-like activity. Regular observation with TRAPPIST were conducted to characterize it. In early 2019, the obtained lightcurves were flats because of the dust still hiding the surface (Moreno et al., 2019). However, dust-free observation in 2020 contributed to find the short rotation period  $P = 2.4929 \pm 0.0003$  h, which is consistent with Gault's activity being triggered by the YORP spin-up mechanism (Devogèle et al., 2021). Regular observation of the MBA (52246) Donaldjohanson, that the NASA mission Lucy will encounter in 2025, revealed a slow rotation ( $P \sim 252$  h) and a large lightcurve amplitude of  $\sim 1$  mag (Appendix B.4).

Finally, we regularly observe NEAs during their close encounters with Earth. The

## 2. Optical lightcurves – 2.2. The TRAPPIST telescopes

solar phase angle is rapidly varying during an asteroid flyby of the Earth, which allows to gather data with very different viewing conditions. This is very helpful to determine their shape and to construct photometric phase curves. Such observations of the dynamically linked NEAs (3200) Phaethon and (155141) 2005 UD were used in [Devogèle et al. \(2021\)](#), and helped to study their physical properties and origins. The results of TRAPPIST observations of NEAs and of the MBAs not concerned by the ESO large program are presented in Appendix B.

The opportunity to use the TRAPPIST telescopes has been a great chance as they offer many advantages. The first is the large amount of observing time available as it is only shared between the exoplanets and the small bodies projects. The asteroids observations also complement well the comets when the Moon is too bright to observe their faint coma. Thanks to the telescopes being operated by the OrCA group, we avoid the need to write time consuming time requests and proposals, and we can be more reactive and flexible. Importantly, the presence in the two hemispheres and the longitude difference of  $63^\circ$  gives us access to the whole sky. For targets near the equator (declination between  $+30^\circ$  and  $-30^\circ$ ), it is even possible to observe on the same night first with **TN** and then with **TS** the same target. The combined data increase the observation time span up to  $\sim 13$  h in the best cases. This is highly beneficial during a NEA flyby (as illustrated in [Ferrais et al. 2020a](#)), for slow rotators, or to reduce the number of aliases in period determination.

### 2.2.2. Observation sites

TRAPPIST-South was installed in 2010 in the La Silla Observatory, the first ESO installations built in Chile. It is located at an altitude of 2400 m, at the southern extremity of the Atacama Desert. This geographical area is a privileged place for astronomy because of its dryness and its isolation from human activities that generate light pollution and dust. The observing conditions are among the best on Earth, with excellent atmospheric stability and about 300 clear nights per year.



Figure 2.1.: TRAPPIST-S telescope at ESO La Silla Observatory.

The telescope is a 0.6-m Ritchey-Chrétien operating at  $f/8$  on a German Equatorial

## 2. Optical lightcurves – 2.2. The TRAPPIST telescopes

mount. It has been built by the German company ASTELCO<sup>3</sup>. The camera is an FLI ProLine PL3041-BB of 2048×2048 pixels with a pixel scale of 0.64'' per pixel and a field of view of 22'×22'. Details on the site, mount, camera and the filters available in the double filter wheel are given in Table 2.1. Available filters comprise the Johnson-Cousins B, V, Rc, Ic filters, and the Exo filter which cut the blue part of the visible spectrum (Fig. 2.2).

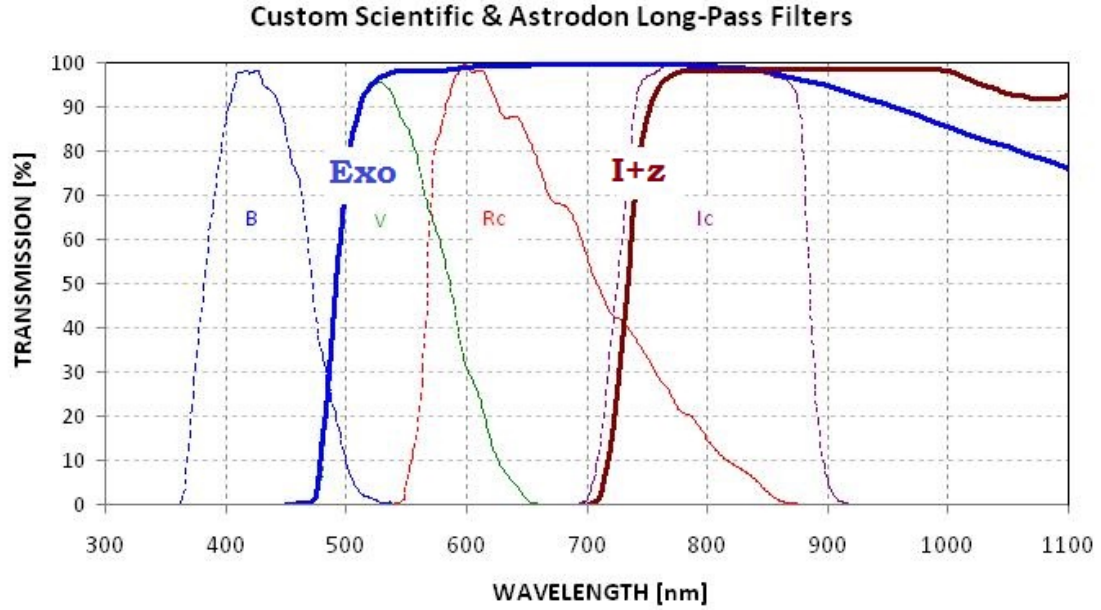


Figure 2.2.: Transmission curves of the broad band filters used for asteroid photometry with TS and TN.

TRAPPIST-North is located in the Oukaïmeden Observatory, at 2750 m of altitude in the Atlas Mountains of Morocco. The site also offers excellent observing conditions. The telescope is a twin of the Chilean one, with the exception of the camera. On this telescope, it is an Andor IKONL BEX2-DD of 2048×2048 pixels with a pixel scale of 0.60'' per pixel and a field of view of 20'×20'. The broad band B, V, Rc, Ic, and Exo filters are also available. More technical details on the telescopes are given in Table 2.1.

### 2.2.3. Operation of the telescopes

The robotic nature of the two telescopes allows to operate them remotely, simply requiring a secured internet connection. To ensure the observatories safety, a weather station and rain sensors monitor the meteorological conditions in real time. In case of clouds formation, detection of rain or snow, or if the wind speed or humidity exceed threshold values, the dome is automatically closed and the telescope placed back in its home position. The operator has access to the data from the weather station and

<sup>3</sup><http://www.astelco.com/>

## 2. Optical lightcurves – 2.2. The TRAPPIST telescopes

Table 2.1.: Comparison of the characteristics of the TRAPPIST-S and TRAPPIST-N telescopes.

|                                        | <b>TRAPPIST-South</b>                                                                                                                                                                                                                                                | <b>TRAPPIST-North</b>                                                                            |
|----------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| Site                                   | La Silla Observatory (I40)                                                                                                                                                                                                                                           | Oukaïmeden Observatory (Z53)                                                                     |
| Altitude (m)                           | 2315                                                                                                                                                                                                                                                                 | 2751                                                                                             |
| Latitude                               | 29° 15' 16.6" (S) / 29.2546° (S)                                                                                                                                                                                                                                     | 31° 12' 22" (N) / 31.2061° (N)                                                                   |
| Longitude                              | 70° 44' 121.8" (W) / 70.7394° (W)                                                                                                                                                                                                                                    | 7° 51' 29" (W) / 7.8664° (W)                                                                     |
| $\Delta$ LAT - $\Delta$ LON - Baseline | 60.4607° - 62.873° - 8618 km                                                                                                                                                                                                                                         |                                                                                                  |
| Telescope                              | Astelco RC Lightweight Telescope - Ritchey-Chretien - F/8 - 0.6 m - 75 kg                                                                                                                                                                                            |                                                                                                  |
| Mount                                  | Model: Astelco NTM-500 - Type: German equatorial<br>Motors: direct drive systems - Drive accuracy: no periodic error<br>Speed: up to 50 °/s - Pointing accuracy: 5"<br>Differential positioning accuracy: < 1" RMS<br>Tracking accuracy without autoguider: 1"/4 min |                                                                                                  |
| Camera model                           | FLI ProLine PL3041-BB                                                                                                                                                                                                                                                | Andor IKONL BEX2 DD                                                                              |
| CCD type                               | Back-illuminated                                                                                                                                                                                                                                                     | Back Illuminated CCD<br>Deep Depletion with fringe suppression<br>Extended range dual AR coating |
| Array size (pixels)                    | 2048×2048                                                                                                                                                                                                                                                            | 2048×2048                                                                                        |
| Pixel size (μm)                        | 15                                                                                                                                                                                                                                                                   | 13.5                                                                                             |
| Pixel scale (arcsecs/pixels)           | 0.64                                                                                                                                                                                                                                                                 | 0.60                                                                                             |
| Field of view                          | 22' × 22'                                                                                                                                                                                                                                                            | 20' × 20'                                                                                        |
| Full well (e)                          | 100,000                                                                                                                                                                                                                                                              | 100,000                                                                                          |
| Gain (e/ADU)                           | 1.1                                                                                                                                                                                                                                                                  | 1.1                                                                                              |
| Peak QE (%)                            | 96                                                                                                                                                                                                                                                                   | 90                                                                                               |
| Read-out modes (MHz)                   | 1×1 / 1×2 / 2×2                                                                                                                                                                                                                                                      | 1 / 3 / 5                                                                                        |
| Read-out noise (e)                     | 9.5 / 14 / 14                                                                                                                                                                                                                                                        | 7 / 12 / 32                                                                                      |
| Read-out time (s)                      | 6 / 4 / 2                                                                                                                                                                                                                                                            | 5 / 3 / 1.8                                                                                      |
| Dark current (e/s)                     | 0.1                                                                                                                                                                                                                                                                  | 0.15 (at −65 °C)                                                                                 |
| Cooling below ambient (°C)             | −55.0 ± 0.1                                                                                                                                                                                                                                                          | −100.0 ± 0.1                                                                                     |
| Filter Wheel model                     | Double Apogee AI-FW50-10S                                                                                                                                                                                                                                            |                                                                                                  |
| Filters (wheel 1)                      | B, V, Rc, Ic, Sloan z, I+z',<br>Exo (cut blue), NaI, H <sub>2</sub> O <sup>+</sup>                                                                                                                                                                                   | B, V, Rc, Ic, Sloan z,<br>Exo (cut blue), NaI                                                    |
| Filters (wheel 2)                      | OH, NH, CN, C <sub>3</sub> , CO <sup>+</sup> ,<br>BC, C <sub>2</sub> , GC, RC                                                                                                                                                                                        | OH, NH, CN, C <sub>3</sub> , H $\alpha$ ,<br>BC, C <sub>2</sub> , GC, RC                         |





Figure 2.3.: TRAPPIST-N telescope at the Oukaïmeden Observatory.

the all-sky camera on site, and to satellite images. The mechanical operations (dome and telescopes movements) can be supervised using webcams inside and outside the dome and microphones. A live feed is accessible on the TRAPPIST operation web page<sup>4</sup>. The observations are handled by a computer inside the dome that controls all the robotic operations. This includes the images acquisition, the focusing, the astrometry, the telescope pointing and tracking, and the management of the dome and the filter wheel.

## 2.3. Asteroid observations

To prepare our observations on the telescope, observing plans consisting in simple text files are created on the computer controlling the telescopes. They contain the starting and ending time, the filter, the binning, the number of exposure and the target coordinates or the orbital elements needed to track moving objects. Asteroid observations are not trivial, and many things need to be taken into account to determine the best observation parameters. The use of a filter is useful to dim the background sky by blocking the blue end of the spectrum and to match the data to a standard magnitude band. The red (R) filter is well suited for asteroid as they re-emit most of the solar light in this part of the spectrum. The Exo blue-blocking filter is broader and is used for fainter target (Fig. 2.2). The exposure time is a key parameter because a longer exposure increases the number of photons  $N$  received by the detector, which affects the incertitude of the measurements that is proportional to  $\sim \sqrt{N}$  in first approximation. However, if it is too long the pixel value will leave the linearity range of the detector or even saturate and invalidate the data. The incoming flux depends on

---

<sup>4</sup><https://www.trappist.uliege.be>



the choice of filter and binning which are fixed during the observation. In addition, two other cumulative effects varying with time make the prediction of the flux more challenging: the intrinsic variation of the asteroid and the airmass extinction. The asteroids amplitudes change from one opposition to the other and is often not known beforehand. The airmass is a measure of the amount of air the light is going through the atmosphere to reach the observer. It is minimal at the zenith and rapidly increases toward the horizon. Asteroid observations often imply to follow them for as long as possible, sometimes down to high airmasses where they can be up to  $\sim 0.5$  mag fainter than at the meridian. In practice, the exposure time is adjusted after the first observations.



Figure 2.4.: Stack of 18 images spanning 2h30 of observation of the MBA (22) Kalliope with TRAPPIST-South on 2021 December 7. The different positions of Kalliope on each image show the linear movement of the asteroid on the plane of the sky.

## 2.4. Data reduction

Modern telescopes are equipped with electronic detectors that are arrays of pixels, where incoming photons are converted into electron charges and stored. In a **Charge Coupled Device (CCD)**, at the end of an integration the electric charges are moved pixel by pixel until they reach the edge of the detector, where they are read. The resulting image is a two-dimensional array with the same size than the detector. Each pixel value would be proportional to the number of incoming photons in an ideal world, but this is not the case in practice. Because no instrument is perfect, the raw images contain all sort of unwanted contributions to the signal that need to be reduced to a minimum. The flux of an image is always affected by electronic and thermal noises and by other effects that introduce variations of light sensitivity across the detector or in individual pixels. These effects are negligible in daylight pictures, but they become much more important in the much fainter conditions of astronomical

observations. It is therefore mandatory to adequately calibrate our images to obtain accurate photometric measurements. In the following, a description is given of the standard method commonly used to perform this so-called data reduction and that are applied to the IRAF (Image Reduction and Analysis Facility; [Tody, 1986](#)) scripts used in this work.

### **Instrumental bias**

The first step in the data reduction is the subtraction of the bias. The bias is an electronic offset signal applied to all pixels when the voltage is converted to a digital number to ensure that only positive numbers are obtained. In an ideal CCD, this signal would be constant across the image and over time. However, a small readout noise of a few electrons is introduced when the pixels are read. To reduce this readout noise, so called "bias frames" are acquired at the end of each night. A bias frame is obtained with the shutter of the camera closed and using zero exposure in order to isolate this noise specifically. A "master bias" is produced by taking the median of several bias frames, effectively reducing the noise. The bias calibration is then simply done by subtracting the master bias to the science images.

### **Dark current**

All CCD images contains a dark current that accumulates linearly over time, even in the absence of light, because of thermal effects. TRAPPIST cameras are thermoelectrically cooled to minimize it, but it remains significant. This signal is small but not constant across the image and a small fraction of pixel, called the hot pixels, accumulate thermally excited electrons faster. The dark current can be subtracted using dark frames which are obtained by integrating with the shutter closed and with the same exposure time than the science images. Several dark frames are then combined to reduce the readout and dark current noises. Unlike for the bias frames which have zero exposure, cosmic rays can reach the sensor during a dark frame integration and produce streaks of bright pixels that would bias the value of the dark frames average. For this reason, the master dark is produced by using a sigma-clip, an average that excludes values too far from the median.

### **Flat fielding**

They are several sources of non-uniformity in the response of the CCD to light. These include: (i) variation in light sensitivity of pixels in the detector coming from the CCD manufacturing; (ii) the presence of dust in the camera window or in the filters that results in shadows looking like donuts; (iii) vignetting resulting in dimming of the corners of the image. Flat corrections are done by acquiring flat field frames. They are images in which the illumination is uniform so only the CCD response is measured. Flat field frames can be obtained by observing the uniform glow of the sky at twilight or dusk with the same filter than the science images. Bright stars can still be visible on the flat field frames, but the telescope pointing offset between each exposure

change their positions on the detector and allow to remove them when combining several frames together. Similarly than for the science images, bias and dark master frames are subtracted. Then, they are normalized by their median pixel values to 1.0 to compensate for the varying sky brightness and the different exposures used. Finally, they are combined by sigma clipping to reduce the noise and remove outlier pixels.

Once the master bias, dark and flat are created, the reduction is done by subtracting to each science image the master bias and the master dark and then dividing by the master flat:

$$\text{Image}_{\text{reduced}} = \frac{\text{Image}_{\text{raw}} - \text{Bias} - \text{Dark}}{\text{Flat}} \quad (2.1)$$

The result of the process is illustrated in Fig. 2.5. The brightness variations across the image and from pixel to pixel have been reduced and the shadows from dust particles removed.

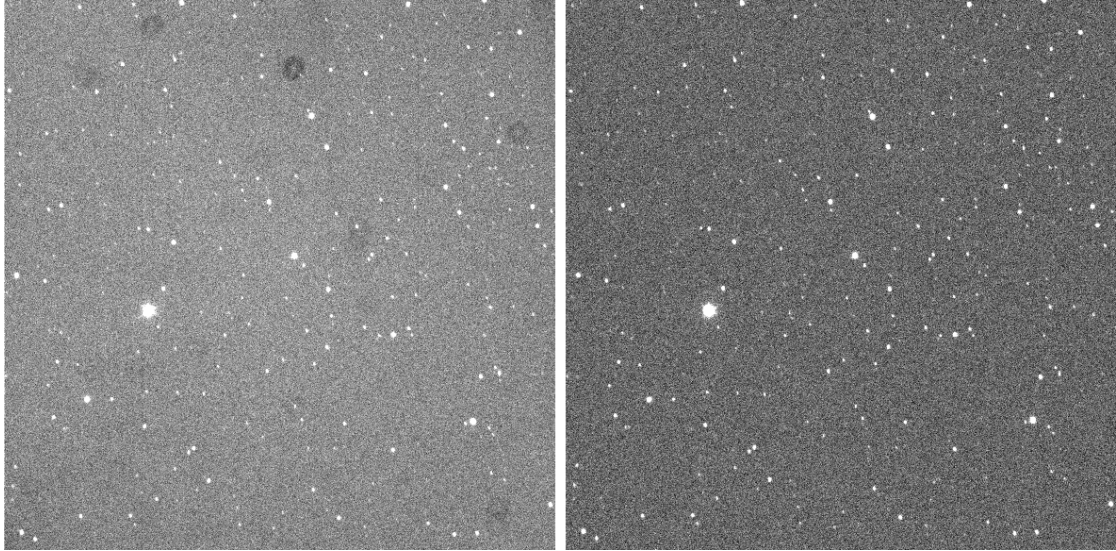


Figure 2.5.: Comparison between a raw image and the corresponding reduced image.

## 2.5. Photometry

Now that our images have been properly calibrated, photometric measurements of the sources they contain can be performed. A point source imaged by a CCD has a round shape that approximate a Gaussian distribution. A simple technique to measure the flux of such a source is called the aperture photometry. It consists in summing up the observed counts of all the pixels contained within an aperture, usually circular, centered on the source. The choice of the aperture radius is critical. A large radius ensures that 100% of the flux of an object is contained in the aperture but it also increases the number of pixels and thus the contribution of the background noise.

The Signal to Noise Ratio (SNR) is thus not maximized at the largest aperture radius but typically at a radius around 1.5 times the Full-Width at Half-Maximum (FWHM) of the PSF (Howell, 2000). An estimation of the background sky contribution is obtained by taking a clipped-average of the flux in an annulus centered on the source but separated from the measuring aperture by a dead zone where no flux is measured.

Following the determination of the aperture radius, the photometric measurements are done for the target but also for the stars present in the field that are not too faint or saturated. In a practice, a collection of IRAF and python scripts are used. To obtain the position of the asteroid in each image, a script retrieves the ephemeris via a query to the NASA/JPL Horizons website<sup>5</sup>.

The raw instrumental measurements of an asteroid brightness are then processed by differential photometry. The difference between the magnitude of the target and the average magnitude of a set of comparison stars is computed. The number of comparison stars is typically of a few tens up to 100 and the variable stars are excluded. Differential photometry allows to correct the brightness variations due to changing airmass, clouds, or any other changes in the transparency of the sky.

While it is not necessary for shape reconstruction purposes, absolute photometry concerns techniques that convert the raw measurements to a standard photometric system allowing. In this work, the PHOTOMETRYPIPELINE (Mommert, 2017) is used to calibrate asteroid magnitudes. This pipeline performs photometric calibration using background stars in the field for each image. The magnitude zero points are determined by comparing the brightness of the field stars with their catalog values.

## 2.6. Results

A presentation is given here of the results of the observations of 31 large main belt asteroids observed with the TRAPPIST telescopes. These photometric measurements were added to the lightcurve collections used by the ADAM and SAGE teams for the shape modeling. Among the 31 observed asteroids, 25 are part of the final asteroid sample of the large program (Vernazza et al., 2021). (65) Cybele and (121) Hermione were observed in the framework of ESO’s P107 Special Call for the submission of time-critical projects to not miss the best opportunity in many years to image these particularly interesting objects. Six asteroids have been observed during two different apparitions, allowing to cover different viewing conditions.

Some of the most interesting and challenging observations are detailed below. The observing circumstances for all the asteroids are given in Table 2.2. The lightcurves plots of the remaining objects are available in Appendix A. All the data have been uploaded to the Asteroid Lightcurve Data Exchange Format (ALCDEF)<sup>6</sup> database to make them available to the community. At this occasion, they were presented in the Minor Planet Bulletin journal where many amateur and professional asteroid

<sup>5</sup><https://ssd.jpl.nasa.gov/horizons>

<sup>6</sup><https://minplanobs.org/alcdef/>

photometry results are published (Ferrais et al., 2019, 2021, 2022).

The lightcurves are plotted as the Rc magnitude against the rotational phase using the period displayed on the plot. The determination of the rotation period is done with the software Peranso<sup>7</sup> that implements, among others, the FALC (Harris et al., 1989) algorithm. The zero phase is shifted to correspond to the maximum of the curve. The data are fitted using Fourier series up to the order indicated on the plot. The fit is displayed as a solid black line and is used to compute the residuals shown in the bottom panel. The obtained synodic period and the amplitude from the Fourier fit are also indicated on the plot.

### (10) Hygiea

(10) Hygiea is the fourth largest asteroid in the main belt with a diameter  $D = 434 \pm 8$  (Vernazza et al., 2021). Its composition is similar to that of the dwarf planet Ceres and it is the parent body of one of the largest asteroid families (Carruba et al., 2014; Vernazza et al., 2012). Before the large program, all lightcurves available for this asteroid agreed to a rotation period close to 27.6 h (Warner et al., 2009), but they were all sparsely sampled. A rotation of 27.6 h is challenging to cover, especially because of its proximity to 24 h. Each day, the observed rotation phase is only shifted by 0.13. We started extensive observations of Hygiea in 2018 to provide densely sampled lightcurves and refine its period, taking advantages of the complementary of the two TRAPPIST telescopes. After a few nights of observation, the lightcurves started to show a classic double-sinusoidal shape when phased with the 27.6 h period. However, the curve was looking extremely symmetric as confirmed by the split halves plot which showed two identical halves. Such a symmetrical shape is highly unlikely. We then phased the data using the half period of 13.8 h, which produced a very convincing fit with a single peak lightcurve (Fig. 2.6). This period was confirmed by the VLT/SPHERE images as they could be properly phased with the new period and by converging 3D shape model (Vernazza et al., 2020). The AO imaged revealed a very spherical shape and albedo features that explain the single-peak shape of the lightcurve. Hygiea's case is a good example of the importance of high-quality and dense photometric data to derive asteroid rotation period.

### (65) Cybele

(65) Cybele is the most prominent member of the Cybeles, a group of asteroids composed of primitive material, located in the outer edge of the main belt, and genetically linked to the outer Solar System. Cybele was observed with VLT/SPHERE during a favorable opposition in July and August 2021 (Marsset et al., subm.). To support these observations, we regularly acquired photometric data between April and August 2021. Because of this large time span, changes in the shape of the 18 different lightcurves can be observed as the orientation and illumination of Cybele as varying (Fig. 2.7).

<sup>7</sup><https://www.cbabelgium.com/peranso/>

## 2. Optical lightcurves – 2.6. Results

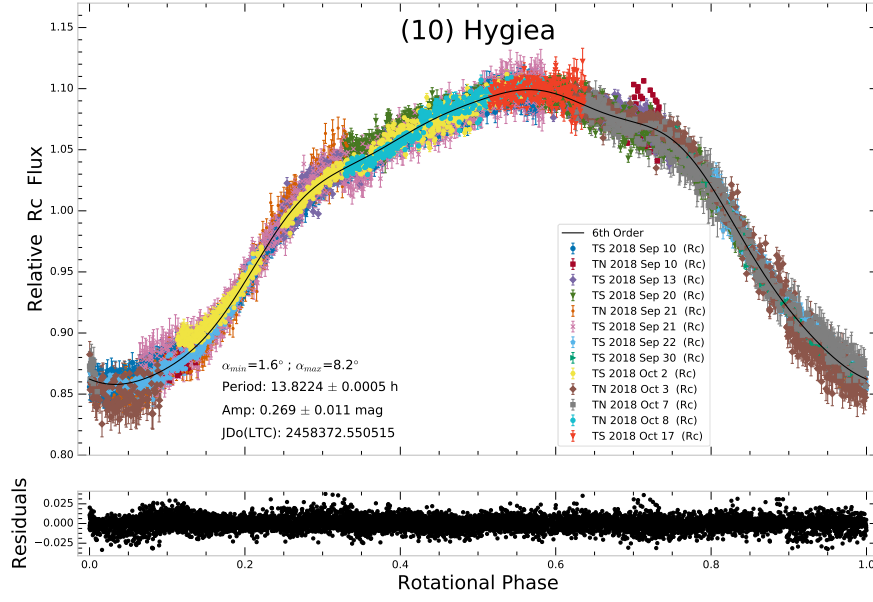


Figure 2.6.: Phased lightcurve of (10) Hygiea.

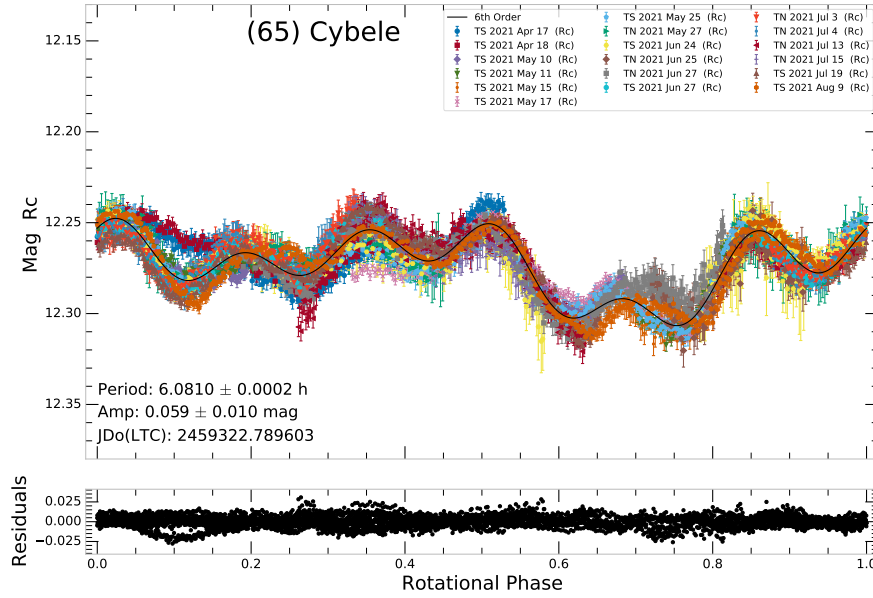


Figure 2.7.: Phased lightcurve of (65) Cybele.

**(128) Nemesis**

(128) Nemesis is known to be a slow rotator but its exact period was still not certain. Previously, [Scaltriti et al. \(1979\)](#) measured a period of 39 h while [Pilcher \(2015\)](#) found a value double of that. We acquired 28 lightcurves between February and Mars 2021 and found a good fit with the shorter period  $P = 38.904 \pm 0.006$  h, resulting in a classic double sinusoidal curve (Fig. 2.8). Moreover, the split halves phased plot does not show any significant variation between the two halves of the lightcurves phased with the double period (Fig. 2.9). With the  $\sim 38.9$  h period, a converging 3D model could be obtained with the SAGE method ([Vernazza et al., 2021](#)). Recently, [Pilcher \(2022\)](#) re-examined his data from 2015 and showed that they are now also compatible with a period near 38.9 h. While the period remains ambiguous with the available data, all the different data sets still favor the shorter period which is why we prefer this solution.

We also acquired BVRI sequences during five different nights to measure Nemesis' colors. By computing the difference in magnitude between several filters, one can learn information on the asteroid surface. The obtained color indexes are:  $BV = 0.795 \pm 0.014$ ,  $VR = 0.406 \pm 0.032$ ,  $VI = 0.718 \pm 0.028$ .

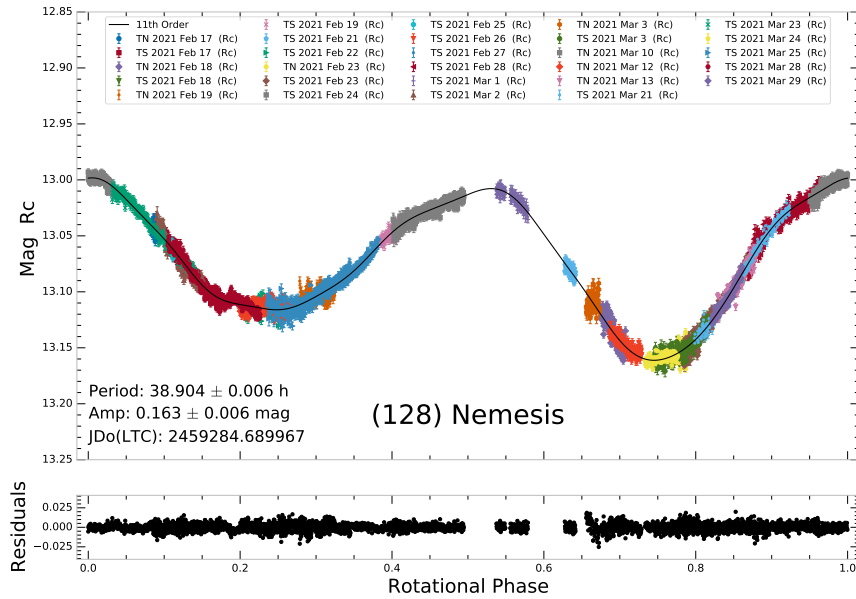


Figure 2.8.: Phased lightcurve of (128) Nemesis with  $P = 38.904 \pm 0.006$  h.

**(324) Bamberga**

(324) Bamberga is another slow rotator but its correct period was already known. Its shape is regular and spherical which results in small brightness changes during its rotation. A good photometric precision is thus required. Combined with the large period, it makes the determination of the spin axis and the shape very challenging, and it was not successfully done before. To solve this, we intensively observed Bamberga



## 2. Optical lightcurves – 2.6. Results

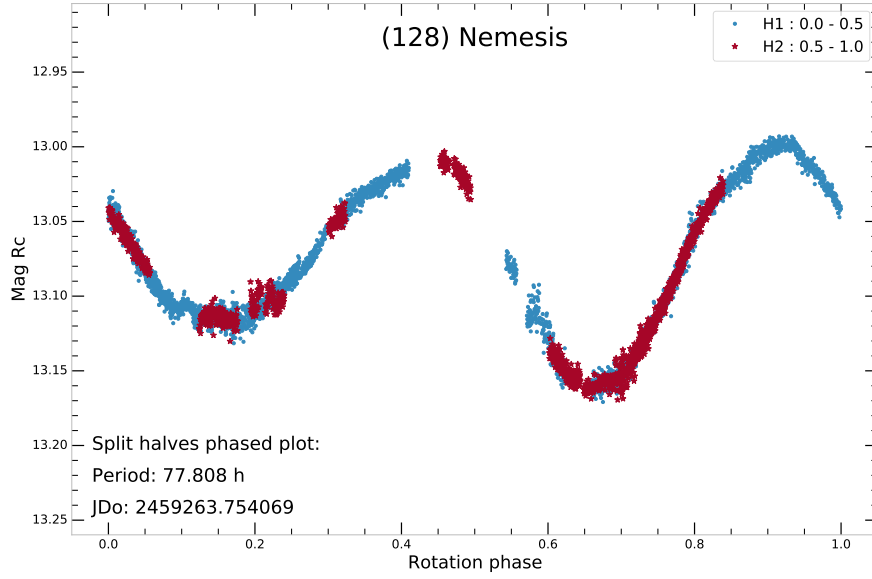


Figure 2.9.: Split halves phased plot using the double period  $2P = 77.808$  h.

during two months in 2019 and again in 2020, gathering more than 15000 data points in total (Fig. 2.10). A spin and shape solution could finally be achieved by the SAGE method and presented in [Vernazza et al. \(2021\)](#).

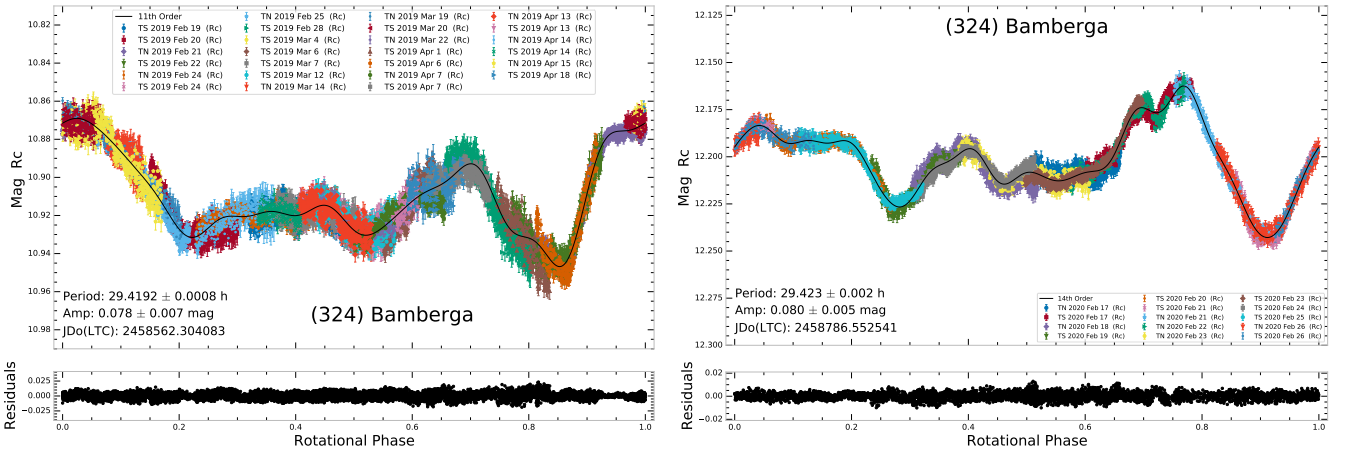


Figure 2.10.: Phased lightcurves of (324) Bamberga in 2019 (left) and 2020 (right).

### (704) Interamnia

(704) Interamnia is the fifth largest main belt asteroid and appear to be at equilibrium ([Hanuš et al., 2020](#)). Its shape is nearly ellipsoidal with almost equal equatorial dimensions. We observed Interamnia during its 2018 and 2019 apparitions, obtaining dense lightcurves with low amplitudes of 0.042 and 0.043 mag, respectively (Fig. 2.11. Our



data participated to the derivation of the first reliable spin-state solution (Hanuš et al., 2020).

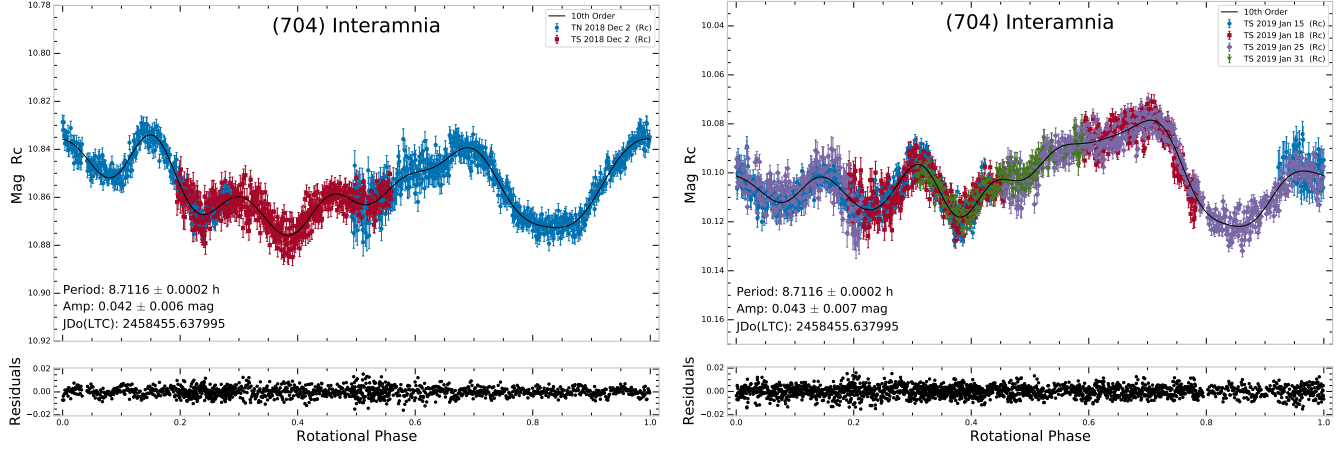


Figure 2.11.: Phased lightcurves of (704) Interamnia in 2018 (left) and 2019 (right).

### (16) Psyche and (22) Kalliope

Finally, the lightcurves of the two asteroids that were mostly studied during this thesis are presented. (16) Psyche and (22) Kalliope are both dense M-type asteroids with short rotation periods, slightly above 4 h. Coincidentally, both were observed in pole-on configuration in 2018, explaining the small amplitude and unique minimum of Psyche's curve and the almost flat shape of Kalliope's lightcurve (amplitude of only 0.026 mag; Fig. 2.12).

## 2. Optical lightcurves – 2.6. Results

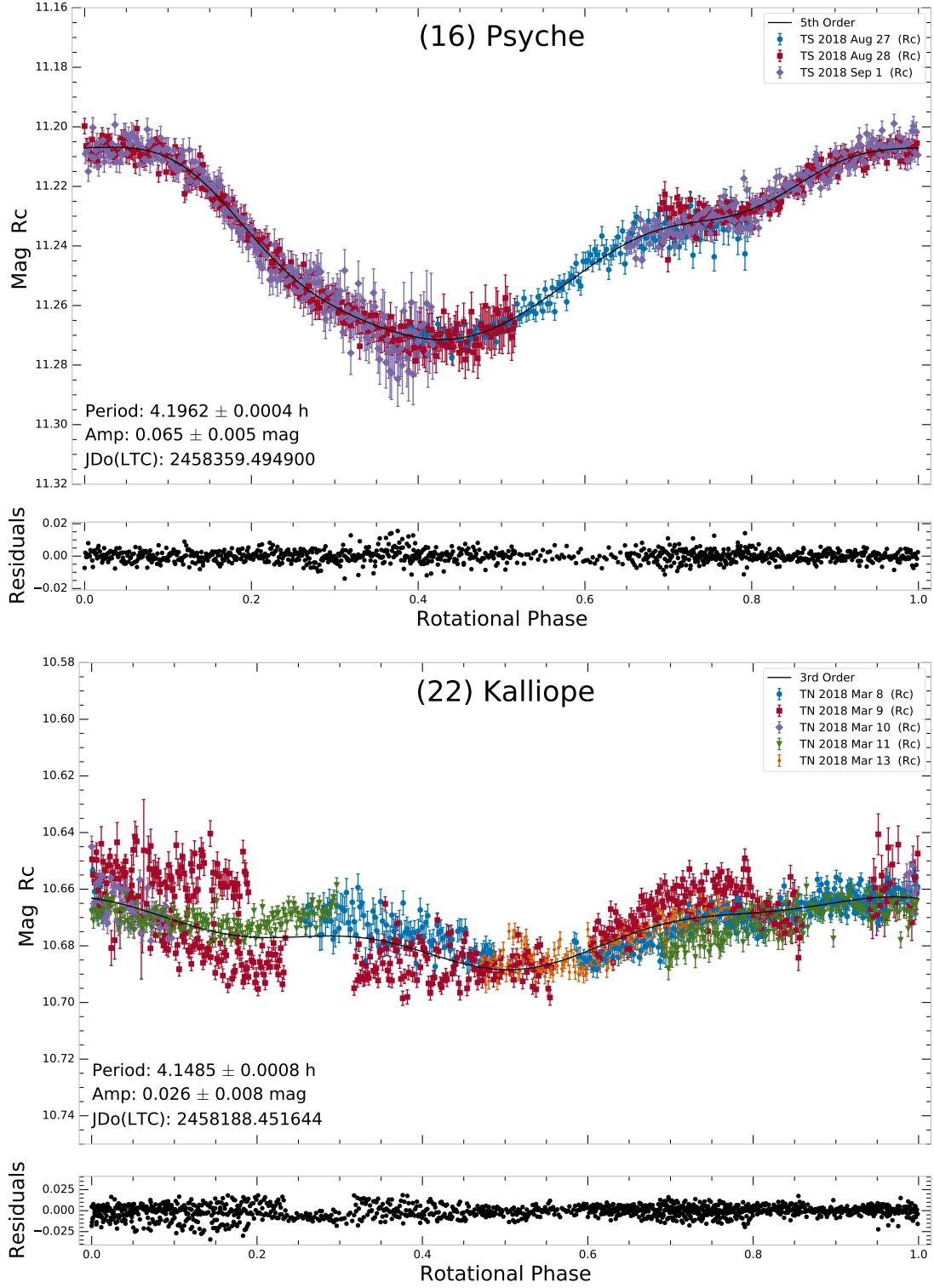


Figure 2.12.: Phased lightcurves of (16) Psyche and (22) Kalliope.

## 2. Optical lightcurves – 2.6. Results

Table 2.2.: Observing circumstances and results of 31 large main-belt asteroids observed with TRAPPIST for the ESO large program.

| Number | Name       | yyyy mm/dd       | Pts   | Phase      | $L_{PAB}$ | $B_{PAB}$ | Period (h) | P.E.   | Amp  | A.E. |
|--------|------------|------------------|-------|------------|-----------|-----------|------------|--------|------|------|
| 7      | Iris       | 2020 06/26-07/10 | 1010  | 1.1,6.1    | 277       | 2         | 7.1385     | 0.0015 | 0.21 | 0.01 |
| 10     | Hygiea     | 2018 09/10-11/17 | 9490  | *4.8,8.2   | 1         | 5         | 13.8224    | 0.0005 | 0.27 | 0.01 |
| 13     | Egeria     | 2019 08/20       | 1340  | 9.5        | 337       | -20       | 7.07       | 0.02   | 0.30 | 0.01 |
| 15     | Eunomia    | 2019 06/13-06/20 | 2681  | 21.0,19.8  | 316       | 3         | 6.083      | 0.001  | 0.46 | 0.04 |
| 16     | Psyche     | 2018 08/27-09/01 | 1028  | 18.0,17.7  | 239       | 3         | 4.1962     | 0.0004 | 0.07 | 0.01 |
| 18     | Melpomene  | 2019 08/17-08/30 | 1934  | 22.4,25.7  | 284       | 7         | 11.571     | 0.003  | 0.32 | 0.01 |
| 20     | Massalia   | 2017 11/10-12/09 | 3228  | 15.8,5.0   | 84        | -1        | 8.0979     | 0.0005 | 0.25 | 0.01 |
| 20     | Massalia   | 2019 03/14       | 1185  | 21.9       | 235       | 0         |            |        | 0.22 | 0.02 |
| 21     | Lutetia    | 2019 09/11       | 2177  | 9.6        | 3         | -4        | 8.16       | 0.05   | 0.16 | 0.01 |
| 22     | Kalliope   | 2018 02/08-03/13 | 1391  | 10.0,8.6   | 190       | 14        |            |        | 0.03 | 0.01 |
| 24     | Themis     | 2017 09/21-11/08 | 3264  | *9.6,7.1   | 27        | 0         | 8.3741     | 0.0002 | 0.12 | 0.01 |
| 24     | Themis     | 2019 01/17-01/28 | 2099  | 1.4,6.0    | 113       | 1         | 8.374      | 0.001  | 0.10 | 0.01 |
| 30     | Urania     | 2020 05/07-05/28 | 944   | 22.0,22.9  | 167       | -2        | 13.693     | 0.002  | 0.26 | 0.01 |
| 31     | Euphrosyne | 2017 11/07-12/07 | 1836  | 19.8,14.8  | 90        | 27        | 5.5312     | 0.0007 | 0.07 | 0.01 |
| 31     | Euphrosyne | 2019 06/13-07/02 | 1061  | 16.1,17.3  | 205       | -1        | 5.5307     | 0.0007 | 0.10 | 0.01 |
| 41     | Daphne     | 2018 07/08-07/09 | 1158  | 19.3,19.1  | 338       | 9         | 5.9912     | 0.0028 | 0.18 | 0.01 |
| 45     | Eugenia    | 2018 03/07       | 1155  | 5.3        | 177       | 4         | 5.65       | 0.05   | 0.16 | 0.01 |
| 51     | Nemausa    | 2019 10/23-11/14 | 1478  | 23.4,22.7  | 319       | 5         | 7.7843     | 0.0005 | 0.20 | 0.01 |
| 52     | Europa     | 2019 08/27       | 635   | 11.1       | 5         | -7        | 5.58       | 0.05   | 0.12 | 0.01 |
| 65     | Cybele     | 2021 04/18-08/10 | 5200  | *19.1,9.4  | 291       | 3         | 6.081      | 0.0002 | 0.06 | 0.01 |
| 87     | Sylvia     | 2019 10/03-11/09 | 1557  | 15.1,15.2  | 112       | 6         | 5.1837     | 0.0002 | 0.32 | 0.01 |
| 88     | Thisbe     | 2019 10/25-11/24 | 1966  | 13.5,2.4   | 66        | 4         | 6.0411     | 0.0004 | 0.12 | 0.01 |
| 89     | Julia      | 2017 09/20-12/23 | 4411  | 11.4,275.0 | 88        | 24        | 11.3844    | 0.0002 | 0.19 | 0.01 |
| 105    | Artemis    | 2020 01/11-02/01 | 5893  | 11.7,15.0  | 106       | -27       | 37.05      | 0.02   | 0.12 | 0.02 |
| 121    | Hermione   | 2021 09/15-10/16 | 1307  | 5.7,7.8    | 4         | -9        | 5.551      | 0.002  | 0.03 | 0.01 |
| 128    | Nemesis    | 2021 02/18-03/30 | 5529  | 18.8,17.1  | 235       | 3         | 38.904     | 0.006  | 0.17 | 0.01 |
| 145    | Adeona     | 2019 02/14-03/24 | 2272  | 17.0,25.0  | 116       | 11        | 15.0826    | 0.0007 | 0.06 | 0.01 |
| 187    | Lamberta   | 2018 05/17-05/18 | 2415  | 15.2,15.6  | 337       | -9        | 10.66      | 0.01   | 0.33 | 0.01 |
| 216    | Kleopatra  | 2021 03/26-03/31 | 1763  | 16.0,15.5  | 247       | 6         | 5.385      | 0.001  | 0.11 | 0.01 |
| 324    | Bamberga   | 2019 02/20-03/18 | 10393 | 12.5,19.9  | 123       | 4         | 29.4192    | 0.0008 | 0.08 | 0.01 |
| 324    | Bamberga   | 2020 02/18-02/27 | 5043  | 10.7,8.4   | 185       | -7        | 29.423     | 0.002  | 0.08 | 0.01 |
| 354    | Eleonora   | 2020 05/01-05/27 | 2167  | 12.2,18.0  | 205       | 22        | 4.2275     | 0.0015 | 0.11 | 0.01 |
| 476    | Hedwig     | 2017 06/19-07/12 | 1132  | *6.1,5.2   | 280       | -2        |            |        | 0.19 | 0.01 |
| 596    | Scheila    | 2017 06/02-06/03 | 1342  | 1.8,2.3    | 249       | 0         | 15.81      | 0.06   | 0.06 | 0.01 |
| 596    | Scheila    | 2019 11/09-11/20 | 2837  | 6.9,3.5    | 68        | -2        | 15.8569    | 0.0013 | 0.07 | 0.01 |
| 704    | Interamnia | 2018 12/02-12/03 | 1395  | 14.8,14.7  | 114       | -2        | 8.7116     | 0.0002 | 0.04 | 0.01 |
| 704    | Interamnia | 2019 01/16-02/01 | 2112  | 2.1,7.0    | 114       | -6        | 8.7116     | 0.0002 | 0.04 | 0.01 |

**Notes:** Pts is the number of data points. Phase is the the solar phase angles for the first and last date. A \* indicates that it reached a minimum during the observation period.  $L_{PAB}$  and  $B_{PAB}$  are the phase angle bisector longitude and latitude at the middle of the date range. Period is the synodic period and Amp is the amplitude determined for the corresponding apparition. P.E. and A.E. are the period and amplitude uncertainties, respectively.

# 3. Three-dimensional shape modeling

This chapter is devoted to the methodology used to reconstruct the 3D shape of the large program targets. The **MPCD** method was initially developed to reconstruct a precise shape model of the comet 67P/C-G. Here, it was applied on the SPHERE images of **MBAs** by using the **ADAM** and **SAGE** shape models as input meshes, with the goal to further refine their shapes. Sect. 3.3 describes the MPCD method and Sect. 3.4 details its application on the SPHERE images.

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## 3.1. Introduction

This chapter describes the methodology used for the 3D shape reconstruction of our asteroids. We present the modeling procedure used in this thesis to reconstruct the 3D shape of the large MBAs imaged by the SPHERE instrument in the first section, as well as the different adaptations to our data that have been implemented in the second. It must be noted that the development of the MPCD method and of the OASIS tool presented here was not part of the thesis, but a good understanding of how they work have been necessary.

We used the modeling method called Multiresolution PhotoClinometry by Deformation (MPCD), that was developed by C. Capanna and L. Jorda at LAM. It was initially developed to model the shape of the targets of the ESA Rosetta mission: the MBAs (2867) Steins (Jorda et al., 2012) and (21) Lutetia (Capanna et al., 2013), and most importantly the comet 67P/Churyumov–Gerasimenko (Jorda et al., 2016). We can note that Lutetia is a  $\sim 100$  km body and is one of the targets of the SPHERE survey. MPCD was optimized to use the high-resolutions images provided by space missions. A particularity compared to the ADAM and SAGE methods (see Sect. 1.2.5) is that it solely uses disk-resolved images as input data. Considering the spatial resolution provided by SPHERE/ZIMPOL for large MBAs, there was an interest to adapt this method to ground-based observations and assess if its application has an interest in complement to the above-mentioned algorithms. The ADAM and SAGE methods are in most cases more adequate to retrieve the global shape due to the utilization of multiple data sources in addition to the AO images, which do not always cover the whole surface. However, MPCD is expected to possibly retrieve fine scale topographic features smoothed out by ADAM and SAGE.

The MPCD method belongs to the family of photoclinometry (PC) methods, also called shape-from-shading, that were originally introduced by (Rindfleisch, 1966) to study the topography of the Moon and extensively studied since then (for a review, see e.g., Zhang et al., 1999). This class of methods is based on the determination of the slopes of surface facets of a 3D object from the relative intensity of the pixels in the images. The radiance reflected by an illuminated object towards an observer depends on the positions of the object and of the light source, on the shape of the object, and on its reflectance properties. The PC methods are usually ill-posed inverse problem because a 3D shape is deduced from a set of 2D images. Hence, it requires external constraints in order to obtain a unique solution.

The basic principle of MPCD is to gradually deform an initial shape model to minimize an objective function  $\mathcal{F}$  measuring the difference between the observed images and the synthetic images generated from the deformed model. The principles of the MPCD method are presented in this section, and a more detailed description can also be found, in french, in C. Capanna's Ph.D. thesis (Capanna, 2013). A flow chart of the

### 3. Three-dimensional shape modeling – 3.1. Introduction

method is presented in Fig. 3.1.

The MPCD method makes the hypothesis of a constant reflectance of the target surface (comprising the albedo). However, it is possible to recompute the albedo (the single scattering albedo in the Hapke model) after the shape modeling from the residuals between observed and synthetic images. Another limitation of MPCD is the possibility of apparition of artifacts in the reconstructed shape. This problem can be mitigated by the visual inspection of the observed images and the model, and by introducing a smoothness constraint.

Sect. 3.4 describes the application of MPCD to the SPHERE images of MBAs, including the preparation of the input data: the choice of the initial shape (Fig. 3.1, p1), the images selection (Fig. 3.1, p2), and the parameters required for the generation of the synthetic images (Fig. 3.1, p3).

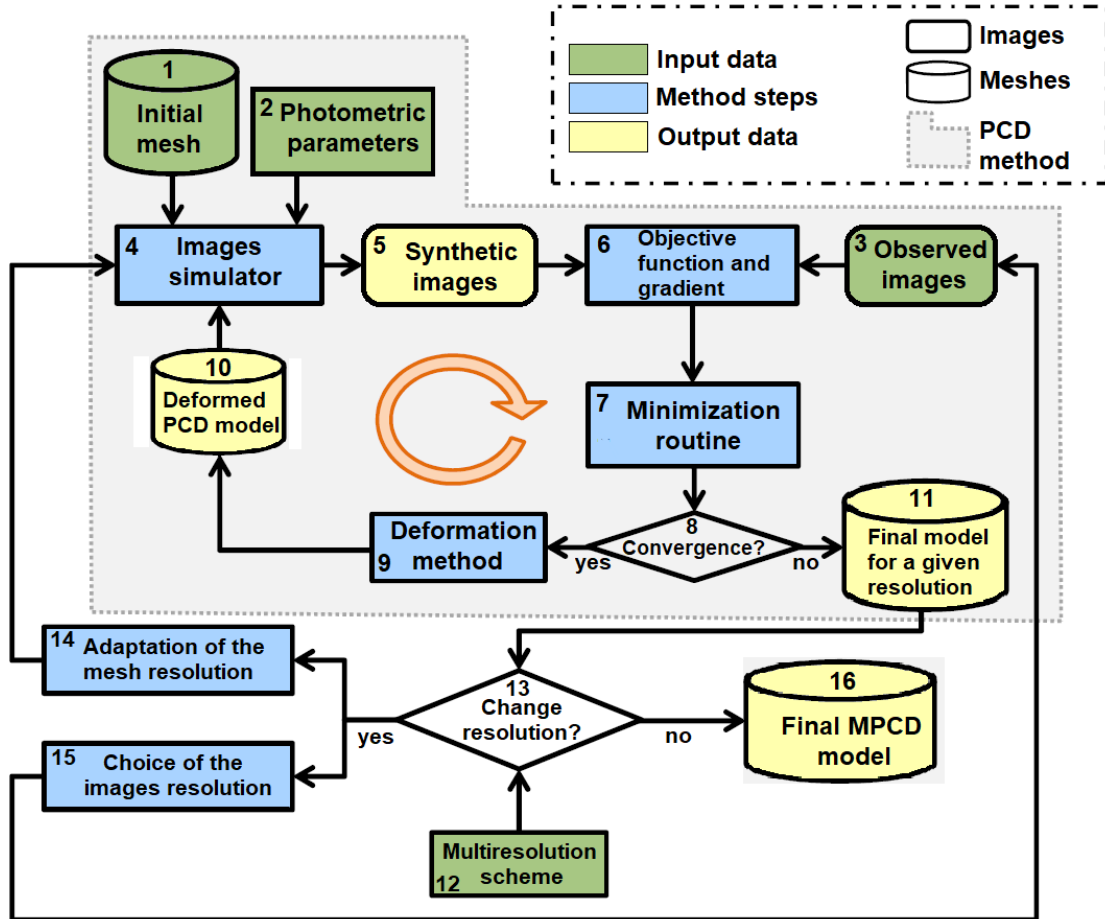


Figure 3.1.: Flow chart of the MPCD method. Adapted from [Capanna et al. \(2013\)](#).

## 3.2. Motivations

In addition to MPCD, two reconstruction methods have been used by the camera team in the course of the Rosetta mission: the StereoPhotoGrammetry (SPG) method (Gwinner et al., 2009) and the StereoPhotoClinometry (SPC) method (Gaskell et al., 2008). Images of the asteroid (2867) Steins have been analyzed by SPC and MPCD, and a better match between observed and synthetic images has been obtained with MPCD. Lutetia has been reconstructed with the three methods and the MPCD shape model is similar to the SPC model, but it has a slightly better surface coverage which allows to better reproduce the limbs on the observed images (Capanna et al., 2013). For comet 67P/C-G, MPCD has been used to create the initial low-resolution model and rotational parameters (used as a starting point by SPC, see Jorda et al., 2016), as well as medium resolution global models (Fig. 3.2). In the frame of the EU H2020 project MiARD (Multi-instrument Analysis of Rosetta Data), high-resolution local Digital Terrain Models (DTMs) have also been generated with MPCD (Nébouy et al., submitted to A&A).

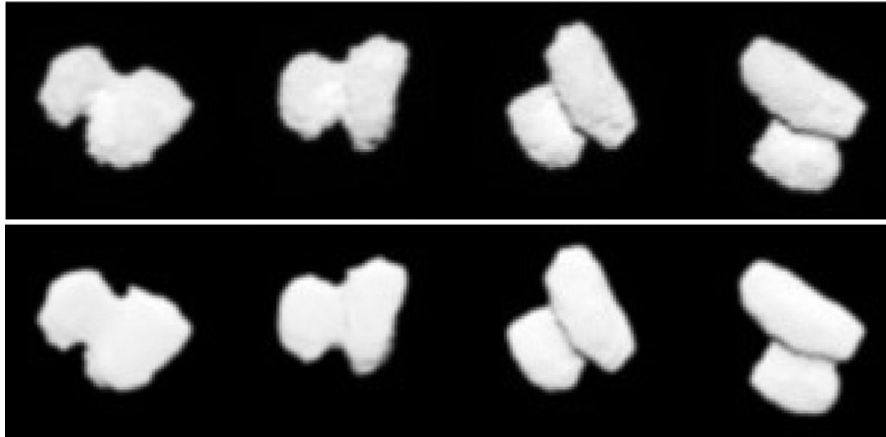


Figure 3.2.: Comparison between image of the comet 67P obtained by the OSIRIS instrument aboard the Rosetta spacecraft, and the synthetic images produced from the MPCD model, illustrating the capacity of the MPCD method to reconstruct the complex bi-lobed shape of the comet nucleus (Jorda et al., 2016).

Given the ability of the MPCD method to reconstruct low- to medium-resolution global shapes in the course of the Rosetta mission, it was tempting to apply the method the SPHERE images of large MBAs. As an example, Capanna (2013) could obtain a global shape of the small asteroid (2867) Steins ( $D \sim 5.6$  km), even in not ideal observation conditions for the photoclinometry. The maximal resolution obtained by the OSIRIS camera was of 80 m/pix, resulting in a size of the asteroid of around 70 pixels on the images, which is comparable to the observation of MBAs with SPHERE.

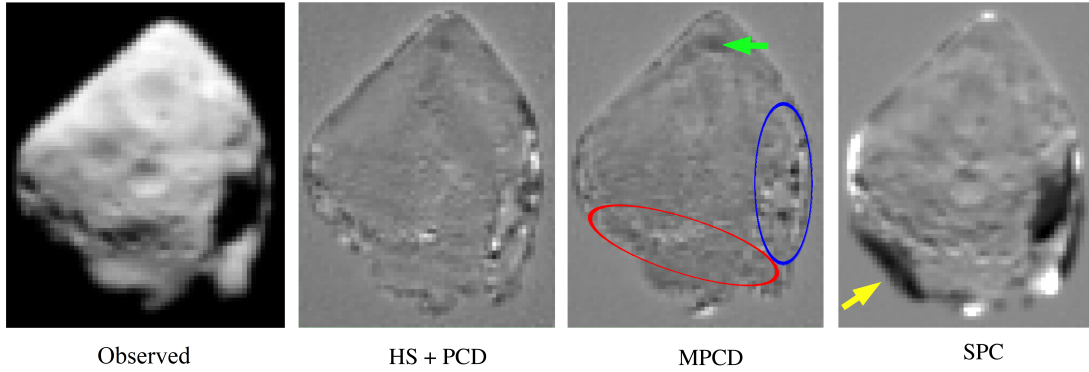


Figure 3.3.: Comparison between an observed image of the asteroid Steins and the corresponding synthetic images from the PCD, MPCD and SPC models. The MPCD model shows a better reconstruction of the small craters (indicated in red) and of the large crater (indicated in blue). Figure adapted from [Capanna \(2013\)](#).

### 3.3. The MPCD method

#### 3.3.1. Synthetic images

Before diving into the details of the MPCD method, we need a tool able to generate calibrated synthetic images of a 3D model (Fig. 3.1, p4 and p5). The synthetic images must accurately reproduce the geometric conditions of the observations as well as the surface reflectance of the objects to allow to directly compare them to the observed images from SPHERE. This is a critical step of the modeling process as a wrong generation of synthetic images will prevent MPCD to reach a correct solution.

MPCD uses a synthetic image simulator called *Optimized Astrophysical Simulator for Imaging Systems* (OASIS). It was developed for the images acquired by the OSIRIS camera onboard the Rosetta spacecraft ([Jorda et al., 2010](#)), but can be adapted to any spacecraft, or to ground-based observations as in the case of this work.

OASIS takes as inputs a shape model (in the form of a triangular mesh), geometric parameters (the position and orientation of the object and of the observer), and instrumental parameters (the geometric and radiometric properties of the camera).

A possible way to represent a 3D surface is by using a piece wise linear approximation called a mesh. A mesh is composed of points, the vertices, that are connected by segments which form polygons, called the facets or faces. The most common type of facets, and the one used by MPCD, are the triangular facets composed of three vertices. A triangular mesh can be fully described by the cartesian coordinates of its vertices in the body-fixed frame, along with the connections between vertices forming a facet, which are described by the three indices of the neighbor vertices. A triangular mesh can be easily deformed by modifying the 3D coordinates of the vertices and adapted to different resolutions using subdivision or decimation operations on the



### 3. Three-dimensional shape modeling – 3.3. The MPCD method

facets. Moreover, an important advantage of the triangular meshes is their capacity to represent the complex topology and the strong curvatures that asteroids can exhibit.

For each image, the tool:

- (i) determines which facets of the model are both illuminated by the Sun and visible to the observer (including cast shadows)
- (ii) computes the intersections between the triangles of the models (projected in the camera frame) and the facets of the shape model
- (iii) computes the signal contribution in Digital Numbers (DN) of the facets.

This allows to build the final synthetic image.

To describe the geometry of the scene, the position of the asteroid and of the observer (in our case, the Paranal Observatory) in equatorial coordinates are retrieved from SPICE kernels (tabulated positions provided by the space agencies, [Acton, 1996](#)). The exact positions are interpolated at the time of the observations minus the light-time correction. The rotation period, the spin axis coordinates, and the initial time of the shape model are also given as inputs to compute the orientation of the object. The rotational parameters can be obtained via other methods such as the lightcurves inversion. Then, OASIS computes the position and orientation of the object in the camera frame that is attached to the telescope.

The facets that are illuminated by the Sun are identified from the angle between the normal to the surface and the direction of the Sun, which must be less than  $90^\circ$ . Then, the illuminated facets are projected to the frame of the CCD to determine which of these facets are also in the field of view of one or more pixels, hence visible to the observer. Finally, it remains to eliminate the facets that are occulted by other facets as seen from the light source or from the observer as it means that they are respectively in regions of projected shadows or not visible by the observer. A ray is cast between the center of the facet and the Sun and another between the facet and the observer. These rays are then tested for intersections with other facets.

#### Signal computation

For each facet that are both visible and illuminated, OASIS computes the intersection between the facets  $i$  and the pixel  $(p, q)$ . This intersection corresponds to a solid angle, called  $\Omega_i^{(p,q)}$ . The number of facets that intersect the pixel  $(p, q)$  is noted  $M_{pq}$ . Finally, the signal in DN in the pixel  $(p, q)$  can be computed as the sum of the contribution of the  $M_{pq}$  facets:

$$S_{(p,q)} \approx \frac{g S_{coll} t_{exp}}{hc R_h^2} \left( \sum_{i=1}^{M_{pq}} r_i(\lambda_0) \Omega_i^{(p,q)} \rho_i \right), \quad (3.1)$$

where  $g$  is the gain of the readout electronics,  $S_{coll}$  is the collecting surface of the telescope,  $t_{exp}$  is the exposure time,  $h$  is the Planck constant,  $c$  is the speed of light, and  $R_h$  is the heliocentric distance of the object.  $r_i(\lambda_0)$  is the bi-directional reflectance

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function at a reference wavelength  $\lambda_0$ .  $\rho_i$  is a calibration parameter that takes into account the quantum efficiency of the CCD  $Q_{(p,q)}$ , the transmission of the optical path  $T$ , and the mean solar irradiance at 1 AU  $M_0$ :

$$\rho_i = Q_{p,q} T M_0. \quad (3.2)$$

#### The Hapke model

The bi-directional reflectance function  $r_i(\lambda_0)$  characterizes how the light reflects on the surface, depending notably on its composition and roughness. OASIS uses the Hapke model (Hapke, 1981, 1984, 2002), which is adequate to represent asteroid surfaces. Three angles are considered: the incidence angle  $i$ , between the normal to the surface and the direction of the Sun; the emission angle  $e$ , between the normal to the surface and the direction of the observer; and the phase angle  $\alpha$ , between the direction of the Sun and the direction of the observer as seen from the asteroid. The model gives the bi-directional reflectance function as:

$$r(i, e, \alpha) = \frac{w}{4\pi} \frac{\cos(i)}{\cos(i) + \cos(e)} ([1 + B(\alpha)]) P(\alpha) + H(\cos i) H(\cos e) - 1) \kappa(\theta) \quad (3.3)$$

The additional parameters allow to characterize the the phase function of the particles and to account for backscattering effects.  $w$  is the single scattering albedo.  $B(\alpha)$  is the opposition effect function that account for the brightening of asteroid surfaces at low phase angles. It is described by the opposition surge amplitude value  $B(0)$ , and the angular extent of this effect  $h$ .  $P(\alpha)$  is the single particle phase function that depends on the asymmetry factor  $g$ .  $H(i, e, \alpha)$  describes the multiple-scattering of light between particles. Finally,  $\kappa$  is the macroscopic roughness function and  $\theta$  is the average topographic slope angle. The parameters  $w$ ,  $B_0$ ,  $h$ ,  $g$ , and  $\theta$  can be adjusted to represent different surface types (Sect. 3.4.3).

#### 3.3.2. Maximum likelihood estimation

The MPCD method is based on an objective function  $\mathcal{F}$  to be minimized and defined as:

$$\mathcal{F}(p_k) = L(\mathbf{O}, p_k) + S_C(p_k), \quad (3.4)$$

where  $L(\mathbf{O}, p_k)$  is minus the log of the maximum-likelihood of the parameters  $p_k$  for quantifying the discrepancies between observed and synthetic images, and  $S_C(p_k)$  is a prior smoothness constraint on the deformed model.

To estimate the maximum likelihood, the observation  $\mathbf{O}$  are modeled by synthetic images  $S(p_k)$  to which an instrumental noise is added. This noise is composed of the readout noise  $k$  and of the photon noise. The instrumental noise at the pixel  $m$  is given by:

### 3. Three-dimensional shape modeling – 3.3. The MPCD method

$$\sigma_m(p_k) = g \sqrt{\frac{S_m(p_k) t_{exp}}{g} + k^2}, \quad (3.5)$$

with  $g$  the gain of the electronics and  $t_{exp}$  the exposure time of the image.

We then have the quantification of the difference between the  $N_{pix}$  pixels of the observed images and the synthetic values given by:

$$L(p_k) = \sum_m^{N_{pix}} \frac{(O_m - S_m(p_k))^2}{\sigma_m^2(p_k)}. \quad (3.6)$$

We note that not only the contour is taken into account but also the pixel variations inside the disk of the object.

#### 3.3.3. Smoothness constraint

The deformation scheme allows the vertices to move independently of their neighbors. This can create artifacts caused by the contours of the asteroid, especially when only one image is covering the surface. This is due to the large values of the derivatives of the maximum likelihood function in these regions combined with an oversampling (many facets included in a single pixel). If let free, large displacement of some vertices can appear independently of the other, creating non physical surfaces. To prevent this effect, a smoothness constraint is added in the form of a prior to the maximum likelihood estimation  $S_C(p_k)$ . Its action is to force the orientation of neighbor facets to remain close one from another. A factor  $\Phi$  allows to tune the weight of the smoothness penalty given by:

$$S_C(p_k) = \Phi \frac{\sum_{i=1}^F \sum_{mi=1}^3 |\mathbf{F}_{mi}(p_k) - \mathbf{F}_i(p_k)|^2 s_{mi}(p_k)}{\sum_{i=1}^F s_i(p_k)}. \quad (3.7)$$

In this formula,  $F$  is the number of facets of the shape model,  $\mathbf{F}_i$  is the normal of the facet  $i$  and  $s_i$  is its surface. The  $mi$  indexes denote the three neighboring facets of facet  $i$ .

#### 3.3.4. Deformation scheme

The triangular mesh composing the shape model is deformed through modifications of the vertex coordinates along its initial local normal to the surface  $\mathbf{N}_k^O$ , computed as the average of the initial normal of the facets which share this vertex. The new coordinates of a vertex after a deformation  $\mathbf{R}_k$  is given by:

$$\mathbf{R}_k = \mathbf{R}_k^O + p_k \mathbf{N}_k^O, \quad (3.8)$$

with  $\mathbf{R}_k^O$  the initial position. The free parameters  $p_k$  to be optimized thus represent the displacement of the vertex  $k$  along its initial local normal.

### 3.3.5. Optimization method

The problem corresponds to the optimization of a nonlinear function of many parameters and for which the gradient can be computed (Eq. 3.4). MPCD uses an optimization routine based on the quasi-Newton method L-BFGS-b (Morales and Nocedal, 2011). This method has the advantages of a high probability of convergence and also allows to include lower and upper boundaries on the parameters, which is useful to avoid errors due to local minima. Details on the evaluation of the objective function gradient can be found in Capanna et al. (2013). The convergence criterion is defined as two thresholds on either the difference of the function values between two successive iterations or the difference of the maximum value of the gradient between two successive iterations

### 3.3.6. Multiresolution scheme

The minimization method L-BFGS-b can ensure convergence only for convex functions. However, it is not necessarily the case of the objective function  $\mathcal{F}$ . This is why a multiresolution scheme was added to the PCD method. Indeed, at lower resolutions, the function tends to become more convex which allows to overcome the local minima before increasing back the resolution. In this scheme, the resolution of the surface mesh and of the images evolve together. The shape model resolution can be modified through subdivisions and decimations while the images are binned (the pixels are averaged in groups of  $2 \times 2$ ) to increase the pixel scale. The scheme used is adapted from the "Full Multigrid" method (Botsch et al., 2007) and is illustrated in Fig. 3.4. The optimization starts by applying the PCD method at the lowest resolution. Then, the method alternates between the current resolution level and the next level 4 or 5 times, to ensure that convergence is reached. After that, the resolution is increased to the next level and the scheme is repeated until the convergence at the last level of resolution is achieved.

### 3.3.7. Error estimation

The residuals between the observed image and its synthetic counterpart for each pixel  $m$  are defined as:

$$v_m = \frac{O_m - S_m(p_k)}{\sigma_m}, \quad (3.9)$$

where  $\sigma_m$  is the instrumental noise (Eq. 3.5). The residual images allow to easily compare the observed and the synthetic images and to identify the regions that are not well reproduced by the shape model.

The residuals can also be projected on the model facets to quantify the errors on the model. The mean residuals for the facet  $i$  is obtained from the average residuals of the  $N_{im}$  images projected on its solid angle  $\Omega_P$ :

### 3. Three-dimensional shape modeling – 3.3. The MPCD method

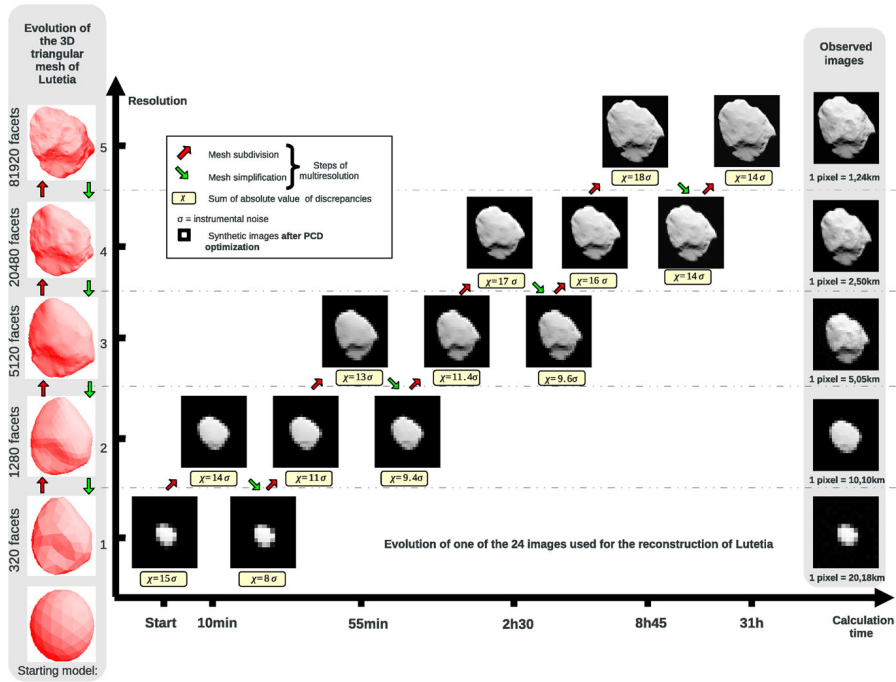


Figure 3.4.: Illustration of the multiresolution scheme adopted by MPCD in the case of the reconstruction of the 3D shape of (21) Lutetia from the Rosetta flyby (Capanna et al., 2013). For clarity, only one back forth change in resolution is shown between each level.

### 3. Three-dimensional shape modeling – 3.4. Application of MPCD

$$\mu_i = \frac{1}{N_{im} \Omega_P} \sum_n^{N_{im}} \sum_m^{N_{pix}} \Omega_{(m,n)}^{(i)} v_{(m)}^{(n)}. \quad (3.10)$$

The residuals on the facets allow to compute the change of the signal in DN resulting from a small variation of the direction of the normal of a given facet. This relation between the slope of the facet and the residuals gives the associated error on the slope of this facet, in degrees. Then, multiplying the error on the slope of the facet by the mean length of its edges provides an estimation of the error on the height, in km. Finally, averaging the error estimates for a given facet on all the images provide an error map in km associated to the facets of the shape model. This error map can be used to estimate the uncertainties on the parameters associated with the reconstructed shape model (see Sect. 3.4.8).

## 3.4. Application of MPCD

This section describes the application of the MPCD method to the SPHERE images of large MBAs, with size in pixel ranging from  $\sim 200$  pixels to only a few tens, depending on their sizes and distances.

### 3.4.1. Initial shape models

The MPCD method requires an initial shape model that will be deformed gradually until convergence is reached. The possible choices for the initial model to reach convergence depend on the input images. If the surface of the object to model is densely covered by several images, like in the case of a spacecraft in orbit or ground-based observations during several apparitions, then it is possible to find a solution even when starting from a simple sphere or ellipsoid shape model scaled to the approximate object size. If it is not the case, a low-resolution shape model obtained by other methods should be used instead to bring additional constraints. This is the case for flybys for which approximately half of the surface is imaged, and also concerns many targets of the SPHERE survey (see the surface coverage values in Table 5.1).

For the large program, several images taken at different phase of the rotation were obtained, usually during five epochs in total. However, a single apparition is sometimes not enough to completely image the asteroid surface, depending on the aspect angle which is the angle between the asteroid spin axis and the line of sight. In the worst case, a pole-on view (aspect angle near  $0^\circ$  or  $180^\circ$ ) only allows to cover one hemisphere, hence  $\sim 50\%$  of the surface. On the contrary, an equator-on view (aspect angle close to  $90^\circ$ ) allows to cover almost completely the surface, except for the poles, and also to determine precisely the dimension along the spin axis. Ideally, combining observations during two apparitions with one close to a pole-on geometry and one close to an edge-on view provide much better surface coverage and constraints on the asteroid dimensions.

### 3. Three-dimensional shape modeling – 3.4. Application of MPCD

Adequate initial models can be obtained via the lightcurves inversion method (see Sect. 1.2.1). Here, we used as input the shape models produced by the ADAM or SAGE methods which already incorporate the SPHERE images use other date types to constrains the region not imaged by SPHERE. Hence, the initial models already fitted well the global shape of our asteroids. This way, MPCD can leave the model unchanged in regions poorly imaged or not imaged at all by SPHERE, but attempts to refine the model in the well covered regions. As a results, the MPCD method is very complementary to the other two modeling methods employed in the large program.

Before using them as inputs for MPCD, the the resolution of the initial shape model must be adapted to the resolution of the images. We aim to have approximately one facet per pixel for a correct sampling. To do that, the mean number of pixels inside the disk of the asteroid  $n_{pix}$  is computed. Then, the number of facets of the shape model is set to about  $4 n_{pix}$  to account for the facets not seen on the image and for the higher number of facets per pixel closer to the edge of the model when projected on the image. The desired resolution is obtained by decimating and subdividing the initial MPCD or SAGE model.

Additionally, several models at lower resolutions are also produced as they are necessary to the multi-resolution scheme described in Sect. 3.3.6. The use of smoother and lower resolution models helps the algorithm to not fall in local minima during the optimization. A resolution level  $n$  corresponds to a binning of the image by  $2^{n-1} \times 2^{n-1}$ . The minimum resolution is determined by the maximum binning that keeps the asteroid size across the image above  $\sim 10$  pixels. We usually used three resolution levels for our targets, but also only two for the smallest and four or five for the largest. When an asteroid is observed during two apparitions with very different angular diameters, we need to use a different number of resolution levels for each apparitions. Four of our targets fall in this category: Iris, Flora, Eunomia, and Melpomene (see Table 5.1).

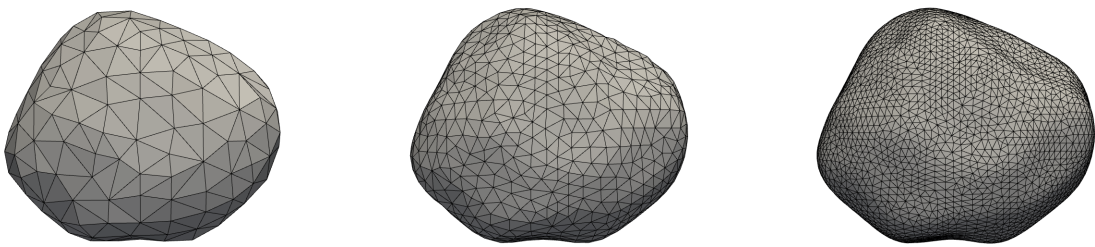


Figure 3.5.: Shape model of the asteroid (16) Psyche at three levels of resolutions, corresponding from left to right to binnings of the SPHERE images of  $4 \times 4$ ,  $2 \times 2$ , and no binning.

### 3.4.2. Image selection

It is not always best to incorporate all the available images in the modeling. For instance, some images might have been obtained at less good observation conditions (worst seeing), others might not bring additional informations. The following selection criteria can be considered.

In the ZIMPOL instrument, a beam splitter separates the beam to two different camera arms, each equipped with their own optics, filter wheels and CCD. For our observations, the same configuration was used for each camera, providing two almost identical images after each exposure. However, the result of the deconvolution by MISTRAL can sometimes slightly differ between the two cameras. In some extreme cases, this can create artifacts in the image from one camera but not on the other. A visual inspection is thus necessary to ensure that only images not affected by such artifacts are used. Most of the time, however, only the images from one camera have been chosen as they are equally good. Otherwise, a mix of images from both cameras is also possible.

Another criteria that was considered is to limit the observations to a minimum phase angle of  $\sim 10^\circ$ , with the goal of keeping only the image with the highest contrast on the asteroid disk. However, this criteria is too restrictive in our case because the SPHERE observations were all performed near opposition at  $\alpha \leq 15^\circ$ .

Finally, a minimal change in the rotational phase corresponding to a difference of at least one pixel between two consecutive images was required. This allows to filter images that do not bring new information to the algorithm. All images were usually kept for asteroid with fast rotation periods ( $P \leq 8$  h), while for the others we selected images in each epoch that satisfy the criterion and maximized the time gaps between the images. This step has been automated using the rotation period and the size of the asteroid in the image in pixels.

### 3.4.3. Hapke parameters

Hapke parameters have been determined for some particular targets but also for the main asteroid types (see the compilation in [Li et al., 2015](#)). We tested the importance of the choice of these parameters on the final results. The tests showed that it was adequate to use the average values for the C and S-types from ([Helfenstein and Veverka, 1989](#)), or for our M-type targets, the values derived for (216) Kleopatra by ([Descamps et al. \(2011\)](#)). These values are compiled in Table 3.1. Small modifications of these parameters did not have significant influences on the shape modeling, notably because of the low phase angles ( $\alpha \simeq 15^\circ$ ) at which all our observations were obtained.

### 3.4.4. Convolution of the synthetic images

The deconvolution is never perfect and a faint halo remains around the object in the deconvolved images. This signal can affect the optimization and thus it is removed by



### 3. Three-dimensional shape modeling – 3.4. Application of MPCD

Table 3.1.: Hapke photometric parameters for the average S and C classes, and for (216) Kleopatra that were used for our M-type targets.

| Object          | $w$   | $h$   | $B_0$ | $g$    | $\theta[^\circ]$ |
|-----------------|-------|-------|-------|--------|------------------|
| Average S       | 0.230 | 0.080 | 1.600 | -0.270 | 20               |
| Average C       | 0.037 | 0.025 | 1.030 | -0.470 | 20               |
| (216) Kleopatra | 0.181 | 0.047 | 1.276 | -0.254 | 20               |

setting the pixel values outside the disk to zero. Then, to account for the imperfect deconvolution inside the disk, the synthetic images are convoluted by a Gaussian PSF with a typical FWHM of 1.5 - 2.5 pixels. The best PSF is determined by testing a range of FWHM values to convolute the synthetic images of the initial model and find the PSF yielding the minimal residuals. After a complete modeling with MPCD, this process is repeated with the newly constructed MPCD model. This sometimes led to slight change of the best PSF FWHM. If the resulting  $\chi^2$  decreased by more than 5%, a new MPCD run was performed. The  $\chi^2$  is computed as the square of the difference between the observed and synthetic images, given in units of the instrumental noise:

$$\chi^2 = \frac{1}{N_{pix}} \sum_m^{N_{pix}} \left( \frac{O_m - S_m(p_k)}{\sigma} \right)^2. \quad (3.11)$$

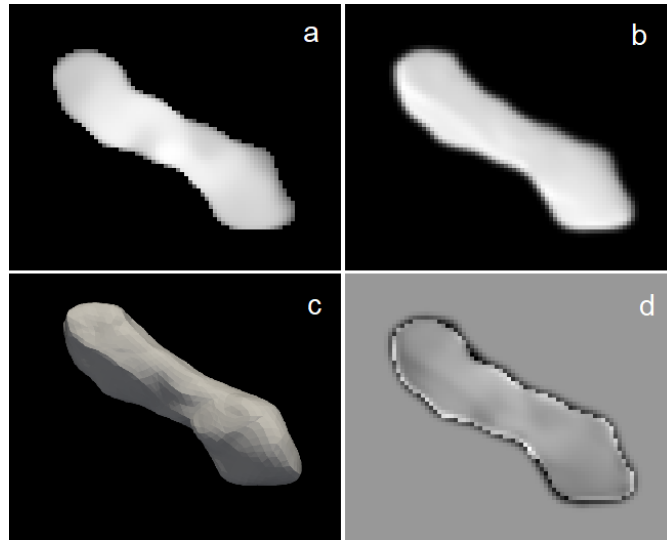


Figure 3.6.: Comparison between a SPHERE image of (216) Kleopatra (a) and the corresponding synthetic images created by OASIS (b) from its shape model (c). The residuals are shown in the bottom right image (d).

### 3.4.5. Instrumental noise

The computation of the instrumental noise is not as straightforward for ground-based observations as for space mission data. Indeed, the signal in our image is affected by the AO and the deconvolution. Moreover, both the AO and the deconvolution processes are never perfect, and they add their own noises to the signal that are difficult to estimate. Because of that, the computation of the signal by OASIS (Sect. 3.3.1) do not correctly reproduces the observed values. To handle this problem, we introduced multiplicative correction factors to the computation of the signal for each synthetic images. These factors are computed for each image to minimize the difference between the observed and the synthetic image. Typical values are between 1 and 10. In Table 3.2 we list the values of the readout noise, bias, and gain used by OASIS, along with other parameters common to each MPCD run.

Table 3.2.: List of parameters with values that are common to all of our targets. The readout noise (RON), bias level, and gain of the detector are provided.  $N_{iter}$  is the number of iterations between two resolutions levels, and  $N_{rec}$  is the number of iteration between topography and image recentring.  $\phi$  is the default value of the smoothing constraint.

| Parameter     | Value |
|---------------|-------|
| RON [e-]      | 30.0  |
| Bias [ADU]    | 0.0   |
| Gain [e-/ADU] | 3.1   |
| $N_{iter}$    | 5     |
| $N_{rec}$     | 5     |
| $\phi$        | 1000  |

### 3.4.6. Smoothness constraint

The value of the weight factor  $\Phi$  of the smoothness constraint (Eq. 3.7) has been empirically determined as to prevent the apparition of artifacts while not stopping the convergence. For most targets, the default value  $\Phi = 1000$  was used. It can be further adjusted depending on the number of images used and the results of the first MPCD run. For instance, if there are regions that have only been covered by only one images and they include the limb of the object, a stronger smoothness constraint will often be needed to prevent the formation of artifacts (up to  $\Phi = 2000$ ). However, when the coverage is better, decreasing  $\Phi$  can help to better reconstruct eventual small-scale features present on the images. The lowest value used was  $\Phi = 200$ .

The initial choice can be guided by the inspection of the coverage maps. If artifacts appear on a shape model, the number of images on the concerned regions can be

retrieved to see if a poor coverage might be the cause. In this cases, increasing the smoothness constraint is recommended. These maps were produced using OASIS and they can be visualized on a flat projection or directly on the 3D model (Fig. 3.7).

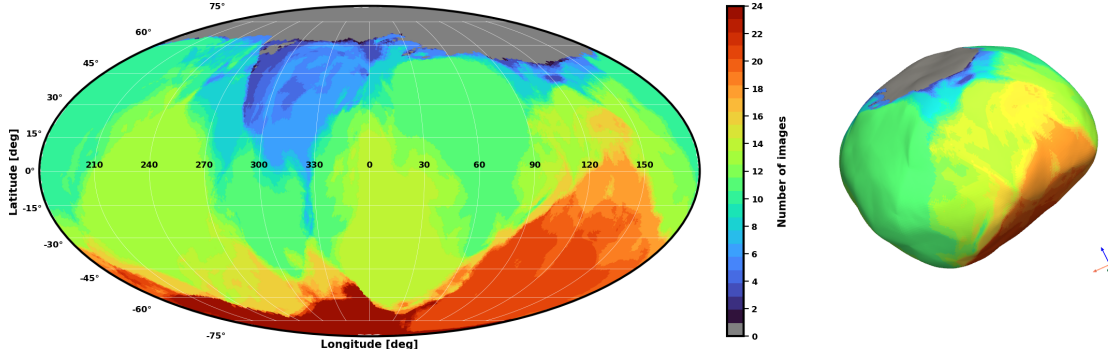


Figure 3.7.: *Left*: Example of a coverage map of an asteroid observed with SPHERE indicating a better coverage of the southern hemisphere while the north pole was not imaged. *Right*: View of the same coverage map projected on the shape model.

### 3.4.7. Pole optimization

For the spin axis, we used the value coordinates determined by ADAM or SAGE. After each MPCD run providing a satisfying shape, we used the reconstructed MPCD model to test for potential spin axis resulting in a better fit of the images. We tested a grid of coordinates of  $\pm 5^\circ$  centered on the initial pole, with a step of  $0.5^\circ$ . For each point of the grid, a new set of synthetic images are generated with the corresponding spin axis orientation, and the  $\chi^2$  is computed. For all of our targets except (216) Kleopatra, the improvement in  $\chi^2$  given by the best fitting pole was always small ( $< 5\%$ ). The typical differences with the initial pole were in the range  $0.5$ - $1.5^\circ$ , within the uncertainties of the ADAM or SAGE solutions. As a consequence, no new pole coordinates were used for the MPCD models. In the case of (216) Kleopatra, we noticed an unusual systematic residuals between our sets of observed and synthetic images when using the ADAM solution. A new pole differing by  $0.6^\circ$  in longitude and  $0.8^\circ$  in latitude was determined, allowing a 67% decrease of the  $\chi^2$ .

### 3.4.8. Errors on the model dimensions

To estimates the uncertainties of the model dimensions, we use the error maps on the facet of the model described in Sect. 3.3.7 to apply deformation on the model and compute the change in the parameters we are interested in. Applying random displacements to the vertices of the model would lead to physically unrealistic models with potentially high local slopes. Instead, we apply fractal deformations that better reproduce asteroid surfaces.

### *3. Three-dimensional shape modeling – 3.4. Application of MPCD*

The deformation follows a fractal law in which the sigma of the Gaussian random displacement distribution follows a power law with respect to the sampling of the multiresolution models used in MPCD. The sampling of each model is calculated as the mean edge length of all triangles. To ensure that the displacements match the error map of the model, the sigma value of the fractal law applied to the highest resolution model is set equal to the standard deviation of the map values. The fractal dimension is taken between 2.1 and 2.3, following the analysis of NEAR/NRL laser altimetry measurements performed by NEAR for the surface of asteroid (433) Eros ([Cheng et al., 2002](#)).

A large number of fractal random models are generated (usually 10000), and for each of them the dimensions and volume are computed. The distribution of the obtained values for each parameters represent their error distribution. A Gaussian curve is fitted on the distributions and the adopted error associated with each parameter corresponds to the sigma value of the Gaussian.

## 4. Study of two dense M-type asteroids

This chapter presents the study of two of the targets of the SPHERE survey: Psyche and Kalliope. They are the two largest M-type asteroids in the main belt, but they also differ in some respects: Psyche has a very metal-rich surface whereas Kalliope is orbited by a satellite, Linus. They are both important targets to characterize, Psyche notably being the target of a NASA rendezvous mission.

We applied the MPCD method to the SPHERE images of these asteroids to reconstruct their 3D shape models, and thus determine their bulk densities. The obtained values potentially make Kalliope and Psyche the two densest small bodies of the Solar System known so far. Their shapes were also analyzed, allowing to propose hypotheses on formation scenarios.

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## 4.1. The metal-rich (16) Psyche

### 4.1.1. Introduction

Asteroid (16) Psyche is the largest M-type asteroid in the main belt. Evidences of a metal-rich surface, including high mean radar albedo and thermal inertia, contributed to define this asteroid as a metallic world that could be an exposed planetary core (Elkins-Tanton et al., 2017). The uniqueness of Psyche's characteristics made it a prime target for spacecraft exploration, resulting in its selection as the rendezvous target of a NASA Discovery mission. The Psyche mission was scheduled to arrive at Psyche in early 2026. Recently, delays in the preparation of the mission forced the team to postpone the launch. Possible future launch windows will be in 2023 and 2024, with corresponding arrival to Psyche in 2029 and 2030, respectively.

To this day, the true nature of Psyche is still unknown and question regarding its interior structure and composition as well as its formation scenarios are still open. It is not known if Psyche is a rubble pile or not, and if its interior is differentiated or stayed homogeneous. Recent estimates of Psyche's density all converge to a value close to  $\sim 4 \text{ g}\cdot\text{cm}^{-3}$ , much lower than the density of iron meteorites. A high macroporosity of  $\sim 50\%$ , would solve this discrepancy, but appears unlikely considering the size of Psyche. While still possible, the exposed core scenario is not the most favored anymore. Psyche's density appears compatible with that of stony-iron meteorites such as mesosiderites (Viikinkoski et al., 2018) as well as that of pallasites and CB chondrites (Elkins-Tanton et al., 2020). Hence, Psyche could potentially originate from the reaccumulation of rocky and metallic parent bodies shattered by impacts. Another possible scenario by Johnson et al. (2020) propose that Psyche could have formed as a differentiated body and that ferrovolcanism would be at the origin of the high metal content of its surface (Shepard et al., 2017).

A better understanding of Psyche's history required a better characterization of its size and shape, making it a particularly interesting target to observe with SPHERE. It was thus decided early during the thesis to first focus on the shape modeling of Psyche. The results of the application of MPCD to Psyche and the analysis of its shape are presented here, and on the paper provided in Sect. 4.1.7.

### 4.1.2. Observations

A first set of images were obtained with SPHERE during the 2018 apparition of Psyche and presented in Viikinkoski et al. (2018). We then obtained 35 new images at 7 epochs in July and August 2019, bringing the total to 60 images at 12 epochs. The images from the two apparitions complement well each other. Whereas the images from 2018 were limited to the northern hemisphere of Psyche (aspect angle<sup>1</sup> of  $11^\circ$ ), those acquired during the second apparition covered well the equatorial region ("edge-on") with an aspect angle of  $101^\circ$ . This allowed us to obtain a complete coverage of the surface of

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<sup>1</sup>The aspect angle is the angle between the spin axis and the Earth line of sight.

#### 4. Study of two dense M-type asteroids – 4.1. The metal-rich (16) Psyche

Psyche, the southern hemisphere being observed everywhere by a minimum of six images (see the coverage map in Paper I: Sect. 4.1.7). Moreover, the first apparition constrained well the x and y axes while the second was crucial to constrain the z-axis, along the spin axis.

##### 4.1.3. 3D reconstruction

A first shape model was generated by J. Hanuš with the ADAM algorithm using the same procedure as in Viikinkoski et al. (2018). In addition to the new SPHERE images, a new stellar occultation by Psyche recorded in October 2019 was included in the modeling. Because albedo variegation are apparent in both the lightcurves and the images, ADAM optimized the shape simultaneously with the albedo. The final model has a volume-equivalent diameter  $D_{\text{adam}} = 224 \pm 5$  km

We then applied the MPCD procedure using the ADAM model as the initial mesh. We selected two to three images per epoch, maximizing the time gap between the images instead of using all of the images, following the criterion described in Sect. 3.4.2. For the rotational parameters of our model, we first used the pole solution of ADAM and its sidereal rotation period of 4.195948 h (Table 4.1). For the reflectance properties of the surface, we used the five-parameter Hapke law (Hapke, 1981) derived for another M-type asteroid, (216) Kleopatra (Descamps et al., 2011). This choice had little influence on the shape reconstruction because of the low phase angle of our observations ( $\alpha_{\text{max}} = 8.7^\circ$ ). A range of Gaussian PSF was tested for the convolution of the synthetic images of the ADAM model. The PSF resulting in the lowest  $\chi^2$  (Eq. 3.11) had a FWHM of 2.1 pixels (7.6 arcsec).

A first MPCD run was performed with these parameters, resulting in a  $\chi^2 = 51$ . Then, we searched for the best spin solution by testing a grid of values around the initial ADAM solution. We found spin-vector coordinates ( $[\lambda; \beta] = [35^\circ; -10^\circ]$  in ECJ2000) close to the values used initially ( $[34^\circ; -9^\circ]$ , Viikinkoski et al. 2018). A second MPCD run was performed using this new spin but resulted in similar  $\chi^2$  and volume. The final step was to recompute the best-fitting PSF, this time with the MPCD model obtained before. As a significantly different FWHM was retrieved (1.5 pixels), we performed a last MPCD run that gave a final shape model with a  $\chi^2 = 43$  and a volume-equivalent diameter  $D_{\text{mpcd}} = 222 \pm 4$  km. This model can be visualized in Fig. 4.2.

A comparison between the SPHERE images and the synthetic images generated with the ADAM and the final MPCD models for each epoch is given in Fig. 4.1. The two models are remarkably similar and the corresponding residual images indicate a good fit of both models to the AO images. Their  $\chi^2$  are compared in Table 4.1 with those of the radar model of Shepard et al. (2017) and the previous ADAM model (without the images of the 2019 apparition), which shows a significant increase in the quality of the fit for the new models.

#### 4. Study of two dense M-type asteroids – 4.1. The metal-rich (16) Psyche

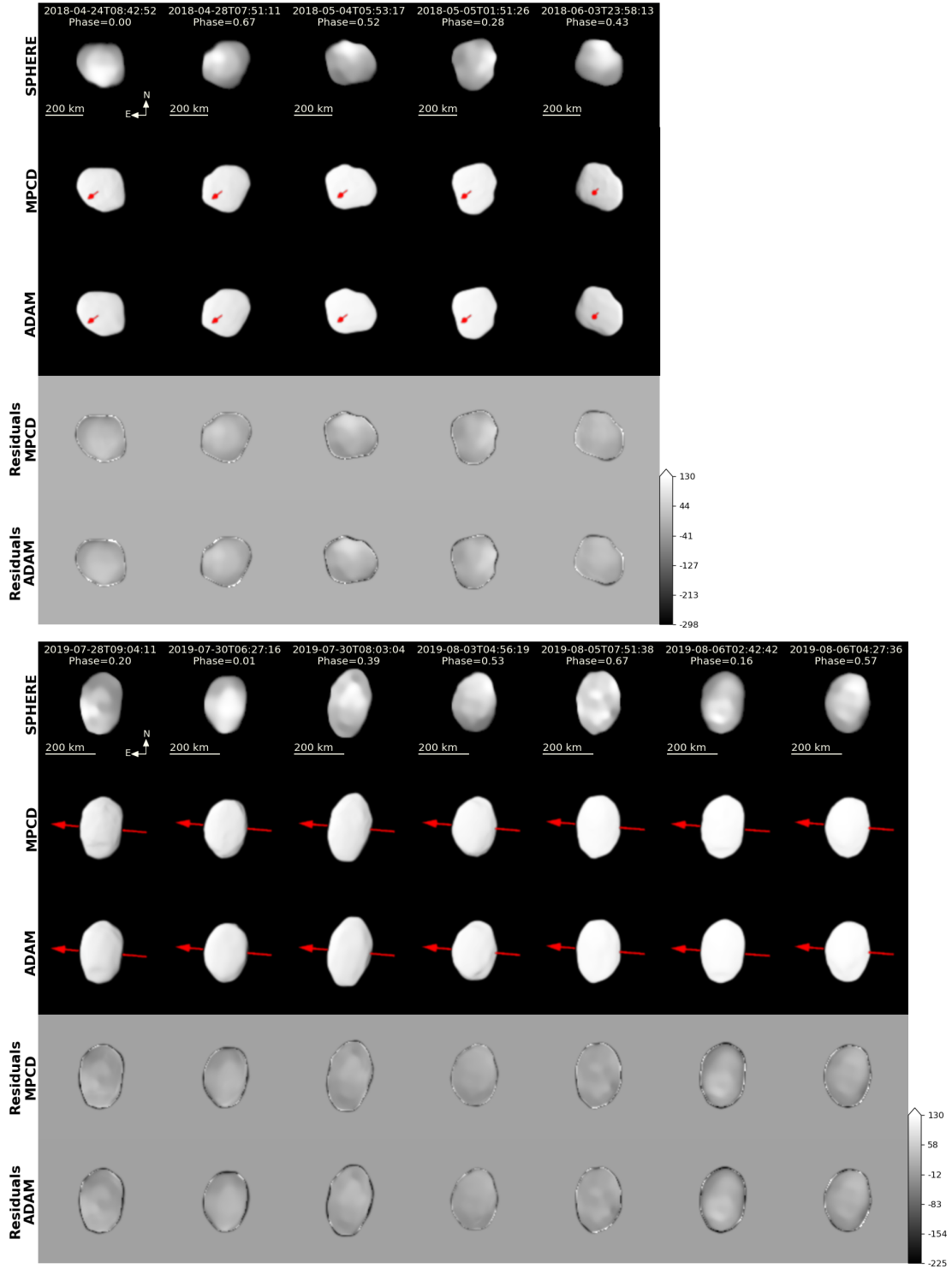


Figure 4.1.: Comparison between the deconvolved images of Psyche (top row) and the corresponding synthetic images generated by the OASIS tool of the MPCD (second row), and ADAM (third row), and the associated residuals (forth and fifth rows). One image is displayed for each epoch, the top image is for the 2018 apparition and the bottom image for the 2019 one. The red arrows indicate the direction of the spin axis.



#### 4. Study of two dense M-type asteroids – 4.1. The metal-rich (16) Psyche

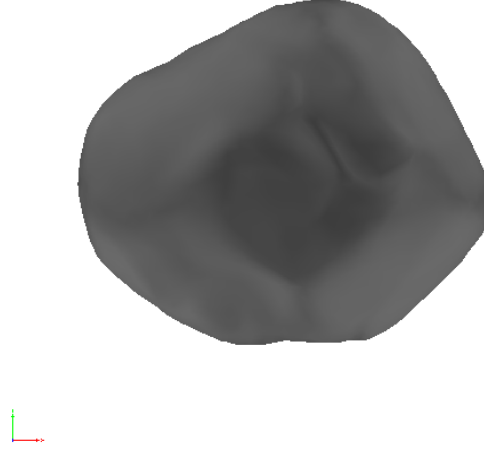


Figure 4.2.: Animated 3D shape model of (16) Psyche reconstructed by MPCD. (Requires Adobe Acrobat PDF reader).

The diameter obtained with MPCD yields a density of  $\rho = 4.20 \pm 0.60 \text{ g}\cdot\text{cm}^{-3}$  when combined with available mass estimates determined in [Viikinkoski et al. \(2018\)](#), value reported in [Ferrais et al. \(2020b\)](#). Recently, [Siltala and Granvik \(2021\)](#) reported a lower mass estimate that decreased our density (average of the ADAM and MPCD values) to  $\rho = 3.89 \pm 0.52 \text{ g}\cdot\text{cm}^{-3}$ . This new density was published in [Vernazza et al. \(2021\)](#).

##### 4.1.4. Shape analysis

We analyzed the shape of Psyche first by measuring its deviation to its best-fit ellipsoid and its sphericity. The deviation to an ellipsoid is computed as the radial differences between Psyche's shape model and its best-fitting ellipsoid. We obtained a (model - ellipsoid) average residuals of 3.6% relative to the mean radius. The sphericity index was measured following the approach described in [Vernazza et al. \(2020\)](#), and in Chapter 5, Sect. 5.2. For comparison, we then repeated this process for the previously studied targets of our large program at the time. Psyche's shape appears to be intermediate between those of larger asteroids such as Interamnia or Vesta and those of smaller or similarly sized bodies such as Iris (Fig. 4.3).

Psyche exhibit a shape close to an ellipsoid along its spin axis direction but with flatter regions on both poles. However, its shape deviates from an ellipsoid in the other directions because of depression regions along the equator, possibly caused by impact basins (Fig. 4.4). To obtain the primordial shape of Psyche, a new ellipsoid fit was performed but this time ignoring the three identified depressions. The derived dimensions of this ellipsoid are  $a = 277 \text{ km}$ ,  $b = 238 \text{ km}$ , and  $c = 168 \text{ km}$ . The three

#### 4. Study of two dense M-type asteroids – 4.1. The metal-rich (16) Psyche

Table 4.1.: Comparison of the physical parameters of Psyche of previous works from [Viikinkoski et al. \(2018\)](#) and augmented with the values derived in this study with the ADAM and MPCD methods.

| Parameter                     | S17             | D18             | V18             | This work, ADAM | This work, MPCD        |
|-------------------------------|-----------------|-----------------|-----------------|-----------------|------------------------|
| $D$ (km)                      | $226 \pm 23$    | $223 \pm 2$     | $226 \pm 5$     | $224 \pm 5$     | $222 \pm 4$            |
| $\lambda$ (°)                 | $34 \pm 34$     | $32 \pm 3$      | $34 \pm 3$      | $35 \pm 2$      | $35 \pm 2$             |
| $\beta$ (°)                   | $-7 \pm 5$      | $-8 \pm 3$      | $-9 \pm 3$      | $-9 \pm 2$      | $-10 \pm 2$            |
| $P$ (h)                       | 4.195948(1)     | 4.195951(2)     | 4.195948(1)     | 4.195948(1)     | 4.195948(1)            |
| $a$ (km)                      | $279 \pm 27$    | $274 \pm 2$     | $290 \pm 5$     | $286 \pm 5$     | $278 \pm 5$ (277)      |
| $b$ (km)                      | $232 \pm 23$    | $231 \pm 4$     | $245 \pm 5$     | $240 \pm 5$     | $232 \pm 6$ (238)      |
| $c$ (km)                      | $189 \pm 19$    | $176 \pm 3$     | $170 \pm 8$     | $172 \pm 4$     | $164 \pm 4$ (168)      |
| $a/b$                         | $1.17 \pm 0.17$ | $1.18 \pm 0.02$ | $1.18 \pm 0.03$ | $1.19 \pm 0.03$ | $1.20 \pm 0.04$ (1.16) |
| $b/c$                         | $1.21 \pm 0.17$ | $1.31 \pm 0.03$ | $1.44 \pm 0.07$ | $1.40 \pm 0.04$ | $1.41 \pm 0.05$ (1.42) |
| $a/c$                         | $1.50 \pm 0.17$ | $1.56 \pm 0.02$ | $1.71 \pm 0.07$ | $1.66 \pm 0.04$ | $1.70 \pm 0.06$ (1.69) |
| $m$ ( $10^{18}$ kg)           | $27.2 \pm 7.5$  | $24.3 \pm 3.5$  | $24.1 \pm 3.2$  | $22.6 \pm 3.2$  | $22.6 \pm 3.2$         |
| $\rho$ ( $\text{g cm}^{-3}$ ) | $4.5 \pm 1.4$   | $4.16 \pm 0.64$ | $3.99 \pm 0.61$ | $3.84 \pm 0.61$ | $3.94 \pm 0.60$        |
| $\chi^2$                      | 167             |                 | 94              | 54              | 43                     |

**Notes:** The listed parameters are the volume equivalent-diameter  $D$ , the dimensions along the major axes ( $a$ ,  $b$ ,  $c$ ), the sidereal period  $P$ , the pole ecliptic longitude  $\lambda$  and latitude  $\beta$ , the mass  $m$ , and the bulk density  $\rho$  with uncertainties reported at  $1\sigma$ . The dimensions of the best-fit ellipsoid are indicated between parenthesis in the MPCD column. The  $\chi^2$  computed with OASIS from our set of SPHERE images is also indicated when possible. S17: [Shepard et al. \(2017\)](#), D18: [Drummond et al. \(2018\)](#), V18: [Viikinkoski et al. \(2018\)](#).

#### 4. Study of two dense M-type asteroids – 4.1. The metal-rich (16) Psyche

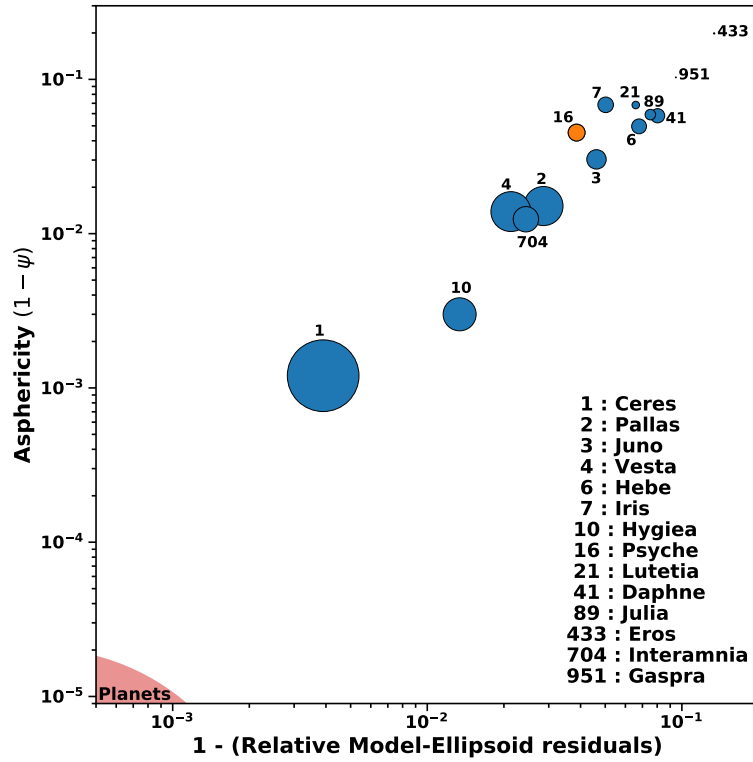


Figure 4.3.: Asphericity of small solar system objects as a function of their departure from their best-fit ellipsoid. The dot sizes are proportionate to the objects mean radius. The red region on the bottom left of the figure indicates typical values for the terrestrial planets.

#### 4. Study of two dense M-type asteroids – 4.1. The metal-rich (16) Psyche

depressions, denoted A, B, and C, appear in the distance map shown in Fig. 4.5 as large regions of negative values, and on the pole-on profile shown in Fig. 4.4.

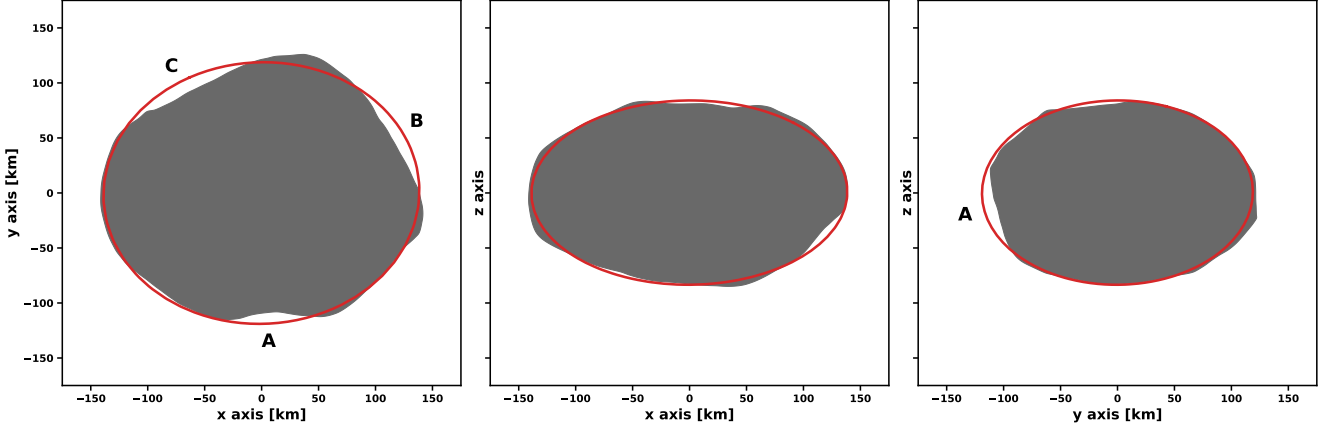


Figure 4.4.: Profiles of the MPCD model and of its triaxial best-fit ellipsoid with a pole-on view (left) and two equatorial views (center and right). The x, y, z axes are aligned along the principal axes of inertia (assuming an homogeneous interior).

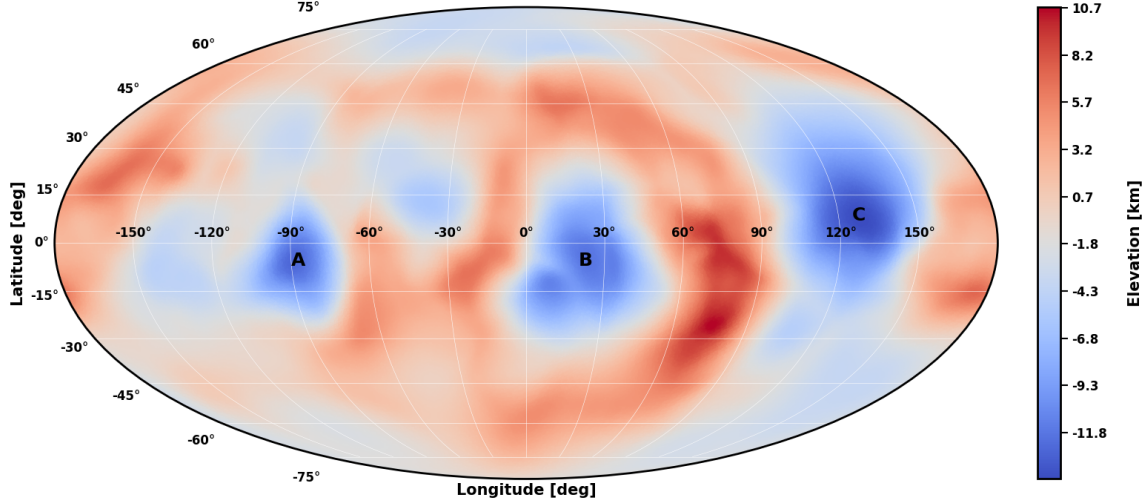


Figure 4.5.: Topography of Psyche in kilometers with respect to its best-fit ellipsoid ( $a = 277$  km,  $b = 238$  km,  $c = 168$  km) after clipping the three depressions A, B, and C.

Finally, we investigated the possibility that Psyche formed at equilibrium and that its shape was subsequently deformed by collisions. This hypothesis was suggested by Psyche's fast rotation ( $P \sim 4.2$  h), flatness ( $a - c \sim 91$  km), and small departure from an ellipsoid. This work was performed by N. Rambaux who first tested the compatibility

#### 4. Study of two dense M-type asteroids – 4.1. The metal-rich (16) Psyche

of Psyche's density, rotation period and shape with a MacLaurin figure at equilibrium assuming an homogeneous interior (see Sect. 5.2). Whereas no solution could be found (Fig. 4.6, left), he also tested whether Psyche's triaxial shape could correspond to a Jacobi ellipsoid. In this case, a solution was obtained when assuming a faster initial rotation period of  $\sim 3$  h (Fig. 4.6, right).

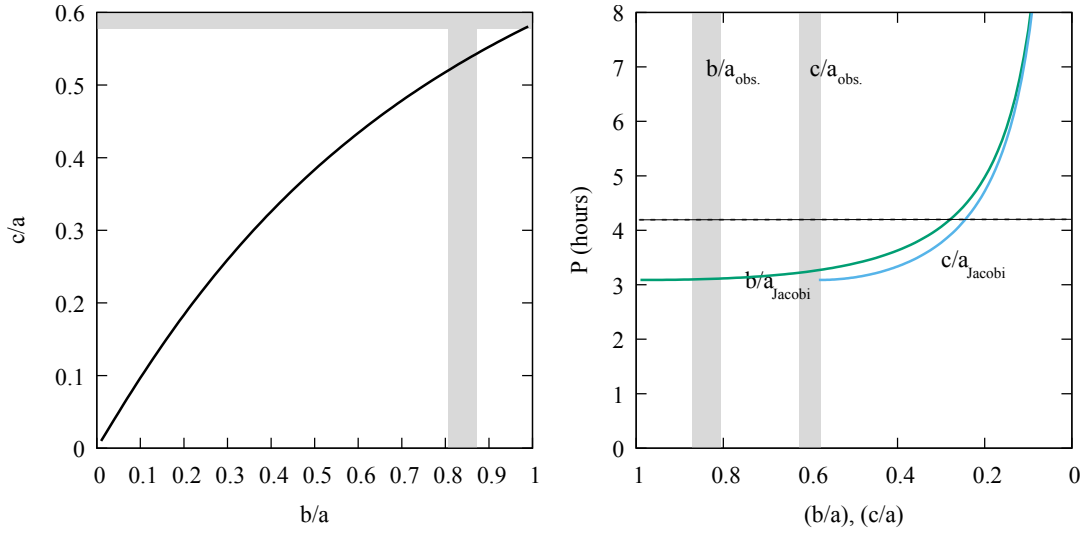


Figure 4.6.: These figures show (a) the variation of the axial ratios  $c/a$  and  $b/a$  for the Jacobi ellipsoid and (b) variations of axial ratios as a function of the rotation period  $P$ . The gray shaded regions corresponds to the observations of Psyche and uncertainties. The horizontal dashed line in figure (b) indicates Psyche's current rotation period. Credit: N. Rambaux.

##### 4.1.5. Formation scenarios

If Psyche effectively formed at equilibrium, this implies that Psyche's primordial shape was acquired while the body behaved as a fluid. This can be achieved via two different formation scenarios: first, a giant impact while Psyche's interior was already frozen followed by a re-accumulation event as in the case of Hygiea (Vernazza et al., 2020) or, second, a giant impact in the very early solar system while the parent body of Psyche was molten as a consequence of the decay of the short-lived radionuclide  $^{26}\text{Al}$ . Of great interest, the latter scenario would somewhat correspond to the scenario invoked to explain the formation of the mesosiderite parent body (Scott et al., 2001). In this scenario, the high metal content of Psyche's surface (Shepard et al., 2017) as well as its mesosiderite-like density (Viikinkoski et al., 2018) would be naturally reproduced. We note that in both cases, the impact had to be extremely energetic to lead to a short rotation period of  $\sim 3$  h, such a rotation period being extremely unusual for a body of that size.

#### 4.1.6. Conclusion

We applied the MPCD method to the SPHERE observation of the metal-rich asteroid Psyche. Its shape was reconstructed and the obtained diameter, along with the ADAM value, yielded a new determination of Psyche's bulk density of  $\rho = 3.89 \pm 0.52 \text{ g}\cdot\text{cm}^{-3}$ .

The comparison of Psyche's sphericity and deviation to an ellipsoid with those of other large MBAs showed that Psyche appears as a transitional object between larger asteroids in hydrostatic equilibrium and the smaller and more irregular asteroids.

The inspection of Psyche's shape allowed the identification of three depressions possibly caused by impacts and that are the main cause for Psyche's deviation to an ellipsoid.

Finally, Psyche's primordial shape appears compatible with a Jacobi ellipsoid when assuming a faster initial rotation, which constrain the possible processes at the origin of its formation.

#### 4.1.7. Paper I: Psyche

### **Asteroid (16) Psyche’s primordial shape: A possible Jacobi ellipsoid**

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F. Colas, G. Dudziński, C. Dumas, J. Ďurech, M. Kaasalainen, A. Kryszczyńska, P. Lamy,  
H. Le Coroller, A. Marciniak, T. Michalowski, P. Michel, T. Santana-Ros, P. Tanga,  
F. Vachier, A. Vigan, O. Witasse, and B. Yang.

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LETTER TO THE EDITOR

## Asteroid (16) Psyche's primordial shape: A possible Jacobi ellipsoid<sup>★,★★</sup>

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### ABSTRACT

**Context.** Asteroid (16) Psyche is the largest M-type asteroid in the main belt and the target of the NASA Psyche mission. It is also the only asteroid of this size ( $D > 200$  km) known to be metal rich. Although various hypotheses have been proposed to explain the rather unique physical properties of this asteroid, a perfect understanding of its formation and bulk composition is still missing.

**Aims.** We aim to refine the shape and bulk density of (16) Psyche and to perform a thorough analysis of its shape to better constrain possible formation scenarios and the structure of its interior.

**Methods.** We obtained disk-resolved VLT/SPHERE/ZIMPOL images acquired within our ESO large program (ID 199.C-0074), which complement similar data obtained in 2018. Both data sets offer a complete coverage of Psyche's surface. These images were used to reconstruct the three-dimensional (3D) shape of Psyche with two independent shape modeling algorithms (MPCD and ADAM). A shape analysis was subsequently performed, including a comparison with equilibrium figures and the identification of mass deficit regions.

**Results.** Our 3D shape along with existing mass estimates imply a density of  $4.20 \pm 0.60 \text{ g cm}^{-3}$ , which is so far the highest for a solar system object following the four telluric planets. Furthermore, the shape of Psyche presents small deviations from an ellipsoid, that is, prominently three large depressions along its equator. The flatness and density of Psyche are compatible with a formation at hydrostatic equilibrium as a Jacobi ellipsoid with a shorter rotation period of  $\sim 3$  h. Later impacts may have slowed down Psyche's rotation, which is currently  $\sim 4.2$  h, while also creating the imaged depressions.

**Conclusions.** Our results open the possibility that Psyche acquired its primordial shape either after a giant impact while its interior was already frozen or while its interior was still molten owing to the decay of the short-lived radionuclide  $^{26}\text{Al}$ .

**Key words.** minor planets, asteroids: general – minor planets, asteroids: individual: (16) Psyche – methods: observational – techniques: high angular resolution

\* The reduced images are only available at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](https://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/638/L15>

\*\* Based on observations made with ESO Telescopes at the Paranal Observatory under programme ID 199.C-0074 (PI: P. Vernazza).



## 1. Introduction

Asteroid (16) Psyche is the largest M-type asteroid in the main belt. This asteroid was defined as a metallic world (Elkins-Tanton et al. 2017) resulting from compelling evidences of a metal-rich surface, including a high mean radar albedo (0.37; Shepard et al. 2017) and a thermal inertia among the highest for an asteroid of this size (Matter et al. 2013). The uniqueness of Psyche’s characteristics and the hypothesis that it could be an exposed planetary core made it a prime target for spacecraft exploration. This was concretized by its selection as the rendezvous target of a NASA Discovery mission that is scheduled to arrive at Psyche in early 2026 (Elkins-Tanton et al. 2017).

To this day, the true nature of Psyche, the only metal-rich asteroid with a diameter above 200 km, remains a mystery that leads to the formulation of several distinct formation scenarios. One of these scenarios involves hit-and-run collisions exposing the core of a differentiated planetesimal, such as Vesta, in the early history of the solar system (Asphaug et al. 2006; Asphaug & Reufer 2014). However, recent estimates of Psyche’s density all agree on a value close to  $\sim 4 \text{ g cm}^{-3}$  (Shepard et al. 2017; Hanuš et al. 2017; Drummond et al. 2018; Viikinkoski et al. 2018), much lower than the density of iron meteorites ( $\sim 7.5 \text{ g cm}^{-3}$ ). A high macroporosity of  $\sim 50\%$ , if Psyche is entirely composed of metal, would solve this discrepancy, but appears unlikely considering the low macroporosity (typically less than 20%) typical of asteroids with masses comparable or greater than Psyche’s ( $m > 10^{19} \text{ kg}$ ; Carry 2012; Scheeres et al. 2015; Carry et al. 2019). Alternatively, Psyche’s density appears compatible with that of stony-iron meteorites such as mesosiderites (Viikinkoski et al. 2018) and pallasites (Elkins-Tanton et al. 2020) as well as that of CB chondrites (Elkins-Tanton et al. 2020). Recently, Johnson et al. (2020) proposed that Psyche formed as a differentiated body and that ferrovulcanism could be at the origin of the high metal content of its surface (Shepard et al. 2017). As of today, it is not understood whether Psyche formed as a differentiated or undifferentiated body.

With the renew of interest in Psyche since its selection as the target of a NASA mission, recent observations suggest that the nature of Psyche might not be a metallic world as initially defined but rather a mix of metal and silicates. A review of the possible compositions, meteorite analogs, and formation and evolution scenarios of Psyche can be found in Elkins-Tanton et al. (2020).

In this paper, we present new high angular resolution imaging observations of Psyche acquired in the framework of our ESO large program (PI: P. Vernazza; ID: 199.C-0074) with the extreme adaptive optics instrument VLT/SPHERE. These new images were used along with those obtained in 2018 (Viikinkoski et al. 2018) to (i) reconstruct Psyche’s three-dimensional (3D) shape using two different modeling techniques and thus to refine its density and spin axis orientation; (ii) perform a detailed analysis of its shape, including a comparison with that of other large asteroids; and (iii) more generally make progress in our understanding of its origin and formation.

## 2. Observations

We obtained 35 images of Psyche at 7 epochs in July and August 2019 using VLT/SPHERE/ZIMPOL (Beuzit et al. 2008; Thalmann et al. 2008). This data set complements the first 25 images taken within our ESO large program that was already presented in Viikinkoski et al. (2018), for a total of 60 images taken

at 12 epochs. All images were reduced following the procedure described in Vernazza et al. (2018) and were subsequently deconvolved with the Mistral algorithm (Fusco et al. 2003; Mugnier et al. 2004). Details about the deconvolution procedure can be found in Fétick et al. (2019).

We selected two to three images per epoch, maximizing the time gap between the images, instead of using all of the images which would not have added more information; the criterion is a difference of at least one pixel between two images owing to the asteroid rotation. The observational circumstances of the images acquired in 2019 are presented in Table A.1 and the deconvolved images are shown in Fig. A.1.

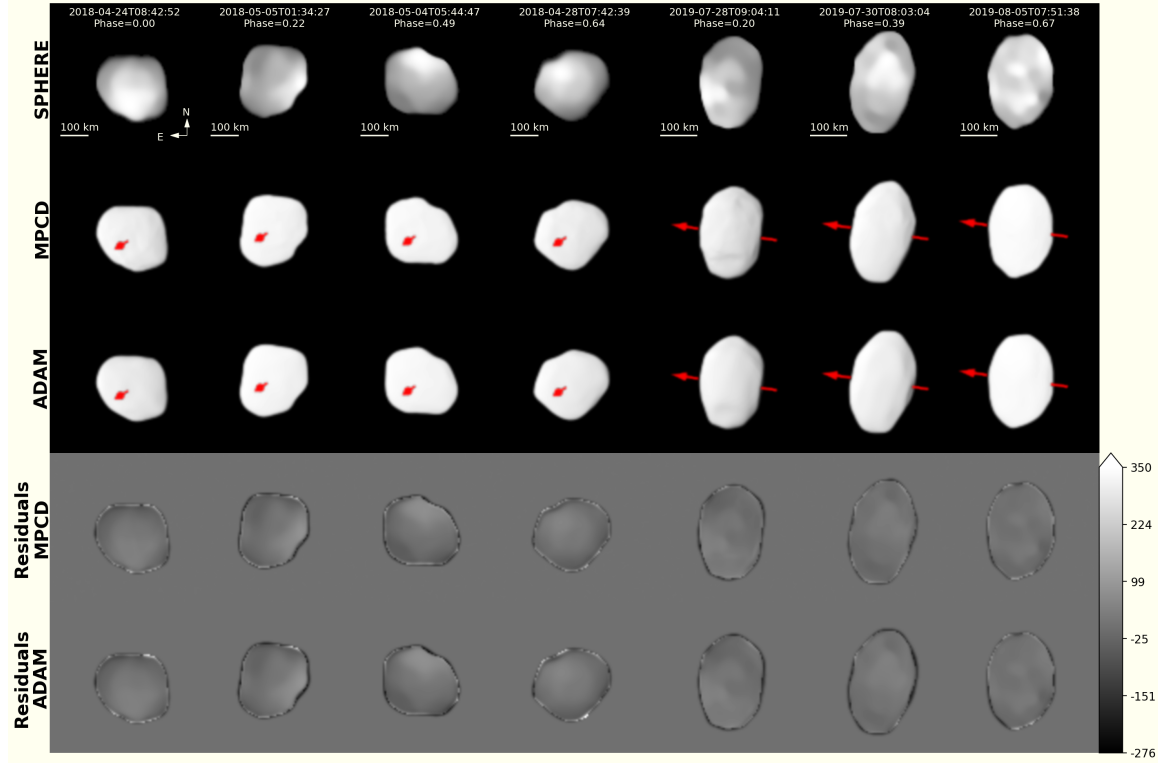
Whereas the images acquired during the first observation campaign (Viikinkoski et al. 2018) were limited to the northern hemisphere of Psyche (sub-observer latitude of  $\sim 75^\circ$ ), those acquired during the second apparition covered well the equatorial region (“edge-on”) with a sub-observer latitude of  $\sim -10^\circ$ . This allowed us to obtain a complete coverage of the surface of Psyche, the southern hemisphere being observed everywhere by a minimum of six images (see the coverage map, Fig. A.2). Moreover, whereas the “pole-on” apparition allowed us to obtain robust constraints on the dimensions along the  $x$  and  $y$  axes, the new “equator-on” apparition was crucial to constrain the  $z$ -axis dimension and thus to refine Psyche’s volume.

## 3. Methods: Three-dimensional shape reconstruction

First, an updated shape model of Psyche was generated with the All-Data Asteroid Modeling (ADAM) algorithm (Viikinkoski et al. 2015) using the same procedure as in Viikinkoski et al. (2018). In addition to the new VLT/SPHERE images, a new stellar occultation by Psyche recorded in October 2019 was included in the modeling (Fig. A.3), whereas two previous occultations (Dunham et al. 2017) were only used for shape validation. The shape was again optimized simultaneously with the albedo variegation apparent both in the light curves and the images. The derived relative albedo distribution is shown in Fig. A.4.

We then applied the so-called Multi-resolution Photoclinometry by Deformation (MPCD) method (Capanna et al. 2013; Jorda et al. 2016) on our sample of 35 VLT/SPHERE/ZIMPOL images from 12 different epochs to reconstruct the 3D shape of Psyche. This method gradually deforms the vertices of an initial mesh to minimize the difference between the observed images and synthetic images of the deformed model created with the OASIS software (Optimized Astrophysical Simulator for Imaging Systems; Jorda et al. 2010). The OASIS software uses a shape model described by a triangular mesh along with geometric and radiometric parameters to generate realistic images of the surface. As inputs, this software takes the position and orientation of the target in the camera frame, the radiometric properties of the camera, the rotational parameter of the object, and the reflectance properties of its surface. The MPCD method has already been successfully applied to images of small bodies observed by the Rosetta mission, notably those of comet 67P (Jorda et al. 2016).

For the rotational parameters of our model, we first used the pole solution of ADAM and its sidereal rotation period of 4.195948 h. We also adopted the ADAM shape model as the initial model for our reconstruction. For the reflectance properties of the surface, we used the five-parameter Hapke law (Hapke 1981) derived for another M-type asteroid, (216) Kleopatra (Descamps et al. 2011). This choice had little influence on the shape reconstruction because of the low phase angle of our observations



**Fig. 1.** Comparison between VLT/SPHERE/ZIMPOL deconvolved images of Psyche (*top row*) and the corresponding synthetic images generated by OASIS of our MPCD (*second row*) and ADAM (*third row*) shape models. The red arrows indicate the direction of the spin axis. *Fourth and fifth rows*: residuals in units of instrumental noise between the observed images and the synthetic images of the MPCD and ADAM shape models, respectively. Given that all images were taken close to opposition with a phase angle less than  $9^\circ$ , the color variation across the disk reflects a variation of albedo rather than a variation in topography. A map of the albedo variegation is shown in Fig. A.4.

( $\alpha_{\max} = 8.7^\circ$ ). This was verified by testing the Hapke parameters of other asteroid types, resulting in similar shape models. The best point-spread function (PSF) to use for the convolution of the synthetic images was determined by testing a range of Gaussian PSF on the ADAM model. The PSF resulting in the lowest  $\chi^2$  had a full width at half maximum (FWHM) of 2.1 pixels (7.6").

The first run resulted in a shape model with a  $\chi^2 = 51$ . The  $\chi^2$  corresponds to the square of the difference between the observed and synthetic images, given in units of the instrumental noise without taking into account possible residual noise from the deconvolution process (Capanna et al. 2013). Then, we searched for the best spin solution by testing a grid of values around the initial ADAM solution. We found spin-vector coordinates ( $[\lambda; \beta] = [35^\circ; -10^\circ]$  in ECJ2000) close to the values used initially ( $[34^\circ; -9^\circ]$ , Viikinkoski et al. 2018). A second MPCD run was performed using this new spin but resulted in similar  $\chi^2$  and volume. The final step was to recompute the best-fitting PSF, this time with the MPCD model. As a significantly different FWHM was retrieved (1.5 pixels), we performed a last MPCD run that gave a final shape model with a  $\chi^2 = 43$ .

## 4. Results

### 4.1. Comparison of the ADAM and MPCD models

In order to compare the two methods, the OASIS synthetic images were generated using the same PSF and pole direction for each model. A comparison between the observed images and the corresponding synthetic images of both MPCD and ADAM models is given in Fig. 1, along with the residual images. The two

models are remarkably similar. They have a volume difference of 2.6% and the distribution of their radial differences measured along the normal direction has a mean of  $-0.7$  km with a standard deviation of  $\sim 2$  km (Fig. A.5). Their  $\chi^2$  are compared in Table 1 with those of the radar model of Shepard et al. (2017) and the previous ADAM model (without the images of the 2019 apparition), which shows a significant increase in the quality of the fit to the images by the new models.

### 4.2. Bulk density

Both of our shape models feature a slightly smaller volume-equivalent diameter with respect to the model presented in Viikinkoski et al. (2018). Combining our new volume estimates with the average of available mass estimates determined in Viikinkoski et al. (2018) yields a density of  $4.20 \pm 0.60$  g cm $^{-3}$  for MPCD and  $4.10 \pm 0.61$  g cm $^{-3}$  for ADAM. We did not include the lower mass ( $1.5 \times 10^{19}$  kg) derived by Siltala & Granvik (2020) in the mass estimation as we consider this value to be an outlier. The physical characteristics of our new models compared to those of previous works are reported in Table 1.

### 4.3. Shape analysis

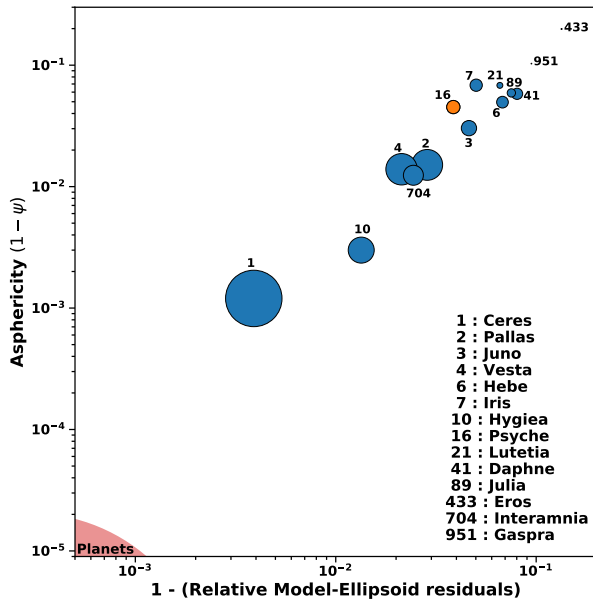
The analysis of Psyche's shape was first performed by computing the radial differences between Psyche's shape model and its best-fitting ellipsoid, leading to a (model – ellipsoid) average residuals of 3.6% relative to the mean radius (computed as the square root of the reduced  $\chi^2$ ). We then calculated the sphericity index of Psyche following the same approach as in Vernazza et al. (2019), and obtained a value of  $\psi = 0.9548$ . For

**Table 1.** Comparison of the physical parameters of Psyche of previous works from Viikinkoski et al. (2018) and augmented with the values derived in this study with the ADAM and MPCD methods.

| Parameter                     | S17             | D18             | V18             | This work, ADAM | This work, MPCD        |
|-------------------------------|-----------------|-----------------|-----------------|-----------------|------------------------|
| $D$ (km)                      | $226 \pm 23$    | $223 \pm 2$     | $226 \pm 5$     | $224 \pm 5$     | $222 \pm 4$            |
| $\lambda$ ( $^\circ$ )        | $34 \pm 34$     | $32 \pm 3$      | $34 \pm 3$      | $35 \pm 2$      | $35 \pm 2$             |
| $\beta$ ( $^\circ$ )          | $-7 \pm 5$      | $-8 \pm 3$      | $-9 \pm 3$      | $-9 \pm 2$      | $-10 \pm 2$            |
| $P$ (h)                       | 4.195948(1)     | 4.195951(2)     | 4.195948(1)     | 4.195948(1)     | 4.195948(1)            |
| $a$ (km)                      | $279 \pm 27$    | $274 \pm 2$     | $290 \pm 5$     | $286 \pm 5$     | $278 \pm 5$ (277)      |
| $b$ (km)                      | $232 \pm 23$    | $231 \pm 4$     | $245 \pm 5$     | $240 \pm 5$     | $232 \pm 6$ (238)      |
| $c$ (km)                      | $189 \pm 19$    | $176 \pm 3$     | $170 \pm 8$     | $172 \pm 4$     | $164 \pm 4$ (168)      |
| $a/b$                         | $1.17 \pm 0.17$ | $1.18 \pm 0.02$ | $1.18 \pm 0.03$ | $1.19 \pm 0.03$ | $1.20 \pm 0.04$ (1.16) |
| $b/c$                         | $1.21 \pm 0.17$ | $1.31 \pm 0.03$ | $1.44 \pm 0.07$ | $1.40 \pm 0.04$ | $1.41 \pm 0.05$ (1.42) |
| $a/c$                         | $1.50 \pm 0.17$ | $1.56 \pm 0.02$ | $1.71 \pm 0.07$ | $1.66 \pm 0.04$ | $1.70 \pm 0.06$ (1.69) |
| $m$ ( $10^{18}$ kg)           | $27.2 \pm 7.5$  | $24.3 \pm 3.5$  | $24.1 \pm 3.2$  | $24.1 \pm 3.2$  | $24.1 \pm 3.2$         |
| $\rho$ ( $\text{g cm}^{-3}$ ) | $4.5 \pm 1.4$   | $4.16 \pm 0.64$ | $3.99 \pm 0.61$ | $4.10 \pm 0.61$ | $4.20 \pm 0.60$        |
| $\chi^2$                      | 167             |                 | 94              | 54              | 43                     |

**Notes.** Listed parameters are the volume equivalent-diameter  $D$ , the dimensions along the major axes ( $a$ ,  $b$ ,  $c$ ), the sidereal period  $P$ , the pole ecliptic longitude  $\lambda$  and latitude  $\beta$ , the mass  $m$ , and the bulk density  $\rho$  with uncertainties reported at  $1\sigma$ . The dimensions of the best-fit ellipsoid (see Sect. 4.3) are indicated between parentheses in the MPCD column. The  $\chi^2$  computed with OASIS from our set of SPHERE images is also indicated when possible.

**References.** S17: Shepard et al. (2017), D18: Drummond et al. (2018), V18: Viikinkoski et al. (2018).



**Fig. 2.** Asphericity of small solar system objects as a function of their departure from their best-fit ellipsoid. The dot sizes are proportionate to the objects mean radius. The red region on the bottom left of the figure indicates typical values for the terrestrial planets.

comparison, we repeated this process for the previously studied targets of our large program, as well as for the terrestrial planets, dwarf planet Ceres, and a few other asteroids visited in situ by space missions (Fig. 2). Psyche’s shape appears to be intermediate between those of larger asteroids such as Interamnia or Vesta and those of smaller or similarly sized bodies such as Iris.

The appearance of Psyche is close to an ellipsoidal shape along its spin axis direction and has flat regions on both poles. On the other hand, its shape deviates from an ellipsoid in the other directions because of depression regions along the equator, possibly caused by impact basins. To obtain the 3D shape of the triaxial ellipsoid that represents the primordial shape of Psyche, we clipped those three depressions in the MPCD model

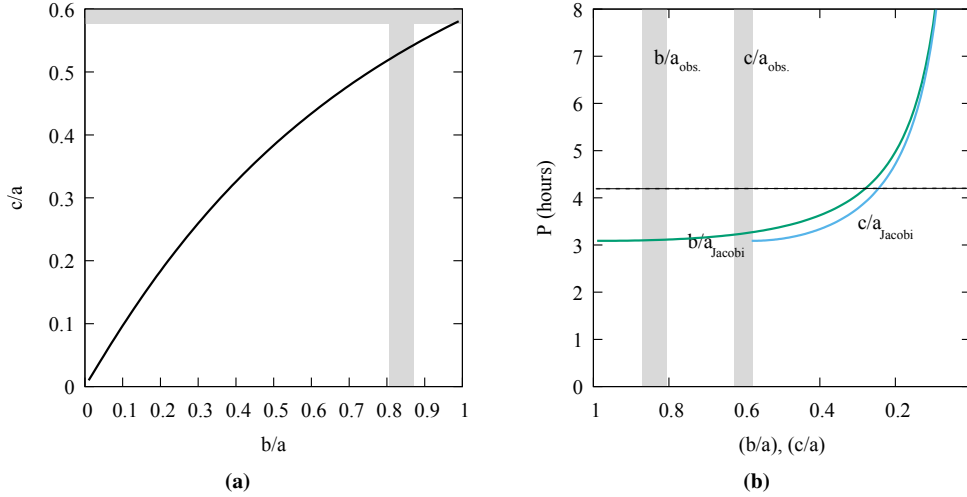
**Table 2.** Approximate coordinates of the center and sizes of the three equatorial depressions.

|                        | A   | B  | C   |
|------------------------|-----|----|-----|
| Latitude [ $^\circ$ ]  | -7  | -7 | 7   |
| Longitude [ $^\circ$ ] | -90 | 30 | 130 |
| Length [km]            | 50  | 78 | 90  |
| Width [km]             | 44  | 60 | 80  |

in order to ignore the corresponding vertex in the computation of the best-fit ellipsoid. The result is a triaxial ellipsoid with dimensions  $a = 277$  km,  $b = 238$  km, and  $c = 168$  km. The three depressions, denoted A, B, and C, appear in the distance map in Fig. A.6 as large regions of negative values. The approximate body-centered latitude and longitude of their centers are reported in Table 2. The presence of such three large cavities ( $D > 50$  km) seems to be incompatible with a pure metallic composition (Marchi et al. 2020). The difference between the equatorial and the pole-on views is highlighted in Fig. A.7, which shows three profiles of the MPCD model along with the best-fit ellipsoid. The mass-deficit region noted B was already detected in the radar model of Shepard et al. (2017) and is clearly visible in Viikinkoski et al. (2018). A protrusion between the B and C depressions can also be seen in the pole view, potentially owing to compression caused by impacts on both sides.

## 5. Discussion

Both the flatness of Psyche’s shape ( $a-c \sim 91$  km) and its small departure from an ellipsoid open the possibility that Psyche formed at equilibrium and that its shape was subsequently deformed by collisions. We thus investigated whether the shape of Psyche may be close to the equipotential shape of a hydrostatic body. As in previous studies (Rambaux et al. 2015; Park et al. 2016; Vernazza et al. 2019; Hanuš et al. 2020; Marsset et al. 2020), we compared the equipotential shape with the observed shape. First, we computed axisymmetric solutions. The computation is based on the numerical resolution of Clairaut’s equations



**Fig. 3.** (a) Variation of the axial ratios  $c/a$  and  $b/a$  for the Jacobi ellipsoid. (b) Variations of axial ratios as a function of the rotation period  $P$ . The gray shaded regions corresponds to the observations of Psyche and uncertainties. The horizontal dashed line in figure (b) indicates Psyche's current rotation period.

(see Chabmat et al. 2010 and Rambaux et al. 2015). If we assume a homogeneous interior, the density and rotation period of Psyche compatible with a MacLaurin figure at equilibrium leads to an oblate body with  $a-c$  of about 50 km, which is significantly less than currently observed. If Psyche was to be differentiated, this value would be even lower. Secondly, we also tested whether Psyche's triaxial shape corresponds to a Jacobi ellipsoid. There is no solution compatible with the present density, rotation, and shape of Psyche. On the other hand, an initial rotation of approximately three hours makes it possible to have a Jacobi figure of equilibrium close to the observed shape as illustrated in Fig. 3. The relative difference is below 10% for  $a/c$  and for  $b/a$ . This solution could suggest a possible fossil shape acquired when Psyche had a faster rotation.

If Psyche effectively formed at equilibrium, this implies that Psyche's primordial shape was acquired while the body behaved as a fluid. This can be achieved via two different formation scenarios: first, a giant impact while Psyche's interior was already frozen followed by a re-accumulation event as in the case of Hygiea (Vernazza et al. 2019) or, second, a giant impact in the very early solar system while the parent body of Psyche was molten as a consequence of the decay of the short-lived radionuclide  $^{26}\text{Al}$ . Of great interest, the latter scenario would somewhat correspond to the scenario invoked to explain the formation of the mesosiderite parent body (Scott et al. 2001). In this scenario, the high metal content of Psyche's surface (Shepard et al. 2017) as well as its mesosiderite-like density (Viikinkoski et al. 2018) would be naturally reproduced. We note that in both cases, the impact had to be extremely energetic to lead to a short rotation period of  $\sim 3$  h, such a rotation period being extremely unusual for a body of that size. While the YORP effect is not significant for objects larger than 30–40 km (Vokrouhlický et al. 2015), later impacts may have affected Psyche's rotation and slowed it down. Future dedicated smoothed-particle hydrodynamics simulations would be useful to test whether the metallic core of a differentiated yet frozen body could be mixed up efficiently with its mantle to explain the high metal content of Psyche's surface.

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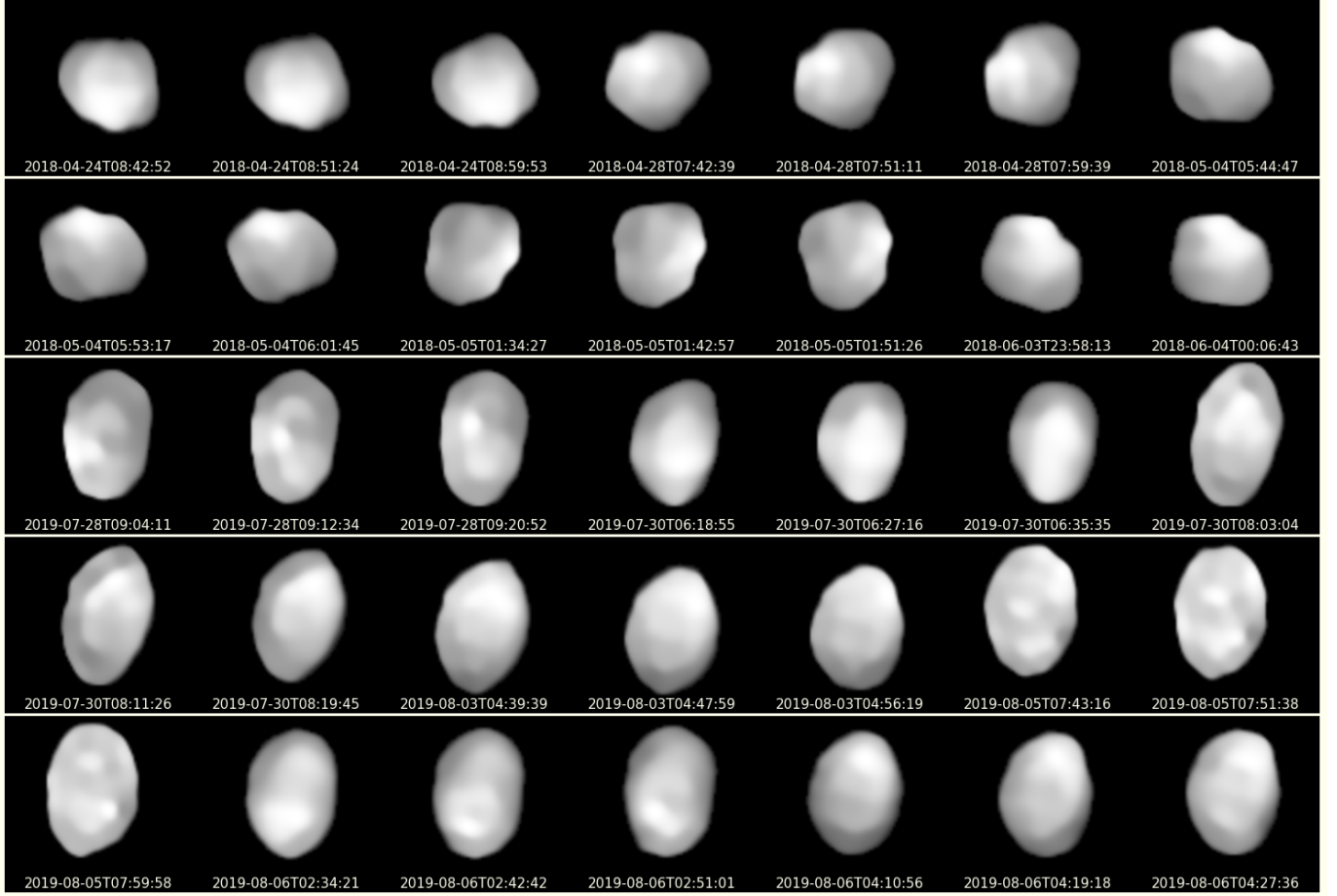
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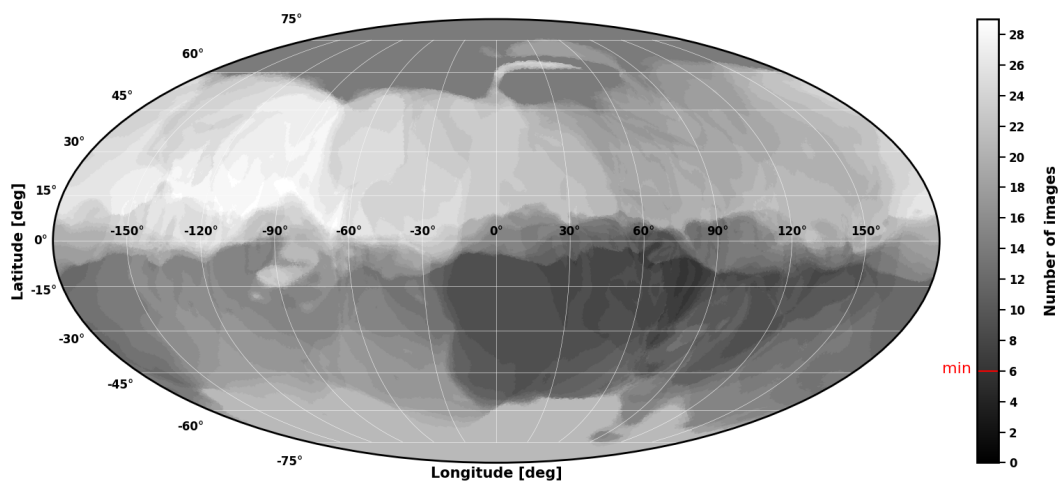
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## Appendix A: Additional figures and tables



**Fig. A.1.** Thirty-five VLT/SPHERE/ZIMPOL images of Psyche selected for our shape reconstruction. The images were obtained at 12 different epochs between April 2018 and August 2019 and deconvolved with the Mistral algorithm.



**Fig. A.2.** Coverage map of the surface of Psyche. The number of times each facet of our shape model has been imaged is represented by different gray levels (zero would be black). Of our total number of 35, the maximum number of images covering a given facet is 29 and the minimum is 6, meaning a 100% surface coverage.

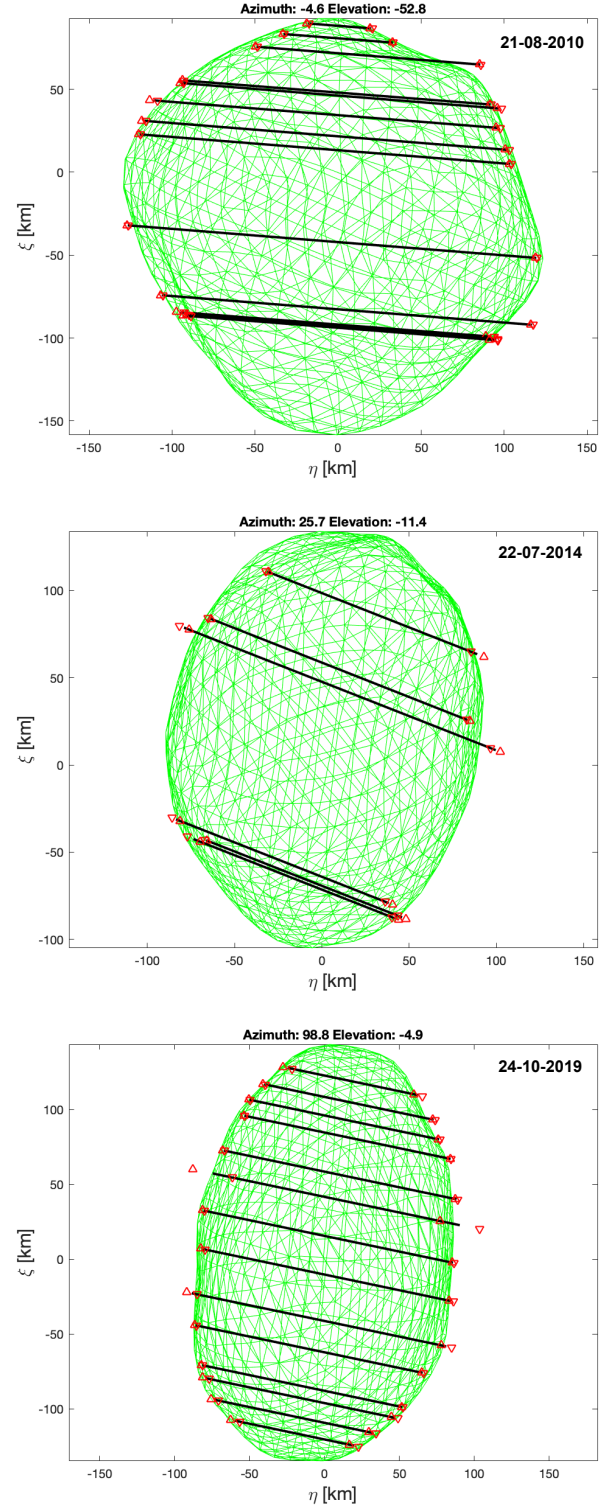
**Table A.1.** Observational circumstances for each selected observation.

| Date       | UT       | Exp<br>(s) | Airmass | $\alpha$<br>( $^\circ$ ) | $D_a$<br>( $''$ ) |
|------------|----------|------------|---------|--------------------------|-------------------|
| 2018-04-24 | 08:42:52 | 245        | 1.30    | 5.8                      | 0.136             |
| 2018-04-24 | 08:51:24 | 245        | 1.34    | 5.8                      | 0.136             |
| 2018-04-24 | 08:59:53 | 245        | 1.39    | 5.8                      | 0.136             |
| 2018-04-28 | 07:42:39 | 245        | 1.16    | 4.5                      | 0.137             |
| 2018-04-28 | 07:51:11 | 245        | 1.19    | 4.5                      | 0.137             |
| 2018-04-28 | 07:59:39 | 245        | 1.21    | 4.5                      | 0.137             |
| 2018-05-04 | 05:44:47 | 245        | 1.03    | 2.6                      | 0.138             |
| 2018-05-04 | 05:53:17 | 245        | 1.03    | 2.6                      | 0.138             |
| 2018-05-04 | 06:01:45 | 245        | 1.04    | 2.6                      | 0.138             |
| 2018-05-05 | 01:34:27 | 245        | 1.59    | 2.3                      | 0.139             |
| 2018-05-05 | 01:42:57 | 245        | 1.53    | 2.3                      | 0.139             |
| 2018-05-05 | 01:51:26 | 245        | 1.48    | 2.3                      | 0.139             |
| 2018-06-03 | 23:58:13 | 245        | 1.34    | 8.7                      | 0.135             |
| 2018-06-04 | 00:06:43 | 245        | 1.30    | 8.7                      | 0.135             |
| 2019-07-28 | 09:04:11 | 240        | 1.57    | 4.2                      | 0.181             |
| 2019-07-28 | 09:12:34 | 240        | 1.64    | 4.2                      | 0.181             |
| 2019-07-28 | 09:20:52 | 240        | 1.72    | 4.2                      | 0.181             |
| 2019-07-30 | 06:18:55 | 240        | 1.04    | 3.5                      | 0.181             |
| 2019-07-30 | 06:27:16 | 240        | 1.05    | 3.5                      | 0.181             |
| 2019-07-30 | 06:35:35 | 240        | 1.06    | 3.5                      | 0.181             |
| 2019-07-30 | 08:03:04 | 240        | 1.28    | 3.4                      | 0.181             |
| 2019-07-30 | 08:11:26 | 240        | 1.32    | 3.4                      | 0.181             |
| 2019-07-30 | 08:19:45 | 240        | 1.36    | 3.4                      | 0.181             |
| 2019-08-03 | 04:39:39 | 240        | 1.02    | 1.8                      | 0.182             |
| 2019-08-03 | 04:47:59 | 240        | 1.02    | 1.8                      | 0.182             |
| 2019-08-03 | 04:56:19 | 240        | 1.01    | 1.8                      | 0.182             |
| 2019-08-05 | 07:43:16 | 240        | 1.32    | 1.0                      | 0.183             |
| 2019-08-05 | 07:51:38 | 240        | 1.35    | 1.0                      | 0.183             |
| 2019-08-05 | 07:59:58 | 240        | 1.40    | 1.0                      | 0.183             |
| 2019-08-06 | 02:34:21 | 240        | 1.20    | 0.7                      | 0.183             |
| 2019-08-06 | 02:42:42 | 240        | 1.17    | 0.7                      | 0.183             |
| 2019-08-06 | 02:51:01 | 240        | 1.15    | 0.7                      | 0.183             |
| 2019-08-06 | 04:10:56 | 240        | 1.03    | 0.7                      | 0.183             |
| 2019-08-06 | 04:19:18 | 240        | 1.02    | 0.7                      | 0.183             |
| 2019-08-06 | 04:27:36 | 240        | 1.02    | 0.7                      | 0.183             |

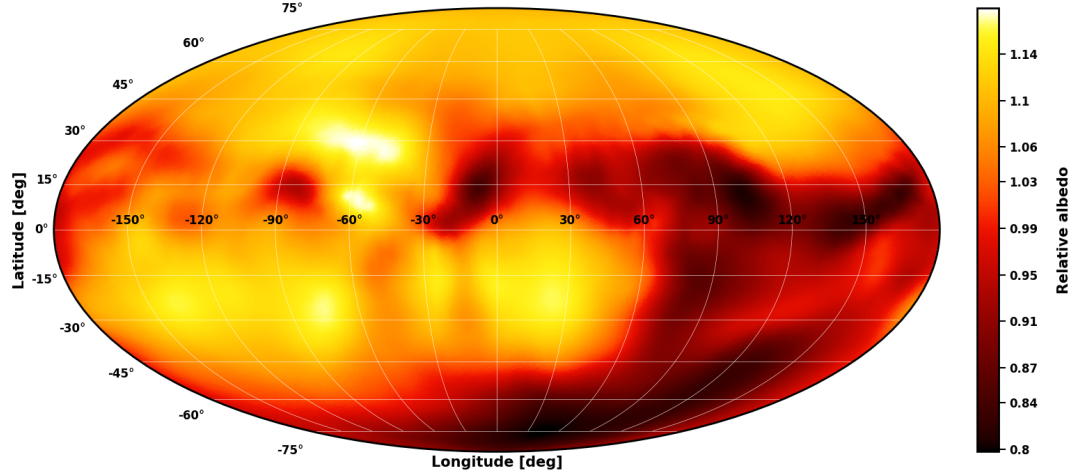
**Notes.** For each of the 35 images selected out of the 60 available, the table gives the epoch, exposure time, airmass, phase angle  $\alpha$ , and angular diameter  $D_a$ . All images were acquired with VLT/SPHERE using the N\_R photometric filter.

**Table A.2.** Observers of the stellar occultation by Psyche on 24 October 2019.

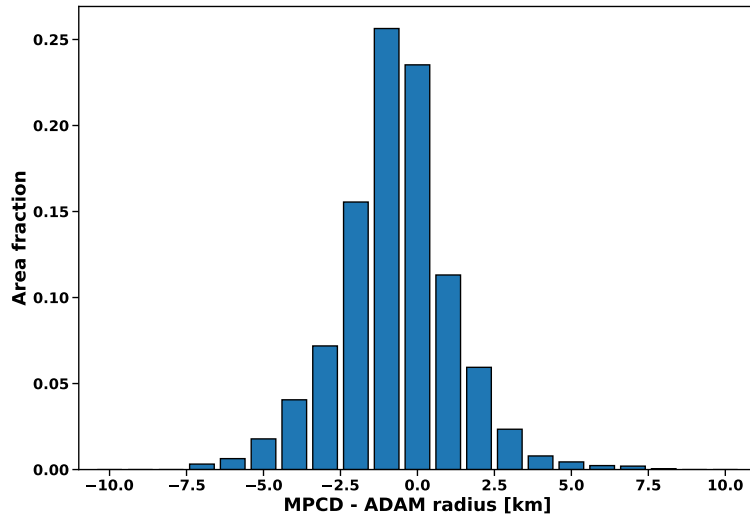
| Observer                                   |
|--------------------------------------------|
| D. Palmer, La Cueva, NM                    |
| P. Maley, Camp Verde, AZ                   |
| D. Dunham, J. Dunham, Nothing, AZ          |
| D. Dunham, J. Dunham, Wikieup, AZ          |
| D. Dunham, J. Dunham, Kingman, AZ          |
| T. George, Scottsdale, AZ                  |
| S. Herchak, Mesa, AZ                       |
| R. Jones, Twentynine Palms, CA             |
| R. Reaves, Parker, AZ                      |
| D. Stanbridge, D. Dunham, Queen Valley, AZ |
| D. Stanbridge, D. Dunham, Gold Canyon, AZ  |
| W. Thomas, Tempe, AZ                       |
| T. Blank, P. Yeargain, Wickenburg, AZ      |
| R. Wasson, Anza, CA                        |



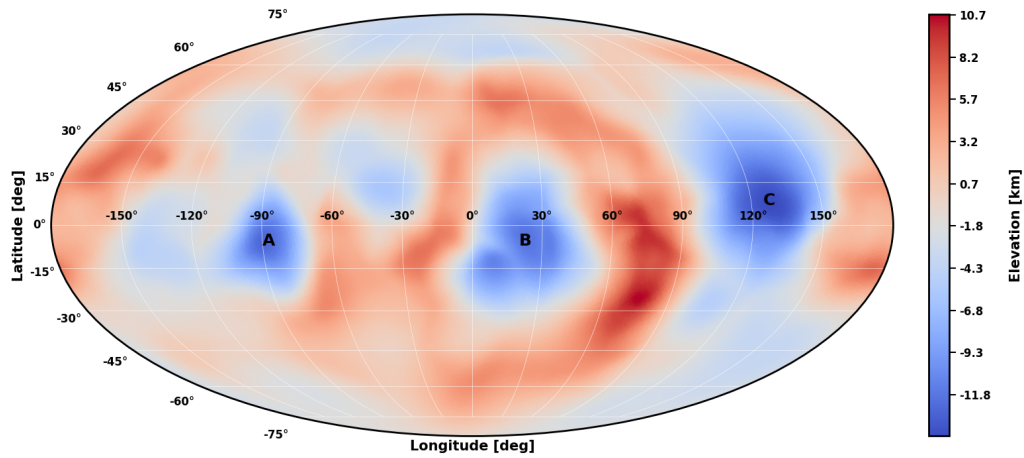
**Fig. A.3.** Three stellar occultations by Psyche compared to the ADAM model. Disappearance and reappearance timings, as well as their uncertainties, are indicated by red triangles. The disagreement between the model and a few chords of the 2010 and 2014 occultations is probably because those chords are wrong or have underestimated uncertainties. Only the 2019 occultation was used in the ADAM shape modeling.



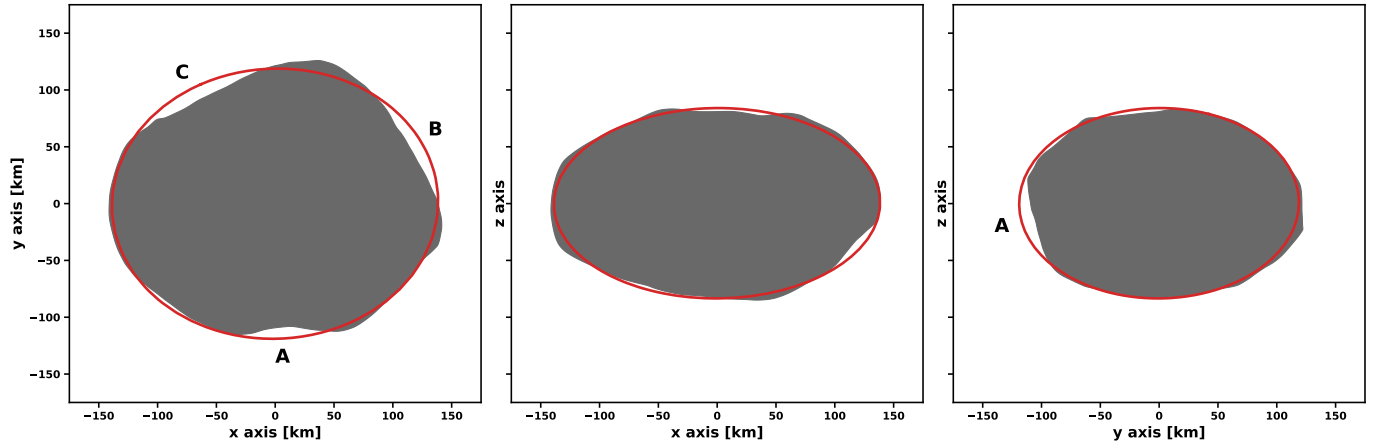
**Fig. A.4.** Relative albedo map distribution derived with ADAM. The bright region visible in the images of 2018 (Fig. A.1), called Panthia in Viikinkoski et al. (2018), is visible around longitude  $\sim -60^\circ$  in the north hemisphere. Other albedo features visible in multiple images of the 2019 apparition include one bright spot on 28 July 2019 and 6 August 2019 at (longitude, latitude) =  $\sim (-60^\circ, -10^\circ)$  and two bright spots on 5 August 2019 at  $\sim (120^\circ, -15^\circ)$  and  $\sim (160^\circ, -10^\circ)$ .



**Fig. A.5.** Distribution of the distances measured along the normal direction between the MPCD and ADAM models.



**Fig. A.6.** Topography of Psyche in kilometers with respect to its best-fit ellipsoid ( $a = 277$  km,  $b = 238$  km,  $c = 168$  km) after clipping the 3 depressions A, B, and C.



**Fig. A.7.** Profiles of the MPCD model and of its triaxial best-fit ellipsoid with a pole-on view (*left*) and two equatorial views (*center and right*). The  $x$ ,  $y$ ,  $z$  axes are aligned along the principal axes of inertia (assuming an homogeneous interior).



#### *4. Study of two dense M-type asteroids – 4.1. The metal-rich (16) Psyche*

## 4.2. The binary (22) Kalliope

### 4.2.1. Introduction

Asteroid (22) Kalliope (hereafter Kalliope) is the second largest M-type asteroid in the main belt after (16) Psyche and before (216) Kleopatra. Kalliope is orbited by a satellite discovered in 2001, Linus, which allows to precisely constrain the mass of Kalliope via the determination of the orbit. This target was thus a good opportunity to obtain an accurate determination of the bulk density of another dense M-type asteroid after Psyche. Unlike Psyche, Kalliope does not possess a metal rich-surface as indicated by its low radar albedo ( $0.18 \pm 0.05$ ; [Shepard et al., 2015](#)).

Whereas its mass was already well constrained, the volume of Kalliope was poorly known. The previous diameter estimates show a large dispersion, ranging between 140 and 196 km ([Marchis et al., 2008](#); [Usui et al., 2011](#)), with an average of  $154 \pm 17$  km ([Drummond et al., 2021](#)). Hence, we expected to significantly improve the determination of the density with a new shape modeling. Most of the recently reported bulk density estimates are between 3.1 and 3.7 g·cm<sup>-3</sup> (e.g., [Carry, 2012](#); [Drummond et al., 2021](#); [Hanuš et al., 2017b](#); [Vachier et al., 2012](#)).

### 4.2.2. Observations

Kalliope was observed at seven epochs between March and May 2018 and in June 2019 with SPHERE, for a total of 35 images. The two apparitions occurred at different viewing geometries. In 2018 only the south pole of Kalliope was visible (aspect angle of  $\sim 167^\circ$ ), while Kalliope was close to an equator-on geometry during the 2019 apparition (aspect angle of  $\sim 110^\circ$ ). Hence, the second apparition allowed to increase the surface coverage and to obtain a better determination of the dimension along the spin axis. However, 16% of the surface could still not be observed, mainly around the north pole (Fig. 4.7).

In addition to the AO images, we compiled 145 lightcurves from the DAMIT and ALCDEF databases to be used by the ADAM and SAGE algorithm. We complemented these data with observations from the 2016 and 2018 apparitions, to which we contributed with five lightcurves obtained with the TN telescope (Fig. 2.12 and Table 2.2).

### 4.2.3. Shape reconstruction

As in the case of Psyche, J. Hanuš first derived a shape model with the ADAM algorithm, resulting in a volume-equivalent diameter  $D_{\text{adam}} = 153 \pm 3$  km. Independently, G. Dudziński and P. Bartczak applied their SAGE algorithm and found a smaller volume-equivalent diameter with  $D_{\text{sage}} = 147^{+8}_{-5}$  km.

Finally, we applied the MPCD method to both the ADAM and the SAGE models as initial models. Because of the relatively small size of Kalliope on the images ( $\sim 30$  pixels), we used only two levels of resolution, resulting in models composed of 2500

#### 4. Study of two dense M-type asteroids – 4.2. The binary (22) Kalliope

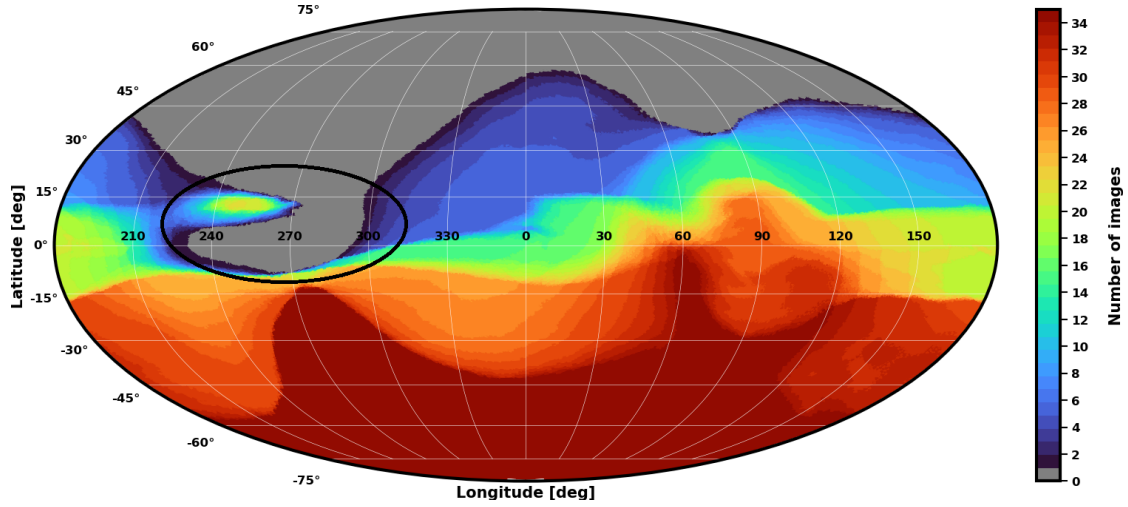


Figure 4.7.: Coverage map of the surface of Kalliope. The number of times each facet the shape model has been imaged by SPHERE/ZIMPOL is represented by different colors. The coverage of the southern hemisphere is much better than the northern, but 84% of the surface has been imaged at least once. The location of a large depression on the shape model is indicated by the black ellipse.

and 642 facets. All the 35 images were kept, and the signal of Linus was removed to prevent it from disturbing the modeling. For the rotational parameters we used the respective solutions obtained by the ADAM and SAGE methods (Table 4.2). For the reflectance properties of the surface, we used the Hapke parameters of Kleopatra as in the case of Psyche. The initial PSF FWHM determined for the ADAM model was 1.6 pixels whereas the larger value of 2.5 pixels found for the SAGE model possibly indicates a slightly undersized model.

In both cases the initial models were only slightly modified by MPCD. The volume-equivalent diameter of the MPCD<sub>adam</sub> model remained equal to the value of the initial ADAM model, whereas for the MPCD<sub>sage</sub> model it increased to from 147 km to 149 km. We then took the average of the two models to obtain the final MPCD diameter, leading to  $D_{\text{mpcd}} = 151 \pm 4$  km. Fig. 4.8 shows the histograms of the difference of the radius between the models measured along the normal direction that range between  $\pm 6$  km.

The average diameter obtained with the three methods is  $D = 150 \pm 5$  km, which yields a bulk density  $\rho = 4.40 \pm 0.46 \text{ g}\cdot\text{cm}^{-3}$  when combined with the mass derived from the orbital model (see the next section).

Kalliope exhibits an elongated shape ( $a/b \sim 1.40$ ,  $a/c \sim 1.72$ ) featuring a large cavity ( $\sim 70$  km) at  $\sim 270^\circ$  in longitude. This basin is responsible for the “pointy” appearance of Kalliope in most AO images. However, the interior of this depression was not imaged by SPHERE, which is well visible on the coverage map (Fig. 4.7).

#### 4. Study of two dense M-type asteroids – 4.2. The binary (22) Kalliope

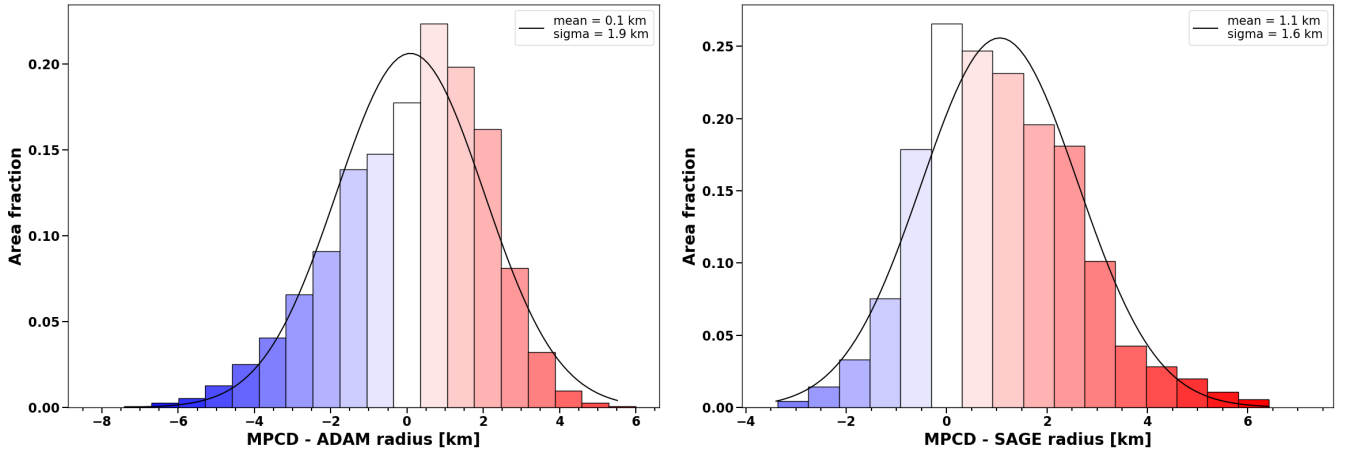


Figure 4.8.: Distribution of the distances measured along the normal direction between the MPCD<sub>adam</sub> and the ADAM models (left) and between the MPCD<sub>sage</sub> and the SAGE models (right).

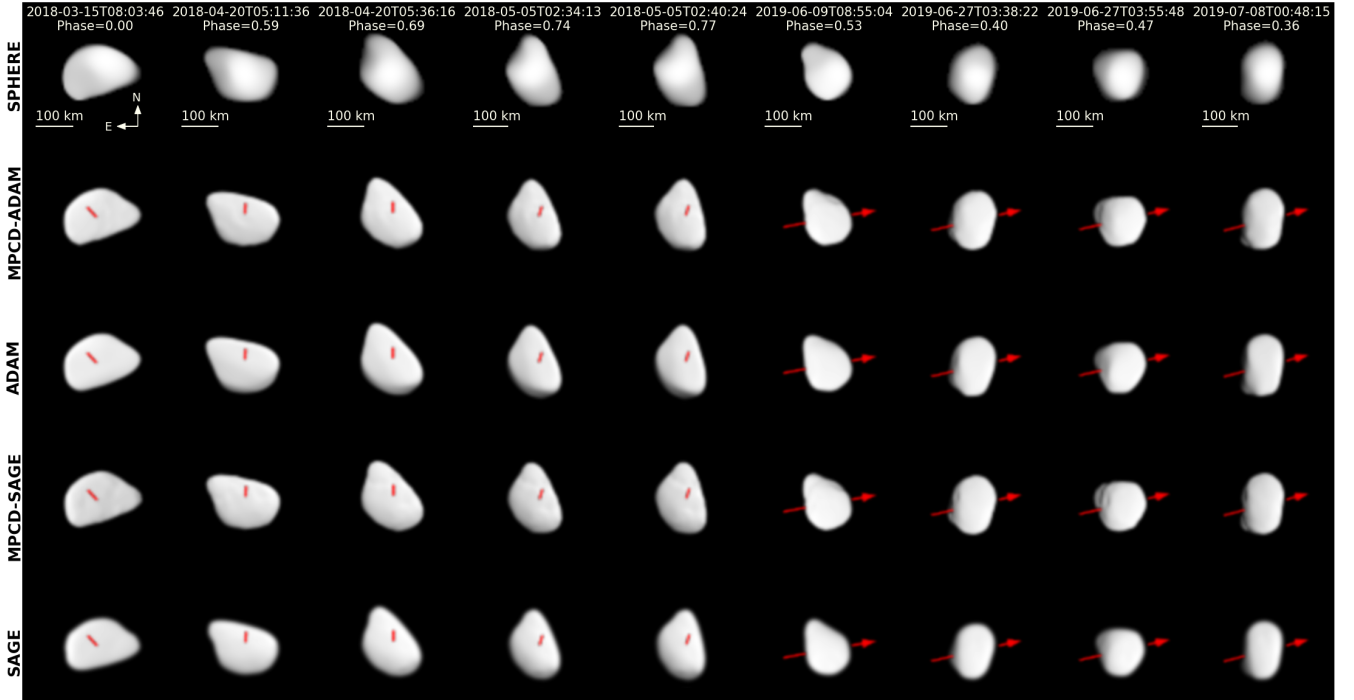


Figure 4.9.: Comparison between the deconvolved images of Kalliope (top row) and the corresponding synthetic images generated by the OASIS tool of the ADAM (third row), SAGE (fifth row), and the two associated MPCD shape models. One image is displayed for each epoch. The red arrows indicate the direction of the spin axis.

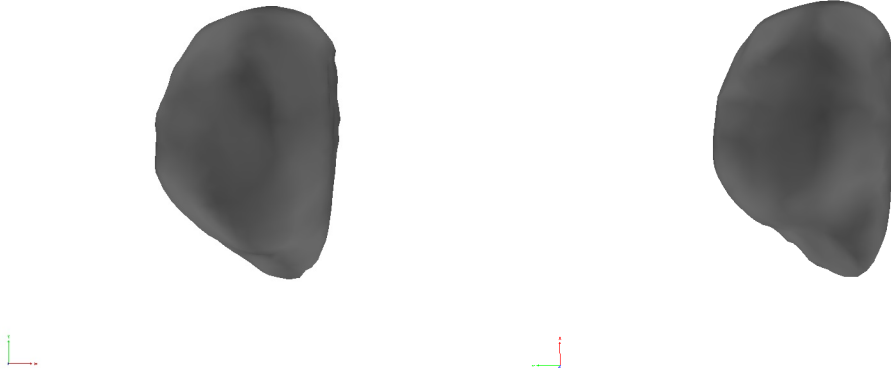


Figure 4.10.: Animated 3D shape models of Kalliope reconstructed with MPCD. The left model is the MPCD<sub>adam</sub> model and the right one is MPCD<sub>sage</sub>. (Requires Adobe Acrobat PDF reader).

#### 4.2.4. Orbit of Linus

For the extraction of the positions of Linus, we complemented the SPHERE data with images from other large ground-based telescopes equipped with AO instruments: Gemini-North, Keck II, and the VLT with the cameras NACO and SPHERE/IRDIS. This allowed us to increase the number of measurements to 94, spanning 48 epochs over 17.5 yr (2001–2019). The images were retrieved from different archives and homogeneously reduced using IDL routines provided by B. Carry. Then, they were sent to B. Carry who measured the relative positions of Linus with respect to Kalliope's photocenter.

These positions were then fed to two different algorithms aiming to explore the dynamics of Linus: the genetic-based algorithm Genoid, by F. Vachier (Vachier et al., 2012); and the multipole numerical model of M. Brož Brož et al. (2021)<sup>2</sup>. They could refine the orbit of Linus and the mass of Kalliope, obtaining  $M = 7.78 \cdot 10^{18}$  kg.

#### 4.2.5. Interpretations

We determined a new diameter of  $D = 150 \pm 5$  km, significantly lower than the latest estimates of  $161 \pm 6$  km (Hanuš et al., 2017b) and  $168 \pm 3$  km (Mainzer et al., 2019). However, these two results suffer from the usage of lower resolution images and from intrinsic errors of thermal modeling, respectively. We were thus able to compute a more robust value of the bulk density of Kalliope by combining our new diameter to a

<sup>2</sup><http://sirrah.troja.mff.cuni.cz/~mira/xitau/>

#### 4. Study of two dense M-type asteroids – 4.2. The binary (22) Kalliope

Table 4.2.: Physical properties of Kalliope based on the ADAM, SAGE and MPCD shape modeling methods.

| Parameter                    | ADAM            | SAGE            | MPCD            |
|------------------------------|-----------------|-----------------|-----------------|
| $P$ (h)                      | 4.148200(1)     | 4.148200(1)     | 4.148200(1)     |
| $\lambda$ (°)                | $195 \pm 3$     | $197^{+1}_{-0}$ |                 |
| $\beta$ (°)                  | $4 \pm 3$       | $3^{+2}_{-2}$   |                 |
| $D$ (km)                     | $153 \pm 3$     | $147^{+8}_{-5}$ | $151 \pm 4$     |
| $a$ (km)                     | $205 \pm 3$     | $194 \pm 5$     | $207 \pm 7$     |
| $b$ (km)                     | $146 \pm 3$     | $141 \pm 3$     | $145 \pm 5$     |
| $c$ (km)                     | $122 \pm 3$     | $114 \pm 5$     | $117 \pm 7$     |
| $a/b$                        | $1.40 \pm 0.04$ | $1.36 \pm 0.05$ | $1.43 \pm 0.07$ |
| $b/c$                        | $1.20 \pm 0.04$ | $1.24 \pm 0.06$ | $1.24 \pm 0.09$ |
| $a/c$                        | $1.68 \pm 0.05$ | $1.70 \pm 0.09$ | $1.77 \pm 0.12$ |
| $\rho$ (g·cm <sup>-3</sup> ) | $4.15 \pm 0.28$ | $4.68 \pm 0.64$ | $4.32 \pm 0.37$ |
| $\chi^2$                     | 171             | 216             | 114 / 111       |

**Notes:** The listed parameters are: sidereal rotation period  $P$ , spin-axis ecliptic J2000 coordinates  $\lambda$  and  $\beta$ , volume-equivalent diameter  $D$ , dimensions along the major axis of the best-fit triaxial ellipsoids ( $a > b > c$ ), their ratios  $a/b$ ,  $b/c$  and  $a/c$ , and bulk density  $\rho$  using the mass given by the orbital multipole model. Uncertainties correspond to 1- $\sigma$  values. The  $\chi^2$  computed with OASIS from our set of SPHERE images is also indicated.

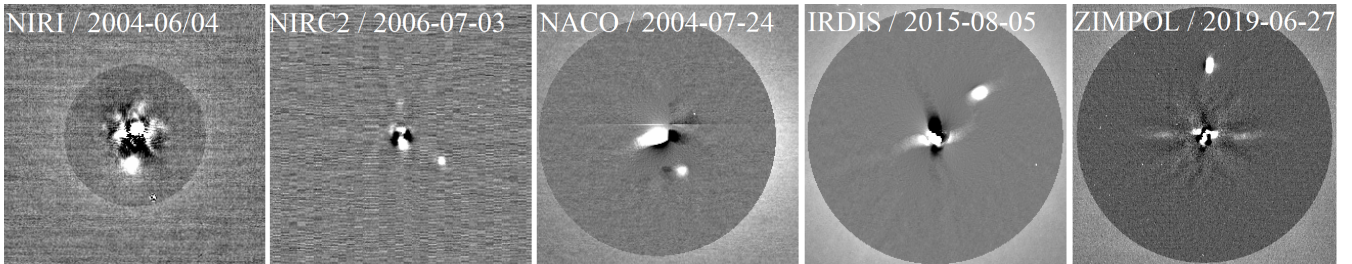


Figure 4.11.: Example of AO images of Kalliope taken with different instruments revealing its satellite Linus. The images have been processed to remove the bright halo around Kalliope, thus enhancing the detectability of Linus. From left to right, the images were taken with Gemini-North/NIRC2, Keck II/NIRC2, VLT/NACO, VLT/SPHERE/IRDIS and VLT/SPHERE/ZIMPOL.

#### 4. Study of two dense M-type asteroids – 4.2. The binary (22) Kalliope

refined measurement of its mass. With  $\rho = 4.40 \pm 0.46 \text{ g}\cdot\text{cm}^{-3}$ , Kalliope has the highest known nominal bulk densities for a small body of the Solar System.

Because of its smaller size, it is very likely that Kalliope is intrinsically more metal-rich than Psyche since macroporosity is known to increase on average with decreasing size (e.g., [Carry, 2012](#)). Assuming a porosity in the 10–25% range for Kalliope (as expected, following [Carry 2012](#) and [Vernazza et al. 2021](#)) implies a density of its building blocks as high as 4.8–5.9  $\text{g}\cdot\text{cm}^{-3}$ . Moreover, assuming density values for iron and silicates of 8  $\text{g}\cdot\text{cm}^{-3}$  and 3  $\text{g}\cdot\text{cm}^{-3}$  respectively, we estimate the metal content of Kalliope to be in the 40–60% range. Such high metal content along with a metal-poor surface is reminiscent of the planet Mercury and is indicative of a differentiated interior.

Several observations point to a large impact as the origin of the formation of Kalliope's moon Linus: (i) a similar surface composition, as implied by component-resolved near-infrared spectra ([Laver et al., 2009](#)); (ii) a large cavity present in Kalliope's shape (Sect. 4.2.3); (iii) the recent identification of a collisional family by [Brož et al. 2022](#); (iv) Kalliope's high metal content and density. Similarly to the case of Mercury ([Benz et al., 1988](#)), collisional stripping of a proto-Kalliope could have resulted in a significant loss of its silicate mantle, explaining its unusually high density as well as the creation of a large moon and a family. Kalliope's high metal content (40–60% in volume) similar to that of Mercury ( $\sim 60\%$ , [Wardinski et al. 2019](#)) and metal-poor mantle makes it the smallest known Mercury-like body.

##### 4.2.6. Conclusion

The reconstruction of the 3D shape of the binary asteroid Kalliope has been achieved. First, lightcurves have been obtained with TN to complement other photometric data used by the ADAM and SAGE algorithm. Then, the shape models produced by these two methods were used as input shape for the MPCD procedure to obtain two additional models. Finally, the volume of Kalliope given by the average of the four models provide a new diameter  $D = 150 \pm 5 \text{ km}$ .

The SPHERE data were complemented by a compilation of previous AO observations of binary system retrieved in different archives. The data were homogeneously processed and sent to other teams to measure the positions of Linus and model its orbit. This allowed to refine the orbit of the satellite Linus, and to determine a new mass value.

The new bulk density obtained,  $\rho = 4.40 \pm 0.46 \text{ g}\cdot\text{cm}^{-3}$ , potentially makes (22) Kalliope the densest known small body in the Solar System. Our results imply a differentiated interior with metal contributing to most of the mass of Kalliope, and suggest a formation scenario that is reminiscent of the planet Mercury.

#### 4.2.7. Paper II: Kalliope

### **M-type (22) Kalliope: A tiny Mercury**

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G. Dudziński, P. Bartczak, F. Vachier, E. Aristidi, P. Beck, F. Marchis, M. Marsset,  
M. Viikinkoski, R. Fetick, A. Drouard, T. Fusco, M. Birlan, E. Podlewska-Gaca,  
T. H. Burbine, M. D. Dyar, P. Bendjoya, Z. Benkhaldoun, J. Berthier, J. Castillo-Rogez,  
F. Cipriani, F. Colas, C. Dumas, J. Ďurech, S. Fauvaud, J. Grice, E. Jehin, M. Kaasalainen,  
A. Kryszczyńska, P. Lamy, H. Le Coroller, A. Marciniak, T. Michalowski, P. Michel,  
J.-L. Prieur, V. Reddy, J.-P. Rivet, T. Santana-Ros, M. Scardia, P. Tanga, A. Vigan,  
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<https://doi.org/10.1051/0004-6361/202243200>



## M-type (22) Kalliope: A tiny Mercury<sup>★,★★</sup>

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(Affiliations can be found after the references)

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### ABSTRACT

**Context.** Asteroid (22) Kalliope is the second largest M-type asteroid in the main belt and is orbited by a satellite, Linus. Whereas the mass of Kalliope is already well constrained thanks to the presence of a moon, its volume is still poorly known, leading to uncertainties on its bulk density and internal structure.

**Aims.** We aim to refine the shape of (22) Kalliope and thus its diameter and bulk density, as well as the orbit of its moon to better constrain its mass, hence density and internal structure.

**Methods.** We acquired disk-resolved observations of (22) Kalliope using the VLT/SPHERE/ZIMPOL instrument to reconstruct its three-dimensional (3D) shape using three different modeling techniques. These images were also used together with new speckle observations at the C2PU/PISCO instrument as well as archival images from other large ground-based telescopes to refine the orbit of Linus.

**Results.** The volume of (22) Kalliope given by the shape models, corresponding to  $D = 150 \pm 5$  km, and the mass constrained by its satellite's orbit yield a density of  $\rho = 4.40 \pm 0.46$  g cm<sup>-3</sup>. This high density potentially makes (22) Kalliope the densest known small body in the Solar System. A macroporosity in the 10–25% range (as expected for this mass and size), implies a grain density in the 4.8–5.9 g cm<sup>-3</sup> range. Kalliope's high bulk density, along with its silicate-rich surface implied by its low radar albedo, implies a differentiated interior with metal contributing to most of the mass of the body.

**Conclusions.** Kalliope's high metal content (40–60%) along with its metal-poor mantle makes it the smallest known Mercury-like body. A large impact at the origin of the formation of the moon Linus is likely the cause of its high metal content and density.

**Key words.** minor planets, asteroids: individual: (22) Kalliope – methods: observational – techniques: high angular resolution

## 1. Introduction

Asteroid (22) Kalliope (hereafter Kalliope) is one of the largest M-type (metallic) asteroids in the main belt, along with (16) Psyche and (216) Kleopatra (Ferrais et al. 2020; Marchis et al. 2021). A satellite was discovered orbiting Kalliope in 2001 by Merline et al. (2001) and Margot & Brown (2001) using the Canada-France-Hawaii Telescope and the Keck II telescope on Mauna Kea, respectively. Initially designated S/2001 (22) I, this satellite was afterward named “Linus”.

The first detailed dynamical characterizations of the binary system were published shortly after in Merline et al. (2002) and Margot & Brown (2003). The latter notably determined an unexpectedly low density of  $2.37 \pm 0.4$  g cm<sup>-3</sup> for an M-type object, when combining their mass measurements with the IRAS diameter of 181 km (Tedesco et al. 2004). They concluded that chondritic material is dominant in the composition of the interior

of Kalliope, with a porosity reaching ~30%, a value surprisingly high for such a large asteroid (Carry 2012).

The previous diameter estimates, however, show a large dispersion, ranging between 140 and 196 km (Usui et al. 2011; Marchis et al. 2008), with an average of  $154 \pm 17$  km (Drummond et al. 2021). In contrast, the determination of Linus' orbital parameters puts stringent constraints on the mass of Kalliope with a weighted average of  $(7.89 \pm 0.09) \times 10^{18}$  kg (Merline et al. 2002; Margot & Brown 2003; Descamps et al. 2008; Marchis et al. 2008; Vachier et al. 2012). As a result, a bulk density of  $4.1 \pm 1.4$  g cm<sup>-3</sup> can be derived from this exploration of the literature. However, most of the recently reported bulk density estimates are between 3.1 and 3.7 g cm<sup>-3</sup> (e.g., Carry 2012; Vachier et al. 2012; Hanuš et al. 2017; Drummond et al. 2021).

Kalliope's surface materials possess a high optical albedo ( $\rho_v = 0.166 \pm 0.005$ ; Mainzer et al. 2019) as well as two absorption bands at 0.9  $\mu$ m and 3  $\mu$ m, as revealed by near-infrared spectroscopic observations (Hardersen et al. 2011; Rivkin et al. 2000; Usui et al. 2019). These two features suggest the presence of low-calcium pyroxene and hydrated minerals, respectively. Finally, Kalliope's low radar albedo of  $0.18 \pm 0.05$  is not compatible with a metal-rich surface (Shepard et al. 2015).

\* Reduced images are only available at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](https://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/662/A71>

\*\* Based on observations made with ESO Telescopes at the Paranal Observatory under program ID 199.C-0074 (PI: P. Vernazza).

† Deceased.

At this stage, a meteoritic analog for Kalliope is still to be determined.

We present here disk-resolved adaptive-optics images of Kalliope obtained as part of our ESO Large Program (PI: P. Vernazza; ID: 199.C-0074; Vernazza et al. 2021) with the VLT/SPHERE instrument. These new data allow Kalliope's three-dimensional (3D) shape to be reconstructed using three different algorithms (Sect. 3). The SPHERE images are also used to refine the orbit of the satellite by complementing them with new speckle observations of the Kalliope–Linus system and archival data (Sect. 4).

## 2. Observations and data reduction

### 2.1. High angular resolution imaging

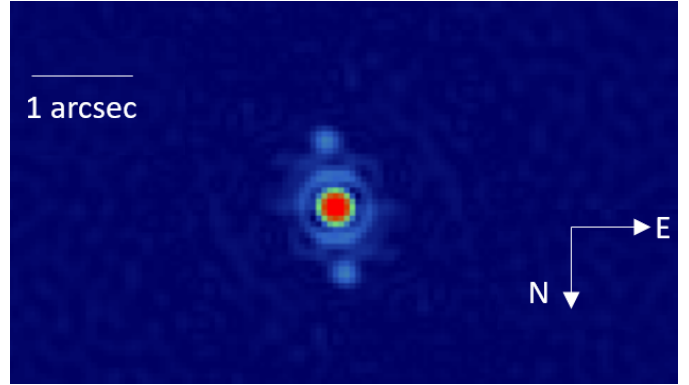
Kalliope was observed at seven epochs between March and May 2018 and in June 2019 with the Zurich Imaging Polarimeter (ZIMPOL) of the SPHERE instrument mounted on the VLT (Beuzit et al. 2019). The images were reduced using the procedure described in Vernazza et al. (2018) and then deconvolved with the Mistral algorithm (Fusco et al. 2003; Mugnier et al. 2004), using a parametric point spread function (PSF, Fétick et al. 2019). The 35 images obtained are presented in Fig. B.1 and the observational circumstances are given in Table B.1. In 2018 only the south pole of Kalliope was visible, while Kalliope was close to an equator-on geometry during the 2019 apparition, allowing us to increase the surface covered by the SPHERE images to 84% (Fig. B.2). Therefore, this data set allowed us to reconstruct a 3D shape model with tight constraints on the asteroid's dimensions.

For the extraction of the positions of Linus, we added a compilation of archival data to the SPHERE images from other large ground-based telescopes equipped with adaptive optic (AO) instruments (Keck II, ESO/VLT and Gemini-North). The camera used at Keck II was the Near InfraRed Camera (NIRC2, van Dam et al. 2004; Wizinowich et al. 2000). At the VLT, it was the NAOS-CONICA camera (NACO, Lenzen et al. 2004; Rousset et al. 2003) and another SPHERE camera, the InfraRed Dual-band Imager and Spectrograph (IRDIS, Dohlen et al. 2008). Finally, images acquired at Gemini-North used the Near InfraRed Imager (NIRI, Hodapp et al. 2003). This allowed us to increase the number of measurements to 94, spanning 48 epochs over 17.5 yr (2001–2019).

These images were reduced using interactive data language (IDL) routines following the standard procedures of bad pixel correction, sky subtraction, and flat-field correction (for details, see Carry et al. 2008). The reduced images were then further processed to remove the bright halo around Kalliope, thus enhancing the detectability of Linus. The procedure is described in detail in Pajuelo et al. (2018) and Carry et al. (2019).

### 2.2. Speckle measurements

We also observed Kalliope in December 2021 with the Pupil Interferometry Speckle camera and COronagraph (PISCO, Scardia et al. 2019) at the 1 m C2PU telescope in Calern, Observatoire de la Côte d'Azur (OCA) (Bendjoya et al. 2012). Observations were carried out during the nights of December 30 and 31, 2021. The conditions were optimal and Kalliope was visible during the full night, with a minimum zenith distance of  $10^\circ$ . Images were recorded in the whole visible domain ( $\lambda = 550$  nm,  $\Delta\lambda = 500$  nm) with an exposure time of 100 ms. This value of



**Fig. 1.** Average autocorrelation from a speckle cube of Kalliope obtained on 2021-12-31T20:48:33 (UT). The measured angular separation is  $678 \pm 6$  mas. The retained position angle value is  $187.7 \pm 0.3^\circ$ , which corresponds to the small peak above the bright central peak.

the exposure time is very long for speckle data (which is usually around 5–20 ms to freeze the turbulence), but we benefited from good seeing conditions ( $\approx 1$  arcsec). The Kalliope–Linus pair, with a visual magnitude  $V \approx 10$  and a magnitude difference  $\Delta V > 3$ , is a difficult target for a 1 m telescope. We were able to make 19 speckle measurements of the Kalliope system during the two nights.

For each measurement we recorded a cube of 14 000 short-exposure frames of both Kalliope and a nearby reference star (HD 47049). Data were processed via the classical Labeyrie's speckle interferometry technique (Labeyrie 1970), resulting in 2D visibilities and autocorrelations of specklegrams, as shown on Fig. 1. The autocorrelation function shows a central bright peak surrounded by two small symmetric spots. The position of these secondary peaks gives the relative astrometry of the pair (angular separation and position angle from the north), but there is a  $180^\circ$  ambiguity on the position angle, leading to two possible solutions. In the example shown in Fig. 1 the measured angular separation was  $678 \pm 6$  mas and the position angle was  $7.7 \pm 0.3^\circ$  or  $187.7 \pm 0.3^\circ$ . The ambiguity was resolved by a comparison with the predicted position, and we retained the value  $187.7 \pm 0.3^\circ$ .

We eventually obtained 19 astrometric measurements of Linus position relative to Kalliope, with a median uncertainty of 7 mas on the angular separation and  $0.6^\circ$  on the position angle. For the best image sequences it was also possible to derive the relative photometry of the couple from the visibility contrast. This makes C2PU the smallest telescope that directly measured the astrometry of a satellite of asteroids.

### 2.3. Optical light curves

We compiled 145 light curves from the DAMIT<sup>1</sup> and ALCDEF<sup>2</sup> databases, including 39 from the SuperWASP survey (Pollacco et al. 2006) for the period 2006–2008 (Grice et al. 2017). We complemented these data with observations from the 2016 and 2018 apparitions. Three light curves were obtained via the Gaia-Ground-based Observational Service for Asteroids (Gaia-GOSA)<sup>3</sup> project; five were acquired using the 60 cm TRAPPIST-North telescope (Jehin et al. 2011); and two by co-author S. Fauvaud with a C11 at  $f/3.2$  and a SBIG ST402

<sup>1</sup> <https://astro.troja.mff.cuni.cz/projects/damit/>

<sup>2</sup> [www.alcdef.org](http://www.alcdef.org)

<sup>3</sup> [www.gaiagosa.eu](http://www.gaiagosa.eu)

M camera. In summary, we gathered a total of 155 light curves obtained between 1953 and 2018 that sample 18 different apparitions. Detailed information for each light curve is provided in Table B.2.

### 3. Three-dimensional shape reconstruction

First, we derived the 3D shape model of Kalliope using the All-Data Asteroid Modeling algorithm (ADAM, Viikinkoski et al. 2015). We simultaneously fitted the sets of optical disk-integrated light curves and the 35 disk-resolved images from SPHERE. As in our previous works (e.g., Yang et al. 2020; Carry et al. 2021), we first derived a low-resolution shape solution with an initial estimate of the rotation state from Hanuš et al. (2017). Then, we increased the weights of the AO data with respect to the optical light curves and derived a shape solution with a higher resolution, leading to a volume-equivalent diameter  $D_{\text{adam}} = 153 \pm 3$  km.

Independently, we derived Kalliope's shape model with the Shaping Asteroid models using Genetic Evolution (SAGE) method, using the same data set of light curves and AO images as for the ADAM model. The method was developed for light curve inversion (Bartczak & Dudziński 2018), and later extended to include AO images as well (Dudziński et al. 2020). The weights for both types of observations are adjusted automatically during the modeling based on the best fits of individual observations. The AO images are treated as binary images, with value 0 set for the background, and 1 set for the pixels where the body is visible. Therefore, only the information about the body's silhouette is used. The SAGE model's axis of rotation is aligned with the axis of greatest moment of inertia, assuming a homogeneous density distribution. In addition, we calculated the model uncertainties (shape, pole, and volume) of the SAGE model using the method described in Bartczak & Dudziński (2019). The synthetic simulations of the nominal model's clones were compared with observations, and only those passing the test were selected (see Bartczak & Dudziński 2019 for details). This subset of clones was then scaled using AO images to derive size and volume uncertainties of the model. During this process, the resulting sizes are weighted by both the resolution and the aspect of AO images. The derived volume-equivalent diameter is  $D_{\text{sage}} = 147^{+8}_{-5}$  km.

Finally, we tried to further refine both the ADAM and SAGE models by using them as initial models for the Multi-resolution PhotoClinometry by Deformation (MPCD) method (Capanna et al. 2013; Jorda et al. 2016), following the procedure described in Ferrais et al. (2020). MPCD uses only the AO images to gradually deform the vertices of the 3D mesh in order to fit the synthetic images of the model to the observed images. The rotational parameters used (period and spin coordinates) were those determined by the initial methods, ADAM or SAGE. For the reflectance properties of Kalliope, we used the geometric albedo of 0.166 from Mainzer et al. (2016) and the Hapke parameters of the M-type asteroid (216) Kleopatra from Descamps et al. (2011). In both cases the initial models were only slightly modified by MPCD. The volume-equivalent diameter of the MPCD<sub>adam</sub> model remained equal to 153 km, whereas for the MPCD<sub>sage</sub> model it increased to 149 km. We report a final MPCD diameter by taking the average of the two models, leading to  $D_{\text{mpcd}} = 151 \pm 4$  km.

The appearances of the ADAM, SAGE, and the two MPCD shape models are shown in Fig. 2, where they are compared with the SPHERE data. Kalliope exhibits an elongated shape ( $a/b \sim 1.40$ ,

**Table 1.** Physical properties of (22) Kalliope based on the ADAM, SAGE, and MPCD shape modeling methods.

| Parameter                    | ADAM            | SAGE            | MPCD            |
|------------------------------|-----------------|-----------------|-----------------|
| $P$ (h)                      | 4.148200(1)     | 4.148200(1)     | 4.148200(1)     |
| $\lambda$ (°)                | $195 \pm 3$     | $197^{+1}_{-0}$ |                 |
| $\beta$ (°)                  | $4 \pm 3$       | $3^{+2}_{-2}$   |                 |
| $D$ (km)                     | $153 \pm 3$     | $147^{+8}_{-5}$ | $151 \pm 4$     |
| $a$ (km)                     | $205 \pm 3$     | $194 \pm 5$     | $207 \pm 7$     |
| $b$ (km)                     | $146 \pm 3$     | $141 \pm 3$     | $145 \pm 5$     |
| $c$ (km)                     | $122 \pm 3$     | $114 \pm 5$     | $117 \pm 7$     |
| $a/b$                        | $1.40 \pm 0.04$ | $1.36 \pm 0.05$ | $1.43 \pm 0.07$ |
| $b/c$                        | $1.20 \pm 0.04$ | $1.24 \pm 0.06$ | $1.24 \pm 0.09$ |
| $a/c$                        | $1.68 \pm 0.05$ | $1.70 \pm 0.09$ | $1.77 \pm 0.12$ |
| $\rho$ (g cm <sup>-3</sup> ) | $4.15 \pm 0.28$ | $4.68 \pm 0.64$ | $4.32 \pm 0.37$ |

**Notes.** The listed parameters are sidereal rotation period  $P$ ; spin-axis ecliptic J2000 coordinates  $\lambda$  and  $\beta$ ; volume-equivalent diameter  $D$ ; dimensions along the major axis of the best-fit triaxial ellipsoids ( $a > b > c$ ); their ratios  $a/b$ ,  $b/c$ , and  $a/c$ ; and bulk density  $\rho$  using the mass given by the orbital multipole model (Table 2). Uncertainties correspond to  $1\sigma$  values.

$a/c \sim 1.72$ ) featuring a large cavity ( $\sim 70$  km) at  $\sim 270^\circ$  east longitude. This basin is responsible for the “pointy” appearance of Kalliope in most AO images. The physical properties of Kalliope are included in Table 1. From our three shape modeling methods we derive a volume-equivalent diameter  $D = 150 \pm 5$  km, which yields a bulk density  $\rho = 4.40 \pm 0.46$  g cm<sup>-3</sup> when combined with the mass  $M = 7.78 \times 10^{18}$  kg derived from the orbital multipole model (see Sect. 4.2).

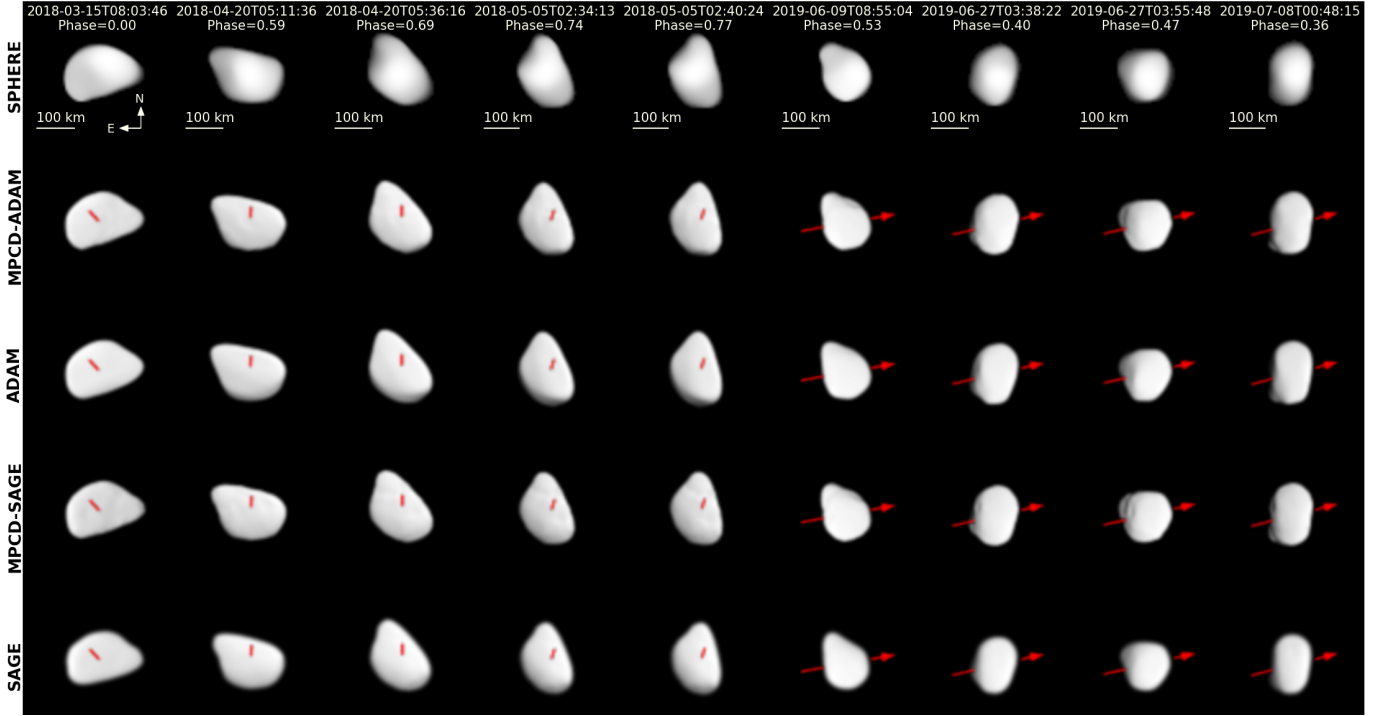
The new diameter is significantly lower than the latest estimates of  $161 \pm 6$  km (Hanus et al. 2017) and  $168 \pm 3$  km (Mainzer et al. 2019). While the value in Mainzer et al. (2019) is an indirect measurements depending on the thermal model and on the viewing geometry at the time of observation, in Hanuš et al. (2017) the same 3D shape modeling was performed with the ADAM method. However, only Keck/NIRC2 images were used, which have a spatial resolution that differs from that of the SPHERE images by a factor  $\sim 2$ .

### 4. Orbit of Linus

We measured 14 positions of Linus on the SPHERE/ZIMPOL images. We also measured 80 positions on the images we re-processed from ESO/VLT, Keck, and Gemini archives. The positions of Kalliope and Linus were respectively measured by adjusting 2D Gaussian functions on the original image and on an image in which the Kalliope's halo was removed (Pajuelo et al. 2018). Finally, we measured 19 positions of Linus with PISCO/C2PU from speckle interferometry. We list these positions in Table B.3.

We complemented these 113 measurements with positions reported by other authors. Most of them were obtained with AO-fed cameras: 17 with the Starfire Optical Range (SOR, Drummond et al. 2021), 9 with PHARO at Palomar (Margot & Brown 2003), 9 with IRCAL at the Lick Observatory (Marchis et al. 2003), and 4 with the SCAM at Keck (Margot & Brown 2003). We also compiled 36 positions from speckle interferometry obtained with the BTA telescope (Sokova et al. 2014; Emelyanov et al. 2019) and one stellar occultation (Sôma et al. 2008). We thus have a data set of 188 positions of Linus spanning 7310 days.





**Fig. 2.** Comparison between the deconvolved images of Kalliope (*top row*) and the corresponding synthetic images generated by the OASIS tool (Jorda et al. 2010) of the ADAM (*third row*), SAGE (*fifth row*), and the two associated MPCD shape models. The red arrows indicate the direction of the spin-axis. The associated residuals are shown in Fig. B.3.

#### 4.1. Genoid

We used the Genoid algorithm (Vachier et al. 2012) to explore the dynamics of Linus, as we did for several other targets of our Large Program (Euphrosyne, Daphne, Sylvia, see Yang et al. 2020; Carry et al. 2019, 2021). As illustrated in the case of (216) Kleopatra (Brož et al. 2021), the topology of the parametric space is highly nontrivial to explore, with numerous local minima for the figure of merit ( $\chi^2$ ) in a high-dimensional space. Whereas gradient descent minimization is unlikely to find the absolute minimum, brute-force grids like Monte Carlo would be extremely CPU expensive. Markov chain Monte Carlo or genetic algorithms offer a compromise, with many trial solutions and denser grids closer to minima (Muinonen et al. 2016; Vachier et al. 2012).

Genoid explores the parameters (orbital period; eccentricity; inclination; longitude of the ascending node; argument of periapsis; time of passage to periapsis; and the lowest-order gravitational moment of the primary, the quadrupole  $J_2$ ) in successive generations of orbital solutions. Each new generation is created by randomly merging the parameters of the best solutions from current generation. At each generation of solutions Genoid also uses a gradient descent to find the minimum closest to the best trial solution. The final orbital elements, mass of Kalliope, and coordinates of the orbital pole from fitting Keplerian motion are given in Table 2.

#### 4.2. Multipole model

To describe the orbital motion of the moon more precisely, we also use the multipole numerical model of Brož et al. (2021)<sup>4</sup>, previously used for (216) Kleopatra. This model accounts for

the irregular shape of the central body, using its multipole expansion up to the order  $\ell = 10$ . We summarize the model in Appendix A.

For comparison, we first converged the Keplerian model ( $\ell = 0$ ) and then re-converged all parameters for the multipole model ( $\ell = 10$ ). These two results are shown in Fig. B.4. Interestingly, we were able to find orbital solutions for both models. Their  $\chi^2_{\text{sky}}$  values are comparable (202 vs. 226) and relatively low, given the number of observations  $N = 2 \cdot 158$  (counting the two sky-plane coordinates separately) and the number of free parameters  $M = 10$ . The uncertainties may be overestimated by a factor of approximately  $\sqrt{(N - M)/\chi^2} \doteq 1.16$ .

On the contrary, the models exhibit an important difference. The best-fit pole is (ECJ2000 longitude  $\lambda$ , latitude  $\beta$ )  $\lambda = 195.6^\circ$  and  $\beta = +2.2^\circ$ , while the nominal pole according to the ADAM model is  $\lambda_{\text{adam}} = 195.0^\circ$  and  $\beta_{\text{adam}} = 3.3^\circ$ . The explanation is that the multipole model is very sensitive; even a very small inclination of the orbit with respect to the equator of the central body would lead to observable precession in the longitude of node,  $\dot{\Omega}_1$ . This is not observed in astrometry and the model must adapt to this (i.e., by tilting the pole). The osculating period  $P_1$  must also be adapted; it is longer by a factor of approximately 1.002 compared to the Keplerian model. Nevertheless, the additional precession results in the same  $\dot{\lambda}_1 \equiv \dot{M}_1 + \dot{\omega}_1 + \dot{\Omega}_1$  with  $\lambda_1$  the true longitude,  $M_1$  the mean anomaly,  $\omega_1$  the argument of the pericenter, and  $\Omega_1$  the longitude of node.

We can actually take advantage of this. If we constrain the pole by the orbit, assuming it is exactly equatorial, we remove the shape  $\leftrightarrow$  pole degeneracy and the shape on its own should be significantly more precise. We checked that it is indeed possible to modify the shape, so that the pole is given by the best-fit pole. The residuals expressed as  $\chi^2_{\text{ao}}$  decreased from 460 to 448 (see Fig. B.5). We conclude that it is useful to account for the

<sup>4</sup> <http://sirrah.troja.mff.cuni.cz/~mira/xitau/>

**Table 2.** Best-fit parameters for the Genoid model (Sect. 4.1) and the three dynamical models described in Sect. 4.2: Keplerian; multipole; multipole with fixed spin-axis pole.

| Var.                    | Unit         | Genoid<br>val. | $\sigma$             | Keplerian<br>val. | Multipole<br>val. | Fixed-pole<br>val. | $\sigma$ |
|-------------------------|--------------|----------------|----------------------|-------------------|-------------------|--------------------|----------|
| $m_1$                   | $10^{18}$ kg | 7.72           | 0.61                 | 7.75              | 7.78              | 7.80               | 0.26     |
| $m_2$                   | $10^{16}$ kg | 0              | –                    | 0                 | 4.72              | 4.71               | 3.96     |
| $P$                     | day          | 3.595678       | 0.00002              | 3.595758          | 3.604302          | 3.604280           | 0.008544 |
| $e$                     |              | 0.002          | $^{+0.012}_{-0.002}$ | 0.005             | 0.005             | 0.005              | 0.010    |
| $i$                     | deg          | 93.9           | 2.6                  | 87.356            | 88.104            | 86.232             | 1.0      |
| $a$                     | km           | 1080           | 28                   |                   |                   |                    |          |
| $\Omega$                | deg          | 285.5          | 1.8                  |                   |                   |                    |          |
| $\omega$                | deg          | 154            | 20                   |                   |                   |                    |          |
| $t_p$                   | JD           | 2452215.18338  | 0.20374              |                   |                   |                    |          |
| $\Omega_1$              | deg          |                |                      | 15.8              | 15.9              | 15.5               | 1.0      |
| $\varpi_1$              | deg          |                |                      | 327               | 326               | 327                | 10       |
| $\lambda_1$             | deg          |                |                      | 206.3             | 206.3             | 206.0              | 1.0      |
| $\lambda_{\text{pole}}$ | deg          | 195.8          | 1.5                  | –                 | 195.6             | 195.1              | 1.0      |
| $\beta_{\text{pole}}$   | deg          | 2.3            | 2.8                  | –                 | 2.2               | 3.3                | 1.0      |
| RMS                     | mas          | 8.1            |                      |                   |                   |                    |          |
| $\chi^2_{\text{sky}}$   |              |                |                      | 202               | 226               | 278                |          |
| $\chi^2_{\text{ao}}$    |              |                |                      | 453               | 460               | 448                |          |

**Notes.** For the Genoid method, the orbital elements of Linus are expressed in EQJ2000. For the multipole method they are osculating for the epoch  $T_0 = 2454047.326750$  JD and expressed in the standard stellar reference frame. If the orbit lies in the equatorial plane of body 1, they fulfill  $i = 90^\circ - b_{\text{pole}}$ ,  $\Omega = 180^\circ + l_{\text{pole}}$ .  $m_1$  denotes the mass of body 1 (i.e., Kalliope),  $m_2$  body 2 (moon),  $P$  the orbital period of the orbit,  $e$  eccentricity,  $i$  inclination,  $a$  semi-major axis,  $\Omega$  longitude of the ascending node,  $\omega$  argument of pericenter,  $t_p$  time of pericenter,  $\Omega_1$  longitude of node,  $\varpi_1$  longitude of pericenter,  $\lambda_1$  true longitude,  $\lambda_{\text{pole}}$  ecliptic longitude of Kalliope's rotation pole,  $\beta_{\text{pole}}$  ecliptic latitude, RMS of residuals for the 113 measurements given in Table B.3,  $\chi^2_{\text{sky}}$  and  $\chi^2_{\text{ao}}$  are defined in Appendix A.

uncertainty of the pole when fitting the orbit(s) of the moon(s). The best-fit parameters for the three dynamical models are given in Table 2.

## 5. Discussion

### 5.1. Bulk composition and density

The smaller diameter determined here implies a much higher bulk density than previously estimated with a nominal value higher than recent estimates of the density of the metal-rich asteroid (16) Psyche:  $4.20 \pm 0.60$  g cm $^{-3}$  (Ferrais et al. 2020) and  $3.88 \pm 0.25$  g cm $^{-3}$  (Siltala & Granvik 2021). This means that Kalliope could be the densest known small body in the Solar System. Furthermore, given its smaller size with respect to Psyche (the second densest known small body in the Solar System), it is very likely that Kalliope is intrinsically more metal rich than Psyche since macroporosity is known to increase on average with decreasing size (e.g., Carry 2012). Assuming a porosity in the 10–25% range for Kalliope (as expected, following Carry 2012; Vernazza et al. 2021) implies a density of its building blocks as high as 4.8–5.9 g cm $^{-3}$ . This density range excludes a number of possible meteoritic analogs, including iron, stony-iron (mesosiderites, pallasites), and CH chondrites (Consolmagno & Britt 1998; Britt & Consolmagno 2003). Neither stony-iron meteorites nor CH chondrites provide a satisfactory match to Kalliope's visible and near-infrared spectrum. What is sure at this stage is that Kalliope's surface is metal poor given its low radar albedo (Shepard et al. 2015). This likely suggests a very metal-rich interior to match the effective density of its building blocks (see above). Assuming a 10–25%

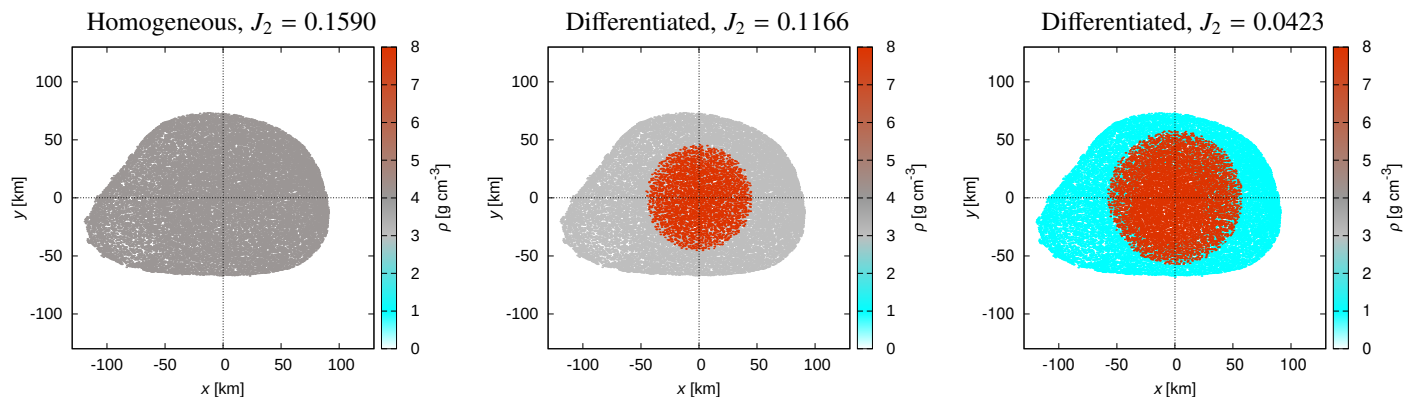
macroporosity range and respectively density values for iron and silicates of 8 g cm $^{-3}$  and 3 g cm $^{-3}$ , we estimate the metal content of Kalliope to be in the 40–60% range. Such high metal content along with a metal-poor surface is reminiscent of the planet Mercury.

### 5.2. Internal structure

The fact that solutions exist for both Keplerian and multipole models means that the  $J_2 \equiv -C_{20}$  value is not well constrained and we cannot determine whether the body is differentiated or not. It would be necessary to have a truly inclined (or eccentric) orbit to measure the precession directly, as  $\dot{\Omega}_1$  (or  $\dot{\varpi}_1$ ).

Nevertheless, some physical limits do exist. Assuming a spherical iron core surrounded by an irregular silicate mantle (densities 8 and 3 g cm $^{-3}$ ), it is necessary to adjust the core–mantle boundary so that the total mass corresponds to the orbital solution (i.e.,  $7.78 \times 10^{18}$  kg), and the resulting  $J_2 = 0.1166$ . The shape is simply too irregular to have  $J_2$  lower than this value (see also Fig. 3). However, Kalliope's high bulk density along with its silicate-rich surface, as implied by its low radar albedo (Shepard et al. 2015), still suggests that its interior is differentiated with a metallic core contributing to most of the mass of the body.

Similar arguments to those made above apply to the internal structure of (87) Sylvia, for which we recently reported differentiation, notably based on a null  $J_2$  determined dynamically (Carry et al. 2021). However, we have now found acceptable orbital solutions for the nominal values of  $J_2 = 0.1723$ , corresponding to a homogeneous interior. In this case the density is low, 1.378 g cm $^{-3}$ . The lower limit of  $J_2$  is probably 0.1521, obtained for a three-layer (core, mantle, crust) differentiated



**Fig. 3.** Density profiles needed to obtain various  $J_2$  values. The ADAM shape is used with fixed total mass  $m_1 = 7.78 \times 10^{18}$  kg. *Left:* Homogeneous body with  $\rho = 4.11 \text{ g cm}^{-3}$ , and nominal  $J_2 = 0.1590$ . *Middle:* Differentiated body with iron core + silicate mantle ( $\rho = 8$  and  $3 \text{ g cm}^{-3}$ ), and slightly lower  $J_2 = 0.1166$ ; the core is spherical ( $R \simeq 46 \text{ km}$ ) and the mantle irregular. *Right:* Extreme example with iron core + icy mantle ( $\rho = 8$  and  $1 \text{ g cm}^{-3}$ ), and  $J_2 = 0.0423$  (not realistic, however). The body is always plotted as a section with  $z < 0$  to see its interior.

body with densities  $1.788$ ,  $1.578$ , and  $1.218 \text{ g cm}^{-3}$ , respectively. So, we do not exclude the possibility of differentiation, but the argument is softened because homogeneity is still not excluded.

### 5.3. Formation of Linus

Several observations point to a large impact as the origin of the formation of Kalliope's moon Linus: (i) a similar surface composition, as implied by component-resolved near-infrared spectra (Laver et al. 2009); (ii) a large cavity present in Kalliope's (Sect. 3); (iii) a recently identified family (to be discussed in a forthcoming paper; Brož et al., in prep.); (iv) Kalliope's high metal content and density. Similarly to the case of Mercury (Benz et al. 1988), collisional stripping of a proto-Kalliope could have resulted in a significant loss of its silicate mantle, explaining its unusually high density as well as the creation of a large moon and a family. Kalliope's high metal content (40–60% in volume) similar to that of Mercury (~60%, Wardinski et al. 2019) and metal-poor mantle makes it the smallest known Mercury-like body.

### 5.4. Dynamics of the system

The homogeneous processing of the data set presented in Sect. 4 allowed us to compute refined orbital elements of Linus, resulting in a RMS of residuals with the Genoid model of  $8.1 \text{ mas}$  over  $20 \text{ yr}$ , significantly lower than previous works:  $15 \text{ mas}$  (Vachier et al. 2012) and  $14 \text{ mas}$  (Drummond et al. 2021). This makes it possible to compute the orbit of Linus with an accuracy of typically  $7 \text{ mas}$  over a similar period in the future. This will greatly help in the prediction of future stellar occultations.

Recently, Emelyanov et al. (2019) announced the detection of the precession of the orbit of Linus around the spin-axis of Kalliope, in contradiction with the present results and several previous studies (Marchis et al. 2008; Vachier et al. 2012; Drummond et al. 2021). Emelyanov et al. 2019 compiled all observation of Linus from 2001 to 2018, divided them into six groups of observations close in time, fitted Keplerian orbits to each group, and determined their poles. The poles of these orbits indicated a polar wandering, featuring an unusual change from a prograde to a retrograde motion. However, the residuals between their predicted and measured positions are quite high ( $4\text{--}120 \text{ mas}$ ) and the authors indicate that the pole coordinates

are heavily dependent on the choice of the observations used in each fit. We use a larger data set (188 vs. 121 observations) that includes theirs, and over a longer time span (7310 vs. 5986 days). The data set is different, however, because we homogeneously reprocessed all the data from VLT, Keck, and Gemini.

The nodal precession  $\dot{\Omega}$  must take place given the irregular shape of the body, but because of the almost-precisely determined equatorial orbit of Linus it is not directly observable. Together with the orbital motion, which occurs at the rate of  $n$ , and the pericenter precession  $\dot{\omega}$ , it does contribute to the total rate of the true longitude (i.e.,  $\dot{\lambda} \simeq n + \dot{\omega} + \dot{\Omega}$ ). The only way to directly observe the effect of nonzero  $J_2$ , would be a detection of short-term perturbations, which occur at half of the rotational period of Kalliope. A continuous series of AO observations, and astrometry with respect to a suitable (stable) comparison star would be needed for this purpose.

## 6. Conclusion

We acquired disk-resolved observations of (22) Kalliope using the VLT/SPHERE/ZIMPOL instrument to reconstruct its 3D shape and determine its density. The volume of (22) Kalliope given by the shape models, corresponding to  $D = 150 \pm 5 \text{ km}$ , and the mass constrained by the orbit of its satellite yield a density of  $\rho = 4.40 \pm 0.46 \text{ g cm}^{-3}$ . This high density potentially makes (22) Kalliope the densest known small body in the Solar System. A macroporosity in the 10–25% range (as expected for such a mass and size) implies a grain density in the  $4.8\text{--}5.9 \text{ g cm}^{-3}$  range. Kalliope's high bulk density, along with its silicate-rich surface implied by its low radar albedo, implies a differentiated interior with metal contributing to most of the mass of the body. A giant impact stripping a large portion of Kalliope's mantle would help to explain the formation of a large moon such as Linus as well as Kalliope's high density and metal content but metal-poor surface, which is reminiscent of Mercury.

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## Appendix A: Multipole model

We describe here the multipole expansion model of Kalliope's shape. Specifically, the potential is expressed as

$$U = -\frac{GM}{r} \sum_{\ell=0}^{10} \left(\frac{R}{r}\right)^\ell \sum_{m=0}^{\ell} P_{\ell m}(\cos \theta) [C_{\ell m} \cos(m\phi) + S_{\ell m} \sin(m\phi)], \quad (\text{A.1})$$

$$C_{\ell m} = \frac{2}{MR^\ell} \frac{(\ell-m)!}{(\ell+m)!} \int_V \rho |r|^\ell P_{\ell m}(\cos \theta) \cos(m\phi) dV, \quad (\text{A.2})$$

$$S_{\ell m} = \frac{2}{MR^\ell} \frac{(\ell-m)!}{(\ell+m)!} \int_V \rho |r|^\ell P_{\ell m}(\cos \theta) \sin(m\phi) dV, \quad (\text{A.3})$$

where  $M$  denotes the mass;  $R$  the reference radius;  $r, \theta, \phi$  the body-frozen spherical coordinates;  $P_{\ell m}$  the Legendre polynomials; and  $\rho$  the density. The derivatives of  $U$  were presented in Brož et al. (2021). Moreover, our model includes the external tides of the Sun. The coefficients computed for the ADAM surface mesh and homogeneous interior are listed in Table B.4. Alternately, we also computed them for differentiated interior  $\rho(|r|)$ . The volume was discretized with the Tetgen program (Si 2006) to 50809 tetrahedral elements. The discretisation error was estimated for an equivalent sphere with irregular (isotropic) mesh, discretized to 63620 elements. The absolute error is about  $10^{-4}$  in  $C_{20}$ ; other coefficients have relative errors of less than  $10^{-2}$ , which is surely smaller than the uncertainties of the surface mesh.

The difference between the Keplerian and the multipole models, and both astrometric observations and adaptive-optics silhouettes, is expressed as

$$\chi^2 = w_{\text{sky}} \chi_{\text{sky}}^2 + w_{\text{ao}} \chi_{\text{ao}}^2, \quad (\text{A.4})$$

$$\chi_{\text{sky}}^2 = \sum_{i=1}^{N_{\text{sky}}} \frac{(u'_i - u_i)^2 + (v'_i - v_i)^2}{\sigma_{\text{sky } i}^2}, \quad (\text{A.5})$$

$$\chi_{\text{ao}}^2 = \sum_{i=1}^{N_{\text{ao}}} \sum_{k=1}^{360} \frac{(u'_{ik} - u_{ik})^2 + (v'_{ik} - v_{ik})^2}{\sigma_{\text{ao } i}^2}, \quad (\text{A.6})$$

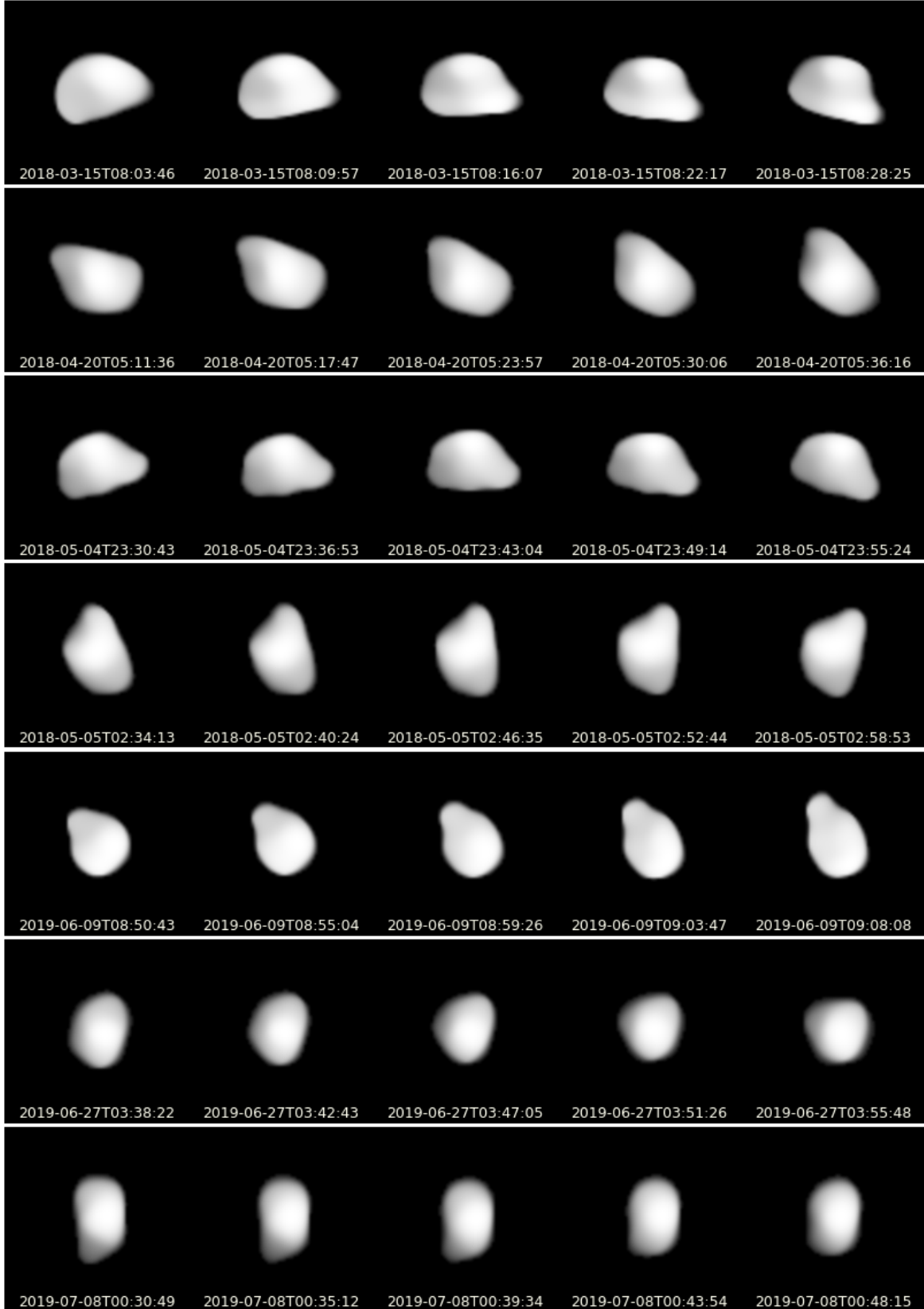
where  $u, v$  denote the observed sky-plane coordinates;  $u', v'$  the corresponding synthetic coordinates;  $\sigma$  the observational uncertainties, and  $w$  the corresponding weights. The  $\chi_{\text{ao}}^2$  term is used for regularization, to prevent incompatible spin-axis pole orientation. We usually assume  $w_{\text{sky}} = 1$ ,  $w_{\text{ao}} = 0.3$  for this purpose. The values of the best-fit parameters are summarized in Table 2.

## Appendix B: Additional figures and tables

**Table B.1:** Observational circumstances for each VLT/SPHERE disk-resolved image obtained by the ZIMPOL camera with the N\_R photometric filter.

| Date       | UT       | Exp<br>(s) | Airmass | $\alpha$<br>(°) | $D_a$<br>(") |
|------------|----------|------------|---------|-----------------|--------------|
| 2018-03-15 | 08:03:46 | 360        | 1.32    | 8.3             | 0.108        |
| 2018-03-15 | 08:09:57 | 360        | 1.34    | 8.3             | 0.108        |
| 2018-03-15 | 08:16:07 | 360        | 1.35    | 8.3             | 0.108        |
| 2018-03-15 | 08:22:17 | 360        | 1.38    | 8.3             | 0.108        |
| 2018-03-15 | 08:28:25 | 360        | 1.40    | 8.3             | 0.108        |
| 2018-04-20 | 05:11:36 | 360        | 1.34    | 8.5             | 0.107        |
| 2018-04-20 | 05:17:47 | 360        | 1.36    | 8.5             | 0.107        |
| 2018-04-20 | 05:23:57 | 360        | 1.38    | 8.5             | 0.107        |
| 2018-04-20 | 05:30:06 | 360        | 1.40    | 8.5             | 0.107        |
| 2018-04-20 | 05:36:16 | 360        | 1.42    | 8.5             | 0.107        |
| 2018-05-04 | 23:30:43 | 360        | 1.83    | 12.3            | 0.102        |
| 2018-05-04 | 23:36:53 | 360        | 1.78    | 12.3            | 0.102        |
| 2018-05-04 | 23:43:04 | 360        | 1.73    | 12.3            | 0.102        |
| 2018-05-04 | 23:49:14 | 360        | 1.68    | 12.3            | 0.102        |
| 2018-05-04 | 23:55:24 | 360        | 1.64    | 12.3            | 0.102        |
| 2018-05-05 | 02:34:13 | 360        | 1.23    | 12.4            | 0.102        |
| 2018-05-05 | 02:40:24 | 360        | 1.23    | 12.4            | 0.102        |
| 2018-05-05 | 02:46:35 | 360        | 1.23    | 12.4            | 0.102        |
| 2018-05-05 | 02:52:44 | 360        | 1.23    | 12.4            | 0.102        |
| 2018-05-05 | 02:58:53 | 360        | 1.24    | 12.4            | 0.102        |
| 2019-06-09 | 08:50:43 | 252        | 1.53    | 2.8             | 0.106        |
| 2019-06-09 | 08:55:04 | 252        | 1.56    | 2.8             | 0.106        |
| 2019-06-09 | 08:59:26 | 252        | 1.59    | 2.8             | 0.106        |
| 2019-06-09 | 09:03:47 | 252        | 1.62    | 2.8             | 0.106        |
| 2019-06-09 | 09:08:08 | 252        | 1.66    | 2.8             | 0.106        |
| 2019-06-27 | 03:38:22 | 252        | 1.00    | 4.9             | 0.106        |
| 2019-06-27 | 03:42:43 | 252        | 1.00    | 4.9             | 0.106        |
| 2019-06-27 | 03:47:05 | 252        | 1.00    | 4.9             | 0.106        |
| 2019-06-27 | 03:51:26 | 252        | 1.00    | 4.9             | 0.106        |
| 2019-06-27 | 03:55:48 | 252        | 1.00    | 4.9             | 0.106        |
| 2019-07-08 | 00:30:49 | 252        | 1.17    | 8.4             | 0.104        |
| 2019-07-08 | 00:35:12 | 252        | 1.16    | 8.4             | 0.104        |
| 2019-07-08 | 00:39:34 | 252        | 1.15    | 8.5             | 0.104        |
| 2019-07-08 | 00:43:54 | 252        | 1.14    | 8.5             | 0.104        |
| 2019-07-08 | 00:48:15 | 252        | 1.13    | 8.5             | 0.104        |

**Notes.** For each image the table gives the epoch, exposure time, air-mass, phase angle  $\alpha$ , and angular diameter  $D_a$  of Kalliope as seen from the Earth.



**Fig. B.1:** VLT/SPHERE/ZIMPOL images of Kalliope used for our shape reconstruction. The 35 images were obtained at seven different epochs between March 2018 and July 2019, and were deconvolved with the Mistral algorithm.

**Table B.2:** Optical disk-integrated light curves used for ADAM shape modeling.

| N  | Epoch        | $N_p$ | $\Delta$<br>(AU) | $r$<br>(AU) | $\varphi$<br>( $^\circ$ ) | Filter | Reference                              |
|----|--------------|-------|------------------|-------------|---------------------------|--------|----------------------------------------|
| 1  | 1953-02-13.5 | 12    | 1.94             | 2.88        | 7.3                       | V      | Ahmad (1954)                           |
| 2  | 1953-02-15.4 | 70    | 1.94             | 2.88        | 7.1                       | V      | Ahmad (1954)                           |
| 3  | 1958-02-24.3 | 84    | 1.96             | 2.90        | 6.9                       | V      | Gehrels & Owings (1962)                |
| 4  | 1965-09-04.9 | 46    | 2.13             | 2.96        | 13.0                      | C      | Zappala & van Houten-Groeneveld (1979) |
| 5  | 1974-06-12.9 | 57    | 2.26             | 3.21        | 7.6                       | C      | Zappala & van Houten-Groeneveld (1979) |
| 6  | 1976-10-18.0 | 167   | 1.81             | 2.61        | 15.8                      | V      | Scaltriti et al. (1978)                |
| 7  | 1976-10-32.0 | 138   | 1.70             | 2.61        | 10.9                      | V      | Scaltriti et al. (1978)                |
| 8  | 1976-11-14.9 | 89    | 1.64             | 2.61        | 5.0                       | V      | Scaltriti et al. (1978)                |
| 9  | 1976-11-16.8 | 112   | 1.63             | 2.61        | 4.1                       | V      | Scaltriti et al. (1978)                |
| 10 | 1976-11-20.0 | 273   | 1.63             | 2.61        | 2.7                       | V      | Scaltriti et al. (1978)                |
| 11 | 1976-11-26.0 | 212   | 1.62             | 2.61        | 0.5                       | V      | Scaltriti et al. (1978)                |
| 12 | 1976-11-27.8 | 157   | 1.62             | 2.61        | 1.1                       | V      | Scaltriti et al. (1978)                |
| 13 | 1976-12-08.8 | 117   | 1.65             | 2.61        | 6.1                       | V      | Scaltriti et al. (1978)                |
| 14 | 1979-05-22.9 | 6     | 2.19             | 3.21        | 0.9                       | V      | Lupishko et al. (1982)                 |
| 15 | 1979-05-25.9 | 50    | 2.19             | 3.21        | 0.4                       | V      | Lupishko et al. (1982)                 |
| 16 | 1979-05-26.8 | 33    | 2.19             | 3.21        | 0.7                       | V      | Lupishko et al. (1982)                 |
| 17 | 1979-05-29.8 | 68    | 2.20             | 3.21        | 1.7                       | V      | Lupishko et al. (1982)                 |
| 18 | 1979-06-02.8 | 6     | 2.20             | 3.21        | 3.2                       | V      | Lupishko et al. (1982)                 |
| 19 | 1979-06-26.7 | 6     | 2.33             | 3.20        | 11.0                      | V      | Lupishko et al. (1982)                 |
| 20 | 1981-08-06.4 | 9     | 2.76             | 2.63        | 21.5                      | C      | Weidenschilling et al. (1987)          |
| 21 | 1981-11-03.9 | 119   | 1.72             | 2.61        | 11.6                      | V      | Lupishko et al. (1989)                 |
| 22 | 1981-11-04.2 | 6     | 1.72             | 2.61        | 11.4                      | V      | Weidenschilling et al. (1987)          |
| 23 | 1981-11-05.3 | 12    | 1.71             | 2.61        | 11.0                      | V      | Weidenschilling et al. (1987)          |
| 24 | 1981-11-06.3 | 6     | 1.70             | 2.61        | 10.6                      | V      | Weidenschilling et al. (1987)          |
| 25 | 1981-11-30.8 | 87    | 1.63             | 2.61        | 0.4                       | V      | Barucci & Dipaolantonio (1983)         |
| 26 | 1981-12-01.6 | 57    | 1.63             | 2.62        | 0.7                       | V      | Zhou et al. (1982)                     |
| 27 | 1982-01-09.3 | 16    | 1.85             | 2.62        | 16.0                      | V      | Weidenschilling et al. (1987)          |
| 28 | 1982-02-17.3 | 21    | 2.34             | 2.64        | 21.8                      | V      | Weidenschilling et al. (1987)          |
| 29 | 1982-12-16.3 | 13    | 2.73             | 2.90        | 19.9                      | V      | Weidenschilling et al. (1987)          |
| 30 | 1982-12-17.3 | 10    | 2.72             | 2.90        | 19.8                      | V      | Weidenschilling et al. (1987)          |
| 31 | 1983-02-18.4 | 8     | 2.08             | 2.96        | 10.3                      | V      | Weidenschilling et al. (1987)          |
| 32 | 1983-02-20.3 | 17    | 2.07             | 2.96        | 9.8                       | V      | Weidenschilling et al. (1987)          |
| 33 | 1983-03-08.1 | 116   | 2.03             | 2.98        | 6.7                       | V      | di Martino & Cacciatori (1984)         |
| 34 | 1983-03-28.4 | 19    | 2.08             | 3.00        | 8.7                       | V      | Weidenschilling et al. (1987)          |
| 35 | 1983-03-29.2 | 18    | 2.08             | 3.00        | 8.9                       | V      | Weidenschilling et al. (1987)          |
| 36 | 1983-05-22.4 | 11    | 2.64             | 3.05        | 18.8                      | V      | Weidenschilling et al. (1987)          |
| 37 | 1983-05-23.3 | 10    | 2.65             | 3.05        | 18.9                      | V      | Weidenschilling et al. (1987)          |
| 38 | 1983-05-24.3 | 7     | 2.67             | 3.05        | 18.9                      | V      | Weidenschilling et al. (1987)          |
| 39 | 1983-07-02.2 | 10    | 3.21             | 3.08        | 18.4                      | V      | Weidenschilling et al. (1987)          |
| 40 | 1984-01-15.4 | 6     | 3.65             | 3.19        | 14.6                      | V      | Weidenschilling et al. (1987)          |
| 41 | 1984-01-16.4 | 8     | 3.64             | 3.19        | 14.7                      | V      | Weidenschilling et al. (1987)          |
| 42 | 1984-04-08.2 | 14    | 2.52             | 3.20        | 14.7                      | V      | Weidenschilling et al. (1987)          |
| 43 | 1984-04-09.3 | 23    | 2.50             | 3.20        | 14.6                      | V      | Weidenschilling et al. (1987)          |
| 44 | 1984-05-08.4 | 15    | 2.24             | 3.20        | 6.8                       | V      | Weidenschilling et al. (1987)          |
| 45 | 1984-05-09.2 | 16    | 2.24             | 3.20        | 6.5                       | V      | Weidenschilling et al. (1987)          |
| 46 | 1984-06-10.4 | 22    | 2.21             | 3.20        | 5.2                       | V      | Weidenschilling et al. (1987)          |
| 47 | 1984-07-05.3 | 9     | 2.38             | 3.20        | 12.7                      | V      | Weidenschilling et al. (1987)          |
| 48 | 1985-10-25.3 | 5     | 2.41             | 2.85        | 19.6                      | V      | Weidenschilling et al. (1987)          |
| 49 | 1985-10-26.3 | 7     | 2.42             | 2.85        | 19.7                      | V      | Weidenschilling et al. (1987)          |
| 50 | 1985-06-25.3 | 9     | 2.31             | 2.97        | 17.0                      | V      | Weidenschilling et al. (1987)          |
| 51 | 1985-06-27.3 | 10    | 2.29             | 2.97        | 16.7                      | V      | Weidenschilling et al. (1987)          |
| 52 | 1985-08-17.2 | 66    | 1.95             | 2.92        | 6.9                       | V      | Surdej et al. (1986)                   |
| 53 | 1985-10-21.3 | 12    | 2.37             | 2.85        | 19.2                      | V      | Weidenschilling et al. (1987)          |
| 54 | 1985-10-23.3 | 6     | 2.39             | 2.85        | 19.5                      | V      | Weidenschilling et al. (1987)          |
| 55 | 1986-11-26.1 | 108   | 1.65             | 2.63        | 3.7                       | V      | Dotto et al. (1992)                    |
| 56 | 1986-12-05.2 | 14    | 1.64             | 2.63        | 1.0                       | C      | Melillo (1987)                         |
| 57 | 1986-12-08.9 | 49    | 1.65             | 2.63        | 2.5                       | V      | Michalowski & Velichko (1990)          |
| 58 | 1987-01-07.9 | 91    | 1.82             | 2.64        | 14.4                      | V      | Dotto et al. (1992)                    |
| 59 | 1987-01-23.8 | 176   | 1.99             | 2.64        | 18.5                      | V      | Dotto et al. (1992)                    |

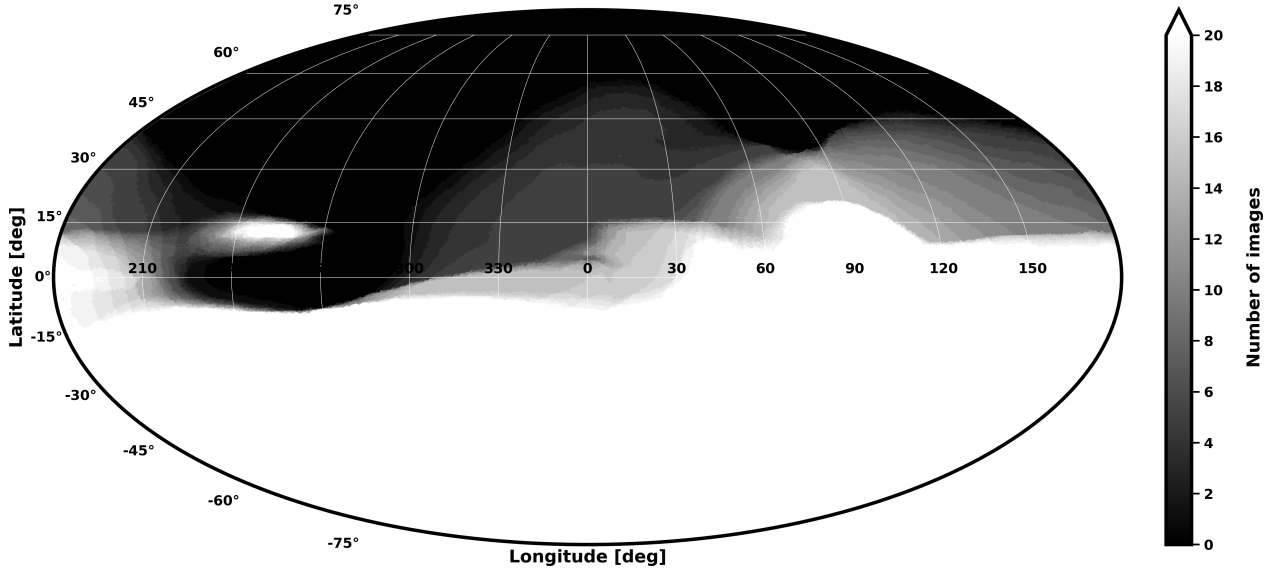
**Table B.2:** continued

| N   | Epoch        | $N_p$ | $\Delta$<br>(AU) | $r$<br>(AU) | $\varphi$<br>(°) | Filter | Reference                     |
|-----|--------------|-------|------------------|-------------|------------------|--------|-------------------------------|
| 60  | 1988-04-25.2 | 20    | 2.29             | 3.03        | 14.9             | V      | Weidenschilling et al. (1990) |
| 61  | 1988-04-26.3 | 6     | 2.30             | 3.03        | 15.1             | V      | Weidenschilling et al. (1990) |
| 62  | 2004-06-06.0 | 75    | 2.18             | 3.20        | 1.1              | C      | Hanuš et al. (2016)           |
| 63  | 2004-06-07.0 | 42    | 2.18             | 3.20        | 1.1              | C      | Hanuš et al. (2016)           |
| 64  | 2004-06-10.0 | 38    | 2.18             | 3.20        | 1.8              | C      | Hanuš et al. (2016)           |
| 65  | 2004-06-10.0 | 48    | 2.18             | 3.20        | 1.8              | C      | Hanuš et al. (2016)           |
| 66  | 2004-06-11.0 | 58    | 2.19             | 3.20        | 2.1              | C      | Hanuš et al. (2016)           |
| 67  | 2004-06-11.0 | 67    | 2.19             | 3.20        | 2.1              | C      | Hanuš et al. (2016)           |
| 68  | 2004-06-14.0 | 37    | 2.19             | 3.20        | 3.1              | C      | Hanuš et al. (2016)           |
| 69  | 2004-06-17.0 | 37    | 2.20             | 3.19        | 4.1              | C      | Hanuš et al. (2016)           |
| 70  | 2004-06-18.0 | 22    | 2.20             | 3.19        | 4.4              | C      | Hanuš et al. (2016)           |
| 71  | 2004-06-19.0 | 129   | 2.20             | 3.19        | 4.8              | C      | Hanuš et al. (2016)           |
| 72  | 2006-11-10   | 54    | 1.83             | 2.62        | 15.6             | C      | Grice et al. (2017)           |
| 73  | 2006-11-03.6 | 125   | 1.90             | 2.62        | 17.7             | C      | Hanuš et al. (2016)           |
| 74  | 2006-11-05.6 | 70    | 1.88             | 2.62        | 17.2             | C      | Hanuš et al. (2016)           |
| 75  | 2006-11-09.6 | 82    | 1.84             | 2.62        | 16.1             | C      | Hanuš et al. (2016)           |
| 76  | 2006-11-12.6 | 119   | 1.82             | 2.62        | 15.2             | C      | Hanuš et al. (2016)           |
| 77  | 2006-12-30.9 | 110   | 1.68             | 2.64        | 6.1              | C      | Hanuš et al. (2016)           |
| 78  | 2006-11-10   | 57    | 1.83             | 2.62        | 15.6             | C      | Grice et al. (2017)           |
| 79  | 2006-11-30   | 40    | 1.69             | 2.63        | 8.6              | C      | Grice et al. (2017)           |
| 80  | 2006-12-13   | 35    | 1.66             | 2.63        | 3.8              | C      | Grice et al. (2017)           |
| 81  | 2006-12-29   | 68    | 1.68             | 2.64        | 5.8              | C      | Grice et al. (2017)           |
| 82  | 2006-12-29   | 89    | 1.68             | 2.64        | 5.8              | C      | Grice et al. (2017)           |
| 83  | 2006-12-30   | 54    | 1.68             | 2.64        | 6.2              | C      | Grice et al. (2017)           |
| 84  | 2007-01-22   | 39    | 1.84             | 2.65        | 14.4             | C      | Grice et al. (2017)           |
| 85  | 2007-01-22   | 40    | 1.84             | 2.65        | 14.4             | C      | Grice et al. (2017)           |
| 86  | 2007-02-03   | 69    | 1.96             | 2.66        | 17.6             | C      | Grice et al. (2017)           |
| 87  | 2007-02-25.2 | 216   | 2.23             | 2.67        | 20.9             | R      | Warner (2007)                 |
| 88  | 2007-02-27.2 | 139   | 2.25             | 2.67        | 21.0             | R      | Warner (2007)                 |
| 89  | 2007-02-28.9 | 65    | 2.28             | 2.68        | 21.2             | C      | Hanuš et al. (2016)           |
| 90  | 2007-03-02.2 | 188   | 2.29             | 2.68        | 21.3             | R      | Warner (2007)                 |
| 91  | 2007-03-04.2 | 176   | 2.32             | 2.68        | 21.4             | R      | Warner (2007)                 |
| 92  | 2007-03-05.2 | 162   | 2.34             | 2.68        | 21.4             | R      | Warner (2007)                 |
| 93  | 2007-02-03   | 72    | 1.96             | 2.66        | 17.6             | C      | Grice et al. (2017)           |
| 94  | 2007-03-05.9 | 179   | 2.35             | 2.68        | 21.5             | C      | Hanuš et al. (2016)           |
| 95  | 2007-03-08.2 | 160   | 2.38             | 2.68        | 21.6             | R      | Warner (2007)                 |
| 96  | 2007-03-09.2 | 176   | 2.39             | 2.68        | 21.6             | R      | Warner (2007)                 |
| 97  | 2007-03-10.0 | 108   | 2.40             | 2.68        | 21.6             | C      | Hanuš et al. (2016)           |
| 98  | 2007-03-12.9 | 292   | 2.44             | 2.68        | 21.7             | C      | Hanuš et al. (2016)           |
| 99  | 2007-03-13.2 | 131   | 2.45             | 2.68        | 21.7             | R      | Warner (2007)                 |
| 100 | 2007-03-14.2 | 84    | 2.46             | 2.69        | 21.7             | R      | Warner (2007)                 |
| 101 | 2007-03-15.9 | 303   | 2.48             | 2.69        | 21.7             | C      | Hanuš et al. (2016)           |
| 102 | 2007-03-17.9 | 53    | 2.51             | 2.69        | 21.7             | C      | Hanuš et al. (2016)           |
| 103 | 2007-03-20.9 | 234   | 2.55             | 2.69        | 21.7             | C      | Hanuš et al. (2016)           |
| 104 | 2007-02-08   | 47    | 2.02             | 2.66        | 18.6             | C      | Grice et al. (2017)           |
| 105 | 2007-05-15.2 | 41    | 3.26             | 2.74        | 16.7             | V      | V. Reddy                      |
| 106 | 2007-05-17.2 | 33    | 3.28             | 2.74        | 16.4             | V      | V. Reddy                      |
| 107 | 2007-05-18.2 | 15    | 3.29             | 2.74        | 16.3             | V      | V. Reddy                      |
| 108 | 2007-02-09   | 47    | 2.03             | 2.66        | 18.8             | C      | Grice et al. (2017)           |
| 109 | 2007-02-09   | 49    | 2.03             | 2.66        | 18.8             | C      | Grice et al. (2017)           |
| 110 | 2007-02-10   | 39    | 2.05             | 2.66        | 19.0             | C      | Grice et al. (2017)           |
| 111 | 2007-02-10   | 44    | 2.05             | 2.66        | 19.0             | C      | Grice et al. (2017)           |
| 112 | 2007-01-14   | 43    | 1.77             | 2.65        | 11.8             | C      | Grice et al. (2017)           |
| 113 | 2007-01-21   | 41    | 1.83             | 2.65        | 14.1             | C      | Grice et al. (2017)           |
| 114 | 2008-02-23.4 | 95    | 2.21             | 3.02        | 12.5             | V      | V. Reddy                      |
| 115 | 2008-02-04   | 67    | 2.38             | 3.00        | 16.4             | C      | Grice et al. (2017)           |
| 116 | 2008-03-04   | 47    | 2.14             | 3.03        | 9.7              | C      | Grice et al. (2017)           |
| 117 | 2008-03-07   | 54    | 2.12             | 3.03        | 8.9              | C      | Grice et al. (2017)           |
| 118 | 2008-03-10   | 66    | 2.11             | 3.04        | 8.1              | C      | Grice et al. (2017)           |
| 119 | 2008-03-18   | 103   | 2.09             | 3.04        | 6.4              | C      | Grice et al. (2017)           |

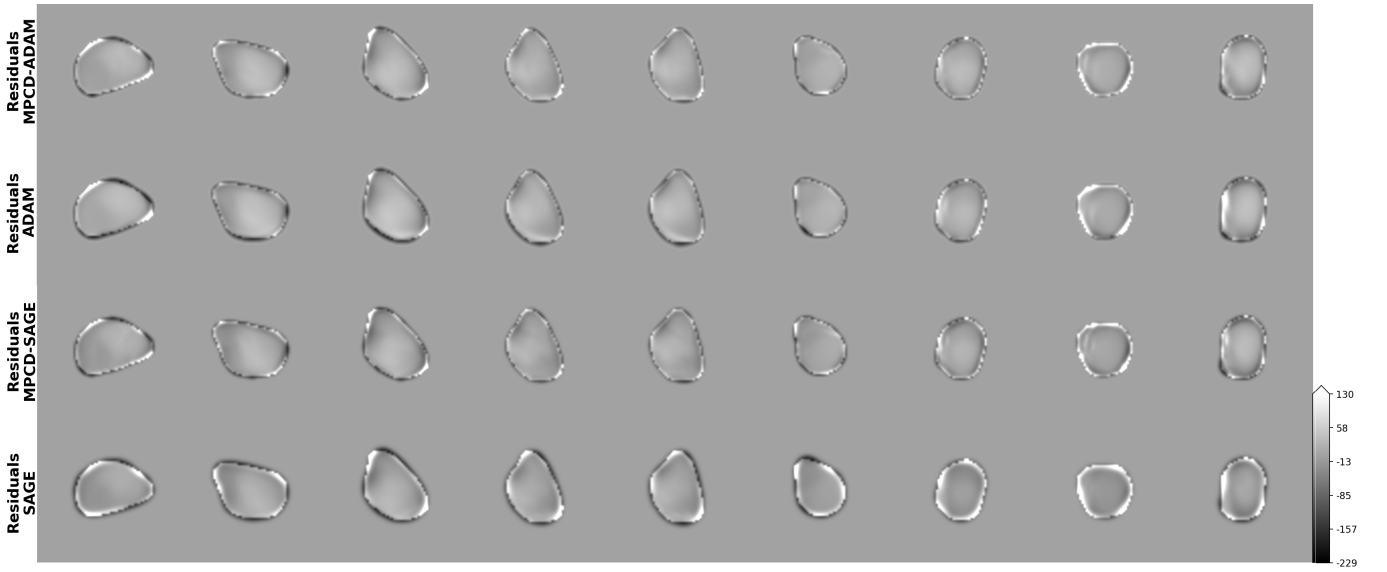
**Table B.2:** continued

| N   | Epoch        | $N_p$ | $\Delta$<br>(AU) | $r$<br>(AU) | $\varphi$<br>(°) | Filter | Reference                           |
|-----|--------------|-------|------------------|-------------|------------------|--------|-------------------------------------|
| 120 | 2008-03-18   | 107   | 2.09             | 3.04        | 6.4              | C      | <a href="#">Grice et al. (2017)</a> |
| 121 | 2008-03-29   | 47    | 2.09             | 3.05        | 5.8              | C      | <a href="#">Grice et al. (2017)</a> |
| 122 | 2008-04-01   | 52    | 2.09             | 3.05        | 6.1              | C      | <a href="#">Grice et al. (2017)</a> |
| 123 | 2008-04-13   | 70    | 2.14             | 3.06        | 8.7              | C      | <a href="#">Grice et al. (2017)</a> |
| 124 | 2008-04-14   | 86    | 2.14             | 3.07        | 8.9              | C      | <a href="#">Grice et al. (2017)</a> |
| 125 | 2008-04-20   | 85    | 2.18             | 3.07        | 10.5             | C      | <a href="#">Grice et al. (2017)</a> |
| 126 | 2008-04-21   | 51    | 2.19             | 3.07        | 10.7             | C      | <a href="#">Grice et al. (2017)</a> |
| 127 | 2008-04-21   | 105   | 2.19             | 3.07        | 10.7             | C      | <a href="#">Grice et al. (2017)</a> |
| 128 | 2008-04-22   | 70    | 2.20             | 3.07        | 11.0             | C      | <a href="#">Grice et al. (2017)</a> |
| 129 | 2008-04-23   | 64    | 2.21             | 3.07        | 11.2             | C      | <a href="#">Grice et al. (2017)</a> |
| 130 | 2008-04-24   | 64    | 2.21             | 3.07        | 11.5             | C      | <a href="#">Grice et al. (2017)</a> |
| 131 | 2008-04-28   | 74    | 2.25             | 3.08        | 12.5             | C      | <a href="#">Grice et al. (2017)</a> |
| 132 | 2008-04-29   | 86    | 2.26             | 3.08        | 12.7             | C      | <a href="#">Grice et al. (2017)</a> |
| 133 | 2008-05-04   | 60    | 2.30             | 3.08        | 13.9             | C      | <a href="#">Grice et al. (2017)</a> |
| 134 | 2008-05-05   | 32    | 2.31             | 3.08        | 14.1             | C      | <a href="#">Grice et al. (2017)</a> |
| 135 | 2008-05-06   | 43    | 2.33             | 3.08        | 14.3             | C      | <a href="#">Grice et al. (2017)</a> |
| 136 | 2012-01-15.9 | 41    | 1.77             | 2.67        | 10.6             | C      | <a href="#">Hanuš et al. (2016)</a> |
| 137 | 2012-01-15.9 | 41    | 1.77             | 2.67        | 10.6             | C      | <a href="#">Hanuš et al. (2016)</a> |
| 138 | 2012-01-16.9 | 77    | 1.77             | 2.67        | 10.9             | C      | <a href="#">Hanuš et al. (2016)</a> |
| 139 | 2012-01-16.9 | 77    | 1.77             | 2.67        | 10.9             | C      | <a href="#">Hanuš et al. (2016)</a> |
| 140 | 2012-02-07.9 | 351   | 1.98             | 2.68        | 17.3             | C      | <a href="#">Hanuš et al. (2016)</a> |
| 141 | 2012-02-08.0 | 90    | 1.98             | 2.68        | 17.4             | R      | <a href="#">Hanuš et al. (2016)</a> |
| 142 | 2012-02-08.0 | 92    | 1.98             | 2.68        | 17.4             | C      | <a href="#">Hanuš et al. (2016)</a> |
| 143 | 2012-02-08.0 | 111   | 1.98             | 2.68        | 17.4             | C      | <a href="#">Hanuš et al. (2016)</a> |
| 144 | 2012-02-08.9 | 210   | 1.99             | 2.68        | 17.6             | C      | <a href="#">Hanuš et al. (2016)</a> |
| 145 | 2012-02-17.0 | 208   | 2.09             | 2.69        | 19.1             | C      | <a href="#">Hanuš et al. (2016)</a> |
| 146 | 2016-11-17.2 | 39    | 1.87             | 2.64        | 16.0             | C      | GaiaGosa                            |
| 147 | 2016-11-18.2 | 41    | 1.86             | 2.65        | 15.7             | C      | GaiaGosa                            |
| 148 | 2016-11-5.1  | 189   | 2.00             | 2.64        | 18.9             | C      | GaiaGosa                            |
| 149 | 2018-3-9.2   | 335   | 2.17             | 3.06        | 10.0             | R      | TRAPPIST-North                      |
| 150 | 2018-3-10.2  | 510   | 2.17             | 3.06        | 9.7              | R      | TRAPPIST-North                      |
| 151 | 2018-3-11.0  | 62    | 2.16             | 3.06        | 9.5              | R      | TRAPPIST-North                      |
| 152 | 2018-3-12.0  | 325   | 2.15             | 3.06        | 9.2              | R      | TRAPPIST-North                      |
| 153 | 2018-3-14.0  | 159   | 2.14             | 3.06        | 8.6              | R      | TRAPPIST-North                      |
| 154 | 2018-4-18.1  | 1112  | 2.15             | 3.09        | 7.9              | R      | S. Fauvaud                          |
| 155 | 2018-4-19.1  | 1387  | 2.15             | 3.09        | 8.1              | R      | S. Fauvaud                          |

**Notes.** For each light curve the table gives the epoch, the number of individual measurements  $N_p$ , the asteroid's distance to the Earth  $\Delta$  and the Sun  $r$ , the phase angle  $\varphi$ , the photometric filter, and the reference. Gaia-GOSA (Gaia-Ground-based Observational Service for Asteroids, [www.gaiagosa.eu](http://www.gaiagosa.eu)).



**Fig. B.2:** Coverage map of the surface of Kalliope. The number of times each facet of our ADAM shape model has been imaged by SPHERE/ZIMPOL is represented by different gray scales. The coverage of the southern hemisphere is much better than the northern, but 84% of the surface has been imaged at least once.



**Fig. B.3:** Residuals in units of instrumental noise between the observed SPHERE images and the corresponding synthetic images from the four shape models.



**Table B.3:** Astrometry of Kalliope's satellite Linus.

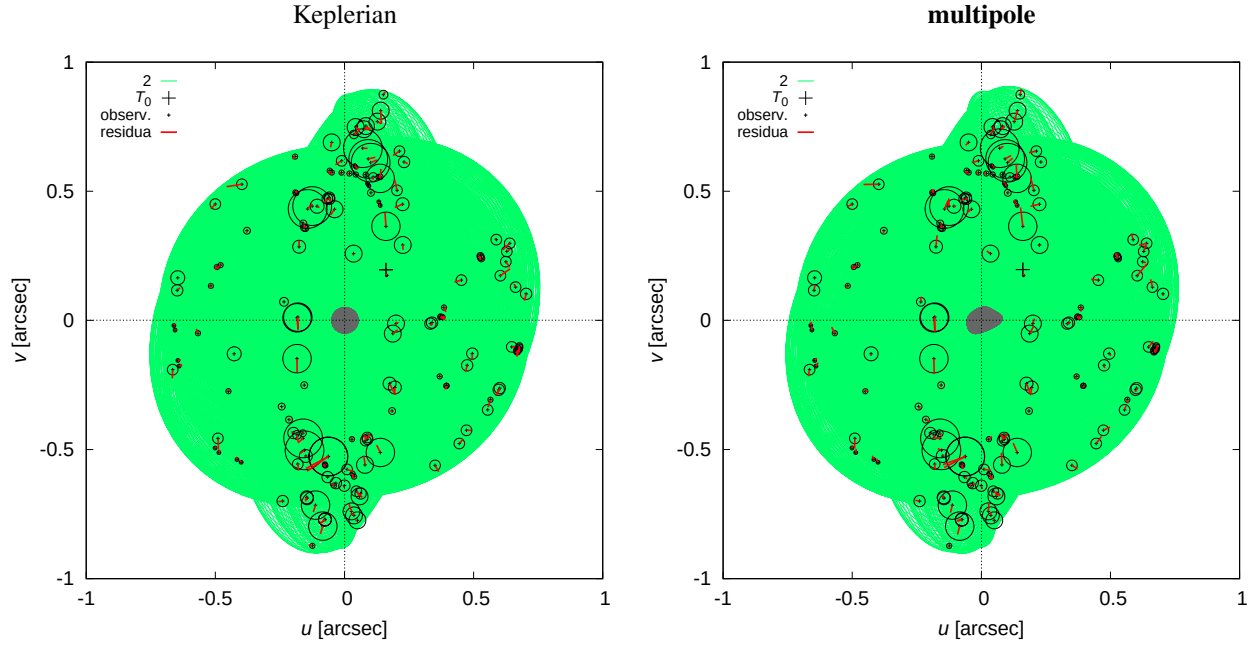
| Date       | UTC         | Tel.   | Cam.  | Filter | $X_o$<br>(mas) | $Y_o$<br>(mas) | $X_{o-c}$<br>(mas) | $Y_{o-c}$<br>(mas) | $\sigma$<br>(mas) | $\Delta M$<br>(mag) | $\delta M$<br>(mag) |
|------------|-------------|--------|-------|--------|----------------|----------------|--------------------|--------------------|-------------------|---------------------|---------------------|
| 2001-12-27 | 10:10:54.83 | Keck   | NIRC2 | Kp     | -370.8         | 12.6           | 19.2               | 1.8                | 10.0              | 4.1                 | 0.1                 |
| 2001-12-27 | 10:14:02.43 | Keck   | NIRC2 | Kp     | -372.5         | 15.7           | 18.0               | 1.6                | 10.0              | 4.1                 | 0.1                 |
| 2001-12-27 | 10:23:07.08 | Keck   | NIRC2 | H      | -379.8         | 12.7           | 12.1               | -11.0              | 10.0              | 4.8                 | 1.2                 |
| 2001-12-27 | 10:39:56.87 | Keck   | NIRC2 | J      | -385.3         | 49.9           | 9.1                | 8.4                | 10.0              | 4.4                 | 0.1                 |
| 2002-12-29 | 14:15:16.72 | Keck   | NIRC2 | H      | 517.1          | 133.6          | -6.6               | 3.8                | 10.0              | 5.8                 | 0.2                 |
| 2002-12-29 | 16:14:26.41 | Keck   | NIRC2 | H      | 479.7          | 214.0          | -20.6              | 12.9               | 10.0              | 6.6                 | 1.2                 |
| 2002-12-29 | 16:17:42.19 | Keck   | NIRC2 | H      | 494.0          | 206.9          | -5.5               | 3.9                | 10.0              | 5.1                 | 0.1                 |
| 2003-01-14 | 08:53:58.49 | VLT    | NACO  | Ks     | -526.3         | 249.6          | -8.5               | 2.3                | 13.3              | 4.1                 | 0.0                 |
| 2003-01-14 | 09:00:18.55 | VLT    | NACO  | H      | -527.9         | 245.2          | -8.1               | 1.8                | 13.3              | 4.1                 | 0.0                 |
| 2003-01-14 | 09:07:38.26 | VLT    | NACO  | J      | -529.9         | 240.0          | -7.9               | 1.1                | 13.3              | 4.2                 | 0.0                 |
| 2003-02-14 | 08:22:00.84 | VLT    | NACO  | H      | 645.7          | 165.1          | 0.5                | -1.5               | 27.1              | 4.5                 | 0.1                 |
| 2003-06-05 | 08:01:52.16 | Keck   | NIRC2 | Ks     | 449.3          | -274.2         | 4.2                | -7.6               | 10.0              | 4.3                 | 0.0                 |
| 2003-06-06 | 08:49:52.28 | Keck   | NIRC2 | Ks     | 190.1          | 495.5          | 0.3                | -7.5               | 10.0              | 4.1                 | 0.0                 |
| 2003-06-06 | 08:56:45.99 | Keck   | NIRC2 | Ks     | 186.6          | 492.7          | 1.0                | -11.5              | 10.0              | 3.5                 | 0.1                 |
| 2003-07-14 | 06:54:55.06 | Keck   | NIRC2 | Kp     | -29.1          | -460.0         | -0.1               | -10.4              | 10.0              | 5.0                 | 1.2                 |
| 2003-07-15 | 00:58:12.96 | VLT    | NACO  | H      | 427.0          | -129.4         | -2.1               | 4.0                | 27.1              | 4.0                 | 0.1                 |
| 2003-07-16 | 00:01:27.97 | VLT    | NACO  | H      | 106.0          | 442.1          | 6.8                | 4.5                | 27.1              | 3.9                 | 0.0                 |
| 2004-03-03 | 10:08:24.53 | VLT    | NACO  | H      | -184.5         | -350.9         | -5.6               | -5.2               | 13.3              | 4.7                 | 0.1                 |
| 2004-03-04 | 10:14:04.55 | VLT    | NACO  | H      | 155.7          | -250.9         | -3.6               | 0.8                | 13.3              | 4.8                 | 0.1                 |
| 2004-06-04 | 09:45:47.30 | Gemini | NIRI  | Kp     | -339.3         | -8.8           | -1.6               | -2.1               | 21.9              | 3.6                 | 0.0                 |
| 2004-06-04 | 09:47:58.05 | Gemini | NIRI  | Kp     | -332.6         | -12.5          | 5.4                | -4.0               | 21.9              | 3.1                 | 0.1                 |
| 2004-06-05 | 08:21:22.80 | Gemini | NIRI  | Kp     | -62.5          | -670.1         | 4.0                | 0.1                | 21.9              | 3.4                 | 0.0                 |
| 2004-06-05 | 11:03:50.60 | Gemini | NIRI  | Kp     | 0.4            | -639.9         | -2.3               | 6.0                | 21.9              | 3.8                 | 0.0                 |
| 2004-06-05 | 12:07:32.15 | Gemini | NIRI  | Kp     | 33.2           | -630.0         | 3.3                | -0.5               | 21.9              | 3.5                 | 0.0                 |
| 2004-06-05 | 13:22:56.93 | Gemini | NIRI  | Kp     | 65.5           | -606.7         | 3.5                | -1.4               | 21.9              | 3.9                 | 0.0                 |
| 2004-06-09 | 09:32:15.35 | Gemini | NIRI  | Kp     | 197.5          | -436.0         | -7.1               | -5.6               | 21.9              | 3.9                 | 1.2                 |
| 2004-06-28 | 02:20:45.88 | VLT    | NACO  | Ks     | 377.5          | 347.2          | -2.8               | 6.9                | 13.3              | 4.0                 | 0.0                 |
| 2004-07-03 | 09:52:52.63 | Keck   | NIRC2 | Kp     | -393.8         | -253.4         | -1.9               | 2.6                | 10.0              | 4.3                 | 0.0                 |
| 2004-07-03 | 09:54:23.50 | Keck   | NIRC2 | Kp     | -395.7         | -253.2         | -3.9               | 3.9                | 10.0              | 4.4                 | 0.1                 |
| 2004-07-04 | 08:19:04.08 | Keck   | NIRC2 | Kp     | 74.0           | -561.7         | -1.8               | 5.3                | 10.0              | 4.2                 | 0.0                 |
| 2004-07-04 | 08:28:54.13 | Keck   | NIRC2 | Kp     | 75.8           | -557.7         | -4.6               | 5.8                | 10.0              | 4.0                 | 0.0                 |
| 2004-07-11 | 09:04:38.59 | Keck   | NIRC2 | Kp     | -37.3          | -605.2         | -1.6               | 4.7                | 10.0              | 3.8                 | 0.0                 |
| 2004-07-11 | 09:06:17.61 | Keck   | NIRC2 | Kp     | -31.4          | -594.0         | 3.5                | 15.7               | 10.0              | 3.2                 | 0.0                 |
| 2004-07-24 | 04:06:15.08 | VLT    | NACO  | H      | -102.4         | 494.0          | -4.1               | -8.3               | 13.3              | 4.1                 | 0.0                 |
| 2004-07-26 | 01:26:46.89 | VLT    | NACO  | H      | 161.2          | -436.9         | 3.0                | 5.3                | 13.3              | 4.1                 | 0.0                 |
| 2004-07-26 | 03:22:05.69 | VLT    | NACO  | H      | 214.8          | -384.2         | 9.8                | 0.6                | 13.3              | 6.6                 | 0.2                 |
| 2004-07-26 | 04:51:30.92 | VLT    | NACO  | H      | 243.1          | -333.7         | 4.5                | 1.4                | 13.3              | 5.0                 | 0.1                 |
| 2004-10-07 | 00:20:01.16 | VLT    | NACO  | Ks     | 156.7          | 359.1          | -1.2               | -6.3               | 13.3              | 4.4                 | 0.1                 |
| 2004-10-07 | 00:30:14.12 | VLT    | NACO  | Ks     | 151.2          | 357.4          | -5.0               | -10.7              | 13.3              | 4.9                 | 0.1                 |
| 2004-10-07 | 00:45:06.38 | VLT    | NACO  | Ks     | 159.2          | 375.5          | 5.5                | 3.5                | 13.3              | 4.6                 | 0.1                 |
| 2005-05-31 | 14:59:17.38 | Keck   | NIRC2 | Kp     | -368.8         | -216.9         | -2.3               | 5.2                | 10.0              | 4.3                 | 0.0                 |
| 2006-12-12 | 13:42:00.42 | Keck   | NIRC2 | Kp     | 124.4          | -873.1         | -15.9              | -10.8              | 10.0              | 4.2                 | 0.0                 |
| 2008-01-21 | 11:36:28.68 | Keck   | NIRC2 | Kp     | 57.2           | 579.7          | -2.8               | 13.8               | 10.0              | 3.7                 | 0.1                 |
| 2008-01-21 | 11:43:51.91 | Keck   | NIRC2 | Kp     | 48.9           | 572.6          | -5.9               | 6.1                | 10.0              | 4.3                 | 0.0                 |
| 2008-01-21 | 12:31:09.49 | Keck   | NIRC2 | Kp     | 11.2           | 572.4          | -10.1              | 3.5                | 10.0              | 4.3                 | 0.0                 |
| 2008-01-21 | 13:12:50.82 | Keck   | NIRC2 | Kp     | -19.3          | 568.6          | -10.9              | -0.9               | 10.0              | 4.2                 | 0.0                 |
| 2008-01-21 | 13:54:28.00 | Keck   | NIRC2 | Kp     | -43.7          | 565.0          | -5.8               | -3.6               | 10.0              | 4.2                 | 0.0                 |
| 2008-01-21 | 14:55:05.79 | Keck   | NIRC2 | Kp     | -82.2          | 564.2          | -1.4               | -0.5               | 10.0              | 4.2                 | 0.0                 |
| 2008-01-21 | 15:57:45.30 | Keck   | NIRC2 | Kp     | -131.6         | 555.7          | -6.9               | -1.8               | 10.0              | 4.1                 | 0.0                 |
| 2008-01-21 | 16:06:05.01 | Keck   | NIRC2 | Kp     | -139.6         | 556.0          | -9.1               | -0.3               | 10.0              | 4.1                 | 0.0                 |
| 2009-06-07 | 11:34:45.65 | Keck   | NIRC2 | K      | 191.1          | 634.3          | -9.5               | 5.8                | 10.0              | 4.0                 | 0.0                 |
| 2010-06-28 | 12:44:51.55 | Keck   | NIRC2 | FeII   | 567.3          | -49.7          | -6.1               | -17.1              | 10.0              | 4.7                 | 1.2                 |
| 2010-08-26 | 12:25:53.86 | Keck   | NIRC2 | Kp     | -565.3         | -307.4         | -5.0               | 17.0               | 10.0              | 4.5                 | 0.0                 |
| 2010-08-26 | 13:22:31.41 | Gemini | NIRI  | Kp     | -597.3         | -268.7         | -6.0               | 12.3               | 21.9              | 3.7                 | 0.0                 |
| 2010-08-26 | 13:33:09.44 | Gemini | NIRI  | Kp     | -601.2         | -262.2         | -4.4               | 10.5               | 21.9              | 3.7                 | 0.0                 |
| 2010-08-30 | 06:42:20.85 | VLT    | NACO  | Ks     | -668.5         | -120.8         | 2.2                | 7.4                | 13.3              | 4.4                 | 0.0                 |
| 2010-08-30 | 06:47:40.78 | VLT    | NACO  | Ks     | -668.6         | -116.7         | 3.9                | 7.1                | 13.3              | 4.4                 | 0.0                 |
| 2010-08-30 | 06:52:58.60 | VLT    | NACO  | Ks     | -669.4         | -115.6         | 5.0                | 3.7                | 13.3              | 4.3                 | 0.1                 |
| 2010-08-30 | 06:57:55.00 | VLT    | NACO  | Ks     | -675.6         | -112.8         | 0.4                | 2.4                | 13.3              | 4.3                 | 0.0                 |



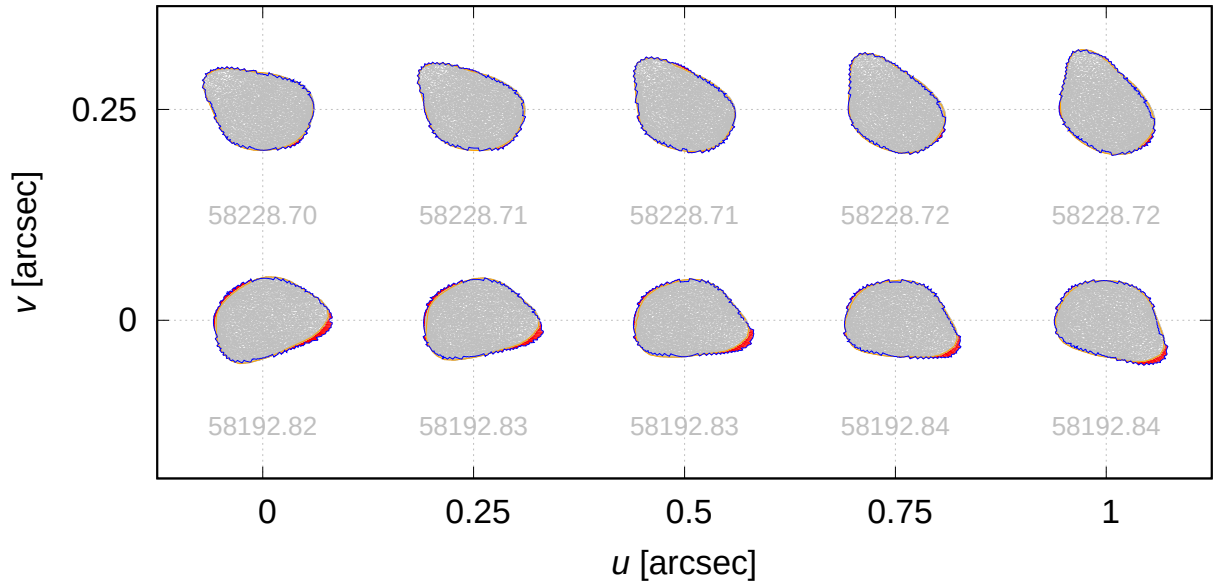
Table B.3: continued

| Date       | UTC         | Tel.   | Cam.   | Filter | $X_o$<br>(mas) | $Y_o$<br>(mas) | $X_{o-c}$<br>(mas) | $Y_{o-c}$<br>(mas) | $\sigma$<br>(mas) | $\Delta M$<br>(mag) | $\delta M$<br>(mag) |
|------------|-------------|--------|--------|--------|----------------|----------------|--------------------|--------------------|-------------------|---------------------|---------------------|
| 2010-08-30 | 07:03:01.82 | VLT    | NACO   | Ks     | -677.5         | -104.9         | 0.3                | 6.0                | 13.3              | 4.3                 | 0.0                 |
| 2010-08-30 | 07:09:26.05 | VLT    | NACO   | Ks     | -677.3         | -99.5          | 2.6                | 6.0                | 13.3              | 4.3                 | 0.0                 |
| 2010-09-15 | 10:31:57.01 | Gemini | NIRI   | Kp     | 647.6          | 116.4          | 12.0               | -9.7               | 21.9              | 3.7                 | 0.0                 |
| 2010-09-16 | 09:18:06.38 | Gemini | NIRI   | Kp     | 239.1          | -699.6         | -11.5              | -2.5               | 21.9              | 3.6                 | 0.0                 |
| 2010-09-17 | 09:52:44.88 | Gemini | NIRI   | Kp     | -703.6         | 102.7          | -5.3               | 14.6               | 21.9              | 3.8                 | 0.0                 |
| 2010-10-30 | 07:15:04.22 | Gemini | NIRI   | Kp     | -475.1         | -173.9         | -3.1               | 14.7               | 21.9              | 3.1                 | 0.0                 |
| 2010-10-30 | 08:22:28.80 | Gemini | NIRI   | Kp     | -495.0         | -128.5         | 2.2                | 11.6               | 21.9              | 3.5                 | 0.1                 |
| 2010-10-31 | 07:17:43.32 | Gemini | NIRI   | Kp     | -230.8         | 613.2          | 11.1               | 4.5                | 21.9              | 3.6                 | 0.0                 |
| 2011-11-10 | 14:56:31.94 | Keck   | NIRC2  | FeII   | 40.6           | -639.7         | -10.1              | -11.9              | 10.0              | 4.2                 | 0.0                 |
| 2015-08-05 | 06:12:36.29 | VLT    | IRDIS  | H      | -255.5         | -583.7         | 5.7                | 11.7               | 12.3              | 4.7                 | 0.0                 |
| 2015-08-06 | 08:50:19.71 | VLT    | IRDIS  | H      | -536.8         | 508.1          | 9.3                | 2.5                | 12.3              | 4.1                 | 0.0                 |
| 2015-08-06 | 08:55:55.18 | VLT    | IRDIS  | H      | -531.9         | 511.3          | 10.9               | 2.7                | 12.3              | 4.4                 | 0.0                 |
| 2015-08-06 | 09:03:38.30 | VLT    | IRDIS  | H      | -527.1         | 514.9          | 11.2               | 2.1                | 12.3              | 4.5                 | 0.0                 |
| 2015-08-22 | 07:32:01.75 | VLT    | IRDIS  | H      | 712.2          | -318.7         | -6.7               | -1.6               | 12.3              | 4.1                 | 0.0                 |
| 2015-08-25 | 04:45:18.09 | VLT    | IRDIS  | H      | 450.0          | 481.0          | -4.1               | -14.6              | 12.3              | 3.7                 | 0.0                 |
| 2015-08-25 | 04:51:33.71 | VLT    | IRDIS  | H      | 455.6          | 476.2          | -3.2               | -15.5              | 12.3              | 3.7                 | 0.0                 |
| 2015-08-28 | 06:19:53.45 | VLT    | IRDIS  | H      | -213.3         | 697.6          | 7.3                | -6.8               | 12.3              | 3.8                 | 0.0                 |
| 2015-08-28 | 06:26:23.81 | VLT    | IRDIS  | H      | -208.0         | 699.2          | 6.7                | -5.9               | 12.3              | 3.8                 | 0.0                 |
| 2015-09-06 | 03:38:54.27 | VLT    | IRDIS  | H      | 334.6          | -683.4         | -1.2               | 5.1                | 12.3              | 3.4                 | 0.0                 |
| 2015-09-06 | 03:45:23.25 | VLT    | IRDIS  | H      | 327.0          | -681.3         | -3.3               | 8.7                | 12.3              | 3.8                 | 0.0                 |
| 2015-09-06 | 03:51:39.55 | VLT    | IRDIS  | H      | 322.4          | -682.3         | -2.6               | 9.1                | 12.3              | 3.8                 | 0.0                 |
| 2018-03-15 | 08:03:46.46 | VLT    | ZIMPOL | R      | 486.4          | -512.0         | 7.1                | -10.7              | 7.2               | 4.7                 | 0.0                 |
| 2018-03-15 | 08:28:25.25 | VLT    | ZIMPOL | R      | 501.0          | -494.3         | 6.9                | -6.8               | 7.2               | 4.6                 | 0.0                 |
| 2018-04-20 | 05:11:36.58 | VLT    | ZIMPOL | R      | 400.1          | -549.6         | 0.1                | -10.8              | 7.2               | 4.6                 | 0.0                 |
| 2018-04-20 | 05:36:16.45 | VLT    | ZIMPOL | R      | 416.3          | -538.9         | -0.3               | -12.0              | 7.2               | 4.6                 | 0.0                 |
| 2018-05-04 | 23:30:43.20 | VLT    | ZIMPOL | R      | 640.4          | -177.0         | 12.8               | -5.6               | 7.2               | 4.1                 | 0.0                 |
| 2018-05-04 | 23:55:24.19 | VLT    | ZIMPOL | R      | 645.2          | -155.1         | 12.2               | -2.1               | 7.2               | 4.1                 | 0.0                 |
| 2018-05-05 | 02:34:13.23 | VLT    | ZIMPOL | R      | 656.0          | -37.6          | 2.2                | -5.1               | 7.2               | 4.1                 | 0.0                 |
| 2018-05-05 | 02:58:53.71 | VLT    | ZIMPOL | R      | 660.4          | -19.8          | 5.6                | -6.2               | 7.2               | 4.1                 | 0.0                 |
| 2019-06-09 | 08:50:43.39 | VLT    | ZIMPOL | R      | -133.0         | 459.3          | -5.7               | -2.3               | 7.2               | 4.6                 | 0.0                 |
| 2019-06-09 | 09:08:08.97 | VLT    | ZIMPOL | R      | -138.5         | 445.1          | -6.5               | -5.7               | 7.2               | 4.6                 | 0.0                 |
| 2019-06-27 | 03:38:22.22 | VLT    | ZIMPOL | R      | -39.9          | 599.3          | 4.7                | 1.3                | 7.2               | 4.7                 | 0.0                 |
| 2019-06-27 | 03:55:48.28 | VLT    | ZIMPOL | R      | -45.0          | 593.3          | 5.9                | 2.0                | 7.2               | 4.8                 | 0.0                 |
| 2019-07-08 | 00:30:49.73 | VLT    | ZIMPOL | R      | -89.1          | 530.2          | -1.4               | -4.8               | 7.2               | 4.8                 | 0.0                 |
| 2019-07-08 | 00:48:15.01 | VLT    | ZIMPOL | R      | -94.6          | 521.1          | -0.4               | -5.7               | 7.2               | 4.8                 | 0.0                 |
| 2021-12-30 | 20:15:00.00 | C2PU   | PISCO  | V      | 58.0           | -368.0         | -21.3              | 13.0               | 8.1               | –                   | –                   |
| 2021-12-30 | 20:53:40.00 | C2PU   | PISCO  | V      | 60.0           | -425.0         | -16.5              | -7.0               | 7.8               | 3.9                 | 0.3                 |
| 2021-12-30 | 21:41:04.00 | C2PU   | PISCO  | V      | 65.0           | -456.0         | -7.9               | 6.1                | 9.2               | 3.9                 | 0.2                 |
| 2021-12-30 | 22:18:43.00 | C2PU   | PISCO  | V      | 47.0           | -494.0         | -22.8              | 1.9                | 10.8              | –                   | –                   |
| 2021-12-30 | 23:12:37.00 | C2PU   | PISCO  | V      | 43.0           | -553.0         | -22.2              | -10.4              | 5.8               | 3.4                 | 0.2                 |
| 2021-12-31 | 00:23:13.00 | C2PU   | PISCO  | V      | 50.0           | -585.0         | -8.7               | 15.1               | 5.8               | 3.4                 | 0.2                 |
| 2021-12-31 | 01:13:00.00 | C2PU   | PISCO  | V      | 48.0           | -645.0         | -5.8               | -7.0               | 10.3              | –                   | –                   |
| 2021-12-31 | 01:43:00.00 | C2PU   | PISCO  | V      | 49.0           | -662.0         | -1.8               | -2.4               | 10.0              | –                   | –                   |
| 2021-12-31 | 02:10:00.00 | C2PU   | PISCO  | V      | 42.0           | -662.0         | -6.0               | 16.4               | 20.6              | –                   | –                   |
| 2021-12-31 | 19:17:59.00 | C2PU   | PISCO  | V      | -63.0          | -744.0         | 5.1                | -1.7               | 5.8               | 3.5                 | 0.4                 |
| 2021-12-31 | 20:23:42.00 | C2PU   | PISCO  | V      | -69.0          | -695.0         | 5.0                | 7.7                | 6.7               | –                   | –                   |
| 2021-12-31 | 20:48:33.00 | C2PU   | PISCO  | V      | -74.0          | -674.0         | 2.1                | 12.5               | 5.8               | 3.6                 | 0.2                 |
| 2021-12-31 | 21:42:32.00 | C2PU   | PISCO  | V      | -74.0          | -643.0         | 6.5                | 6.3                | 6.4               | 4.1                 | 0.4                 |
| 2021-12-31 | 22:36:33.00 | C2PU   | PISCO  | V      | -85.0          | -601.0         | -0.5               | 8.2                | 6.4               | –                   | –                   |
| 2021-12-31 | 23:30:31.00 | C2PU   | PISCO  | V      | -87.0          | -556.0         | 1.3                | 10.7               | 6.7               | –                   | –                   |
| 2022-01-01 | 00:24:54.00 | C2PU   | PISCO  | V      | -70.0          | -528.0         | 21.6               | -6.7               | 13.6              | 3.7                 | 0.2                 |
| 2022-01-01 | 01:17:39.00 | C2PU   | PISCO  | V      | -91.0          | -471.0         | 3.5                | 4.2                | 13.5              | 3.7                 | 0.2                 |
| 2022-01-01 | 02:11:38.00 | C2PU   | PISCO  | V      | 103.0          | -413.0         | -5.8               | 13.1               | 8.6               | –                   | –                   |
| 2022-01-01 | 03:03:20.00 | C2PU   | PISCO  | V      | 108.0          | -399.0         | -8.7               | -21.7              | 5.4               | –                   | –                   |

**Notes.** Date, mid-observing time (UTC), telescope, camera, filter, astrometry ( $X$  is aligned with right ascension, and  $Y$  with declination, and the indices  $o$  and  $c$  stand for observed and computed positions), and photometry (magnitude difference  $\Delta M$  with uncertainty  $\delta M$ ).



**Fig. B.4:** Sky-plane positions  $(u, v)$  and trajectories for two dynamical models: Keplerian (left) and multipole (right). Observed positions are plotted as black crosses and uncertainty ellipses, trajectories (with variable geometry) as green lines, and residuals as red lines. Both models are comparable in terms of  $\chi^2_{\text{sky}}$  (202 vs 226; see Table 2).



**Fig. B.5:** Residuals of AO silhouettes (in red) when using the best-fit pole  $l = 195.6^\circ$ ,  $b = 2.2^\circ$ , according to the multipole model. The surface shape was adjusted for this pole. The value of  $\chi^2_{\text{ao}} = 443$ . A total of 35 silhouettes were used. Only the bottom row is affected by deconvolution artifacts due to fast rotation.

**Table B.4:** Multipole coefficients of Kalliope's gravitational field, using the ADAM model and constant density.

|             |                              |             |                              |
|-------------|------------------------------|-------------|------------------------------|
| $C_{00}$    | 1.00000000                   |             |                              |
| $C_{10}$    | 0.00000000                   |             |                              |
| $C_{11}$    | 0.00000000                   | $S_{11}$    | 0.00000000                   |
| $C_{20}$    | $-1.58875562 \cdot 10^{-1}$  |             |                              |
| $C_{21}$    | $-4.33435120 \cdot 10^{-3}$  | $S_{21}$    | $-2.42113162 \cdot 10^{-3}$  |
| $C_{22}$    | $4.73395888 \cdot 10^{-2}$   | $S_{22}$    | $3.38835106 \cdot 10^{-5}$   |
| $C_{30}$    | $1.16834450 \cdot 10^{-2}$   |             |                              |
| $C_{31}$    | $2.37513333 \cdot 10^{-2}$   | $S_{31}$    | $5.93605589 \cdot 10^{-3}$   |
| $C_{32}$    | $-2.04115124 \cdot 10^{-3}$  | $S_{32}$    | $-2.46015062 \cdot 10^{-3}$  |
| $C_{33}$    | $-7.49059459 \cdot 10^{-4}$  | $S_{33}$    | $-3.37228585 \cdot 10^{-3}$  |
| $C_{40}$    | $4.74784983 \cdot 10^{-2}$   |             |                              |
| $C_{41}$    | $-4.88209013 \cdot 10^{-3}$  | $S_{41}$    | $-3.28678691 \cdot 10^{-3}$  |
| $C_{42}$    | $-4.08073011 \cdot 10^{-3}$  | $S_{42}$    | $-1.03036986 \cdot 10^{-3}$  |
| $C_{43}$    | $1.31697945 \cdot 10^{-4}$   | $S_{43}$    | $1.86676711 \cdot 10^{-4}$   |
| $C_{44}$    | $2.78751167 \cdot 10^{-4}$   | $S_{44}$    | $2.77201832 \cdot 10^{-4}$   |
| $C_{50}$    | $-1.75298664 \cdot 10^{-2}$  |             |                              |
| $C_{51}$    | $-1.71149768 \cdot 10^{-2}$  | $S_{51}$    | $-4.31000895 \cdot 10^{-3}$  |
| $C_{52}$    | $1.11174185 \cdot 10^{-3}$   | $S_{52}$    | $8.17553521 \cdot 10^{-4}$   |
| $C_{53}$    | $4.23873557 \cdot 10^{-4}$   | $S_{53}$    | $4.82680368 \cdot 10^{-4}$   |
| $C_{54}$    | $-4.05737556 \cdot 10^{-5}$  | $S_{54}$    | $-5.48759157 \cdot 10^{-5}$  |
| $C_{55}$    | $-8.11236571 \cdot 10^{-6}$  | $S_{55}$    | $-5.34460804 \cdot 10^{-5}$  |
| $C_{60}$    | $-2.26407423 \cdot 10^{-2}$  |             |                              |
| $C_{61}$    | $1.06155467 \cdot 10^{-2}$   | $S_{61}$    | $3.17450599 \cdot 10^{-3}$   |
| $C_{62}$    | $8.94341691 \cdot 10^{-4}$   | $S_{62}$    | $9.19312511 \cdot 10^{-4}$   |
| $C_{63}$    | $-1.61567819 \cdot 10^{-4}$  | $S_{63}$    | $-1.67419911 \cdot 10^{-4}$  |
| $C_{64}$    | $-8.84803606 \cdot 10^{-6}$  | $S_{64}$    | $-4.37031557 \cdot 10^{-5}$  |
| $C_{65}$    | $7.37179627 \cdot 10^{-7}$   | $S_{65}$    | $5.61944021 \cdot 10^{-6}$   |
| $C_{66}$    | $-4.17890001 \cdot 10^{-7}$  | $S_{66}$    | $3.62295627 \cdot 10^{-6}$   |
| $C_{70}$    | $3.54897487 \cdot 10^{-2}$   |             |                              |
| $C_{71}$    | $-2.69712613 \cdot 10^{-2}$  | $S_{71}$    | $5.68137067 \cdot 10^{-4}$   |
| $C_{72}$    | $-1.08514637 \cdot 10^{-3}$  | $S_{72}$    | $-6.51499801 \cdot 10^{-4}$  |
| $C_{73}$    | $-1.46230432 \cdot 10^{-4}$  | $S_{73}$    | $-1.42955377 \cdot 10^{-4}$  |
| $C_{74}$    | $1.22190952 \cdot 10^{-5}$   | $S_{74}$    | $1.96896452 \cdot 10^{-5}$   |
| $C_{75}$    | $1.48302902 \cdot 10^{-6}$   | $S_{75}$    | $5.23611262 \cdot 10^{-6}$   |
| $C_{76}$    | $-1.01335926 \cdot 10^{-7}$  | $S_{76}$    | $-5.49383918 \cdot 10^{-7}$  |
| $C_{77}$    | $8.59087060 \cdot 10^{-8}$   | $S_{77}$    | $-3.07710303 \cdot 10^{-7}$  |
| $C_{80}$    | $2.06218064 \cdot 10^{-2}$   |             |                              |
| $C_{81}$    | $-1.44307265 \cdot 10^{-2}$  | $S_{81}$    | $-3.51810426 \cdot 10^{-3}$  |
| $C_{82}$    | $-4.64071911 \cdot 10^{-4}$  | $S_{82}$    | $-6.73665797 \cdot 10^{-4}$  |
| $C_{83}$    | $1.41998313 \cdot 10^{-4}$   | $S_{83}$    | $1.23775069 \cdot 10^{-4}$   |
| $C_{84}$    | $8.48390705 \cdot 10^{-7}$   | $S_{84}$    | $1.62927728 \cdot 10^{-5}$   |
| $C_{85}$    | $-8.08521429 \cdot 10^{-7}$  | $S_{85}$    | $-2.56842858 \cdot 10^{-6}$  |
| $C_{86}$    | $1.50086522 \cdot 10^{-7}$   | $S_{86}$    | $-3.68754057 \cdot 10^{-7}$  |
| $C_{87}$    | $-1.24729943 \cdot 10^{-8}$  | $S_{87}$    | $5.30096051 \cdot 10^{-8}$   |
| $C_{88}$    | $-1.40328492 \cdot 10^{-8}$  | $S_{88}$    | $1.73822097 \cdot 10^{-8}$   |
| $C_{90}$    | $-7.38068869 \cdot 10^{-2}$  |             |                              |
| $C_{91}$    | $-4.31387796 \cdot 10^{-3}$  | $S_{91}$    | $-1.97973583 \cdot 10^{-3}$  |
| $C_{92}$    | $1.04198061 \cdot 10^{-3}$   | $S_{92}$    | $5.14153229 \cdot 10^{-4}$   |
| $C_{93}$    | $-1.35824568 \cdot 10^{-4}$  | $S_{93}$    | $5.18308966 \cdot 10^{-4}$   |
| $C_{94}$    | $-8.06877944 \cdot 10^{-6}$  | $S_{94}$    | $-1.41329178 \cdot 10^{-5}$  |
| $C_{95}$    | $-2.35844582 \cdot 10^{-8}$  | $S_{95}$    | $-1.11646481 \cdot 10^{-6}$  |
| $C_{96}$    | $-7.20088131 \cdot 10^{-11}$ | $S_{96}$    | $1.98019520 \cdot 10^{-7}$   |
| $C_{97}$    | $-9.46264001 \cdot 10^{-9}$  | $S_{97}$    | $2.27384973 \cdot 10^{-8}$   |
| $C_{98}$    | $1.53136052 \cdot 10^{-9}$   | $S_{98}$    | $-3.04644339 \cdot 10^{-9}$  |
| $C_{99}$    | $1.08668869 \cdot 10^{-9}$   | $S_{99}$    | $-8.38316486 \cdot 10^{-10}$ |
| $C_{10,0}$  | $-1.52754324 \cdot 10^{-2}$  |             |                              |
| $C_{10,1}$  | $1.68702648 \cdot 10^{-2}$   | $S_{10,1}$  | $4.00489156 \cdot 10^{-3}$   |
| $C_{10,2}$  | $2.19255958 \cdot 10^{-4}$   | $S_{10,2}$  | $3.84832391 \cdot 10^{-4}$   |
| $C_{10,3}$  | $-1.22227813 \cdot 10^{-4}$  | $S_{10,3}$  | $-1.09283485 \cdot 10^{-4}$  |
| $C_{10,4}$  | $1.14264963 \cdot 10^{-7}$   | $S_{10,4}$  | $-6.19634189 \cdot 10^{-6}$  |
| $C_{10,5}$  | $4.66051178 \cdot 10^{-7}$   | $S_{10,5}$  | $1.41886391 \cdot 10^{-6}$   |
| $C_{10,6}$  | $-4.23016143 \cdot 10^{-8}$  | $S_{10,6}$  | $8.23703808 \cdot 10^{-8}$   |
| $C_{10,7}$  | $2.98805253 \cdot 10^{-9}$   | $S_{10,7}$  | $-1.64044820 \cdot 10^{-8}$  |
| $C_{10,8}$  | $1.40038401 \cdot 10^{-9}$   | $S_{10,8}$  | $-1.16432341 \cdot 10^{-9}$  |
| $C_{10,9}$  | $-1.58497488 \cdot 10^{-10}$ | $S_{10,9}$  | $2.06969430 \cdot 10^{-10}$  |
| $C_{10,10}$ | $-8.00938275 \cdot 10^{-11}$ | $S_{10,10}$ | $3.06719370 \cdot 10^{-11}$  |

**Notes.** The normalization is given by Eq. (A.1). The reference radius is  $R = 76.411$  km.

### 4.2.8. Occultation of Kalliope

A new stellar occultation of Kalliope occurred in March 2, 2022. This particular occultation is interesting because at the time of the event Kalliope was oriented in a way that has not been well imaged by SPHERE. The Fig. 4.12 shows how Kalliope was oriented at the time of the occultation and the projected coverage map. Kalliope was seen edge-on, from  $-110^\circ$  to  $70^\circ$  in longitude, the region that encompass most of the surface not visible in any of the SPHERE images (see Fig. 4.7). This occultation was thus an excellent opportunity to test the validity of the shape models for regions not seen in the AO images. The event was visible from the south of the USA and in Mexico. An observation campaign was organized by the International Occultation and Timing Association (IOTA) and 13 evenly spaced positive observations were obtained.

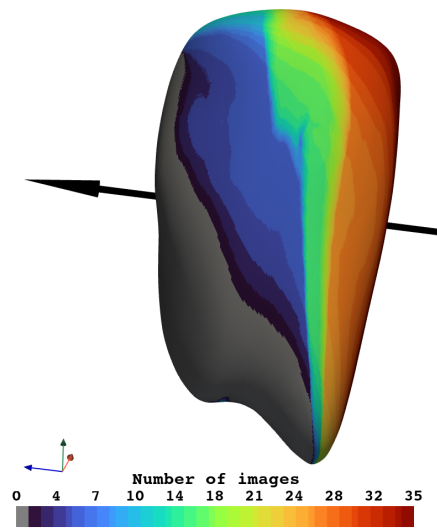


Figure 4.12.: The orientation of Kalliope as seen from the Earth at the time of the stellar occultation of March 2, 2022. The color map indicates the coverage of the surface by the SPHERE images.

The software Occult<sup>3</sup> developed by D. Herald allows to visualize the chords and to compare them to the shape model of the asteroid loaded from the DAMIT or Interactive Service for Asteroid Models (ISAM) databases (Fig. 4.13). Most of the chords fit well the models, validating the global shape. However, the last two chords, numbered 13 and 14, show larger discrepancies, indicating that the depth of the depression at the origin of the pointy aspect of Kalliope have been overestimated by  $\sim 10$  km. In future works, it would be interesting to include these new occultation data to the modeling to better constrain this region.

<sup>3</sup><http://www.lunar-occultations.com/iota/occult4.htm>

#### 4. Study of two dense M-type asteroids – 4.2. The binary (22) Kalliope

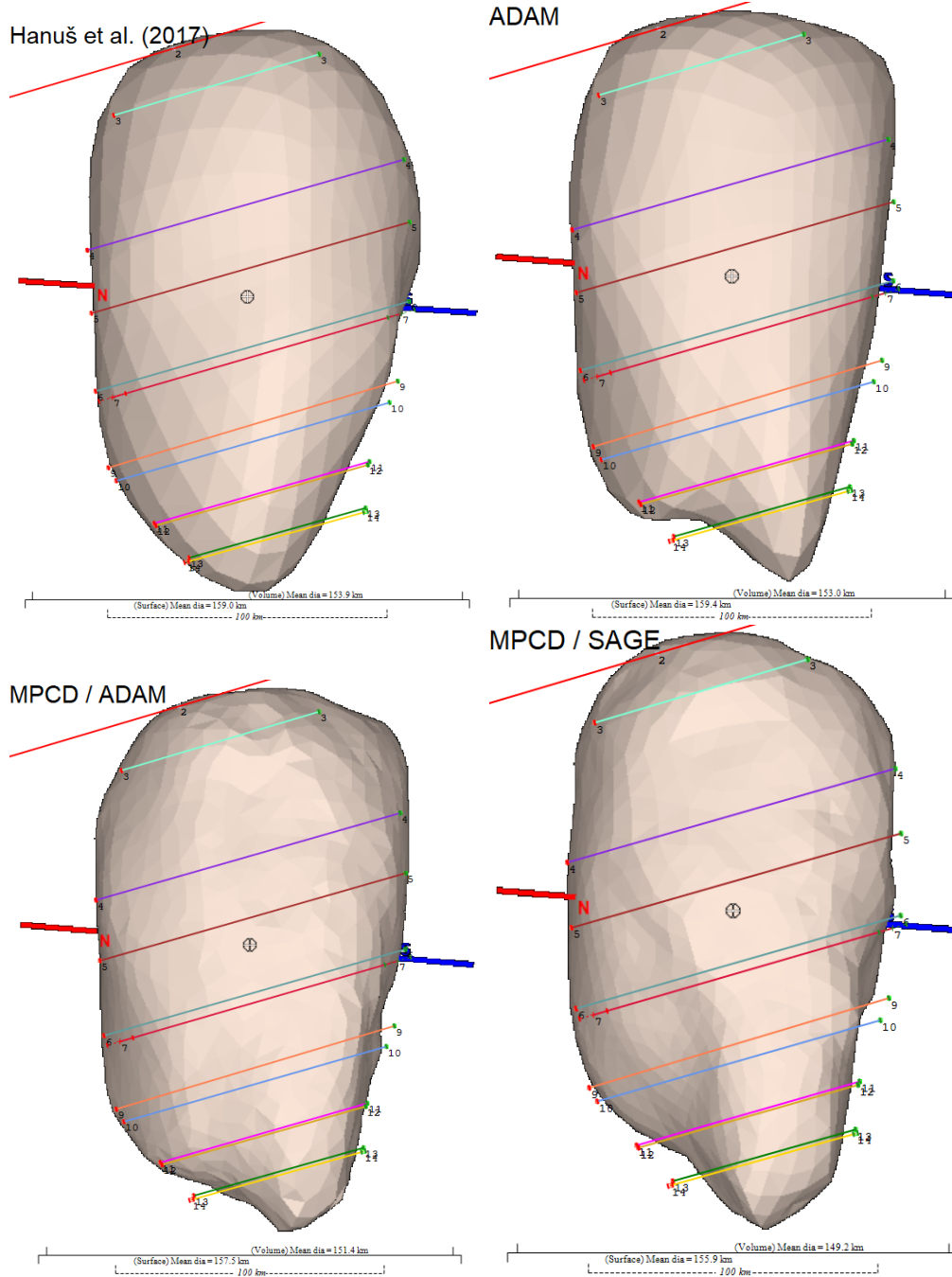


Figure 4.13.: The 13 chords of the stellar occultation of March 2, 2022 compared to different shape models of Kalliope using *Occult4*. Uncertainties on the disappearance and reappearance timings are indicated by red and green segments, most or them being too small to be visible. The first model was produced by lightcurves inversion (Hanuš et al., 2017b). The second is the ADAM model, followed by the two MPCD models based on the ADAM and SAGE models.

#### 4.2.9. Kalliope and Linus mutual events

The orbit plane of Linus regularly becomes aligned with the Earth's line of sight. At these occasions, the Kalliope - Linus system reach seasons of mutual events, where they occult each other in turn. These events result in small attenuation of the total brightness of the binary system (0.02 - 0.08 mag) during a few hours that can be observed in lightcurves. Such observations are important as they represent a good way to test the orbital model of Linus and the shape model of Kalliope. The predicted timings of the events can be compared with the observed values and the shape of the drop curves depends on different parameters, including the effective size of Linus and Kalliope, the orbital pole of Linus, and the shape of Kalliope (Descamps et al., 2008).

Using his orbital model, M. Brož predicted the timings for different sites during the mutual events season of November - December 2021. Two events were predicted for TS on November 27 and December 6. For the northern hemisphere, we asked to use the telescope Artemis because of the small predicted drop in magnitude ( $\leq 0.04$  mag). Artemis is a 1-m telescope located at the Teide Observatory, on the island of Tenerife, Spain. This telescope is part of the SPECULOOS<sup>4</sup> network and is operated by the MIT. It is equipped with an Andor iKon-L camera of  $2048 \times 2048$  pixels, providing a field of view of  $12' \times 12'$  and a pixel scale of  $0.35''$  per pixel. Two events were also predicted to be observable for Artemis, a partial one on November 29 and a full one on December 8.

Table 4.3.: Observed mutual events date, time of ingress / egress, and magnitude drop. The type of event indicates if Linus was occulted by Kalliope or in transit.

| Date       | Telescope | Type        | Egress (UTC) | Ingress (UTC) | Mag. Drop         |
|------------|-----------|-------------|--------------|---------------|-------------------|
| 2021-11-27 | TS        | Occultation | 04:38        | 07:48         | $0.039 \pm 0.009$ |
| 2021-11-29 | Artemis   | Transit     |              | 02:00         | $0.031 \pm 0.006$ |
| 2021-12-06 | TS        | Transit     | 05:02        | 07:12         | $0.018 \pm 0.011$ |
| 2021-12-08 | Artemis   | Occultation | 23:58        | 01:15         | $0.021 \pm 0.006$ |

The four events were successfully observed with good sky conditions, except for slightly worse seeing for TS on December 6. Because the attenuation is faint and is superimposed on the rotation curve of Kalliope, reference curves were obtained just before or after an event, or the night after if it was not possible. The reference curves were fitted with 10th order Fourier fit and the differences with the event data provide the drop curves.

Fig. 4.14 shows the phased lightcurves for the four events chronologically, along with the reference curves to visualize the attenuation. The corresponding drop curves are displayed in the figures on the right. Each curves display a different shapes, depending on if Kalliope was occulting Linus or if Linus was transiting Kalliope, and

<sup>4</sup><https://www.speculoos.uliege.be>

#### *4. Study of two dense M-type asteroids – 4.2. The binary (22) Kalliope*

on the orientation of Kalliope and the orbit plane of Linus. The observed attenuation depths range from 0.02 to 0.04 mag and the duration from 1 h to 3 h (Table 4.3).



#### 4. Study of two dense M-type asteroids – 4.2. The binary (22) Kalliope

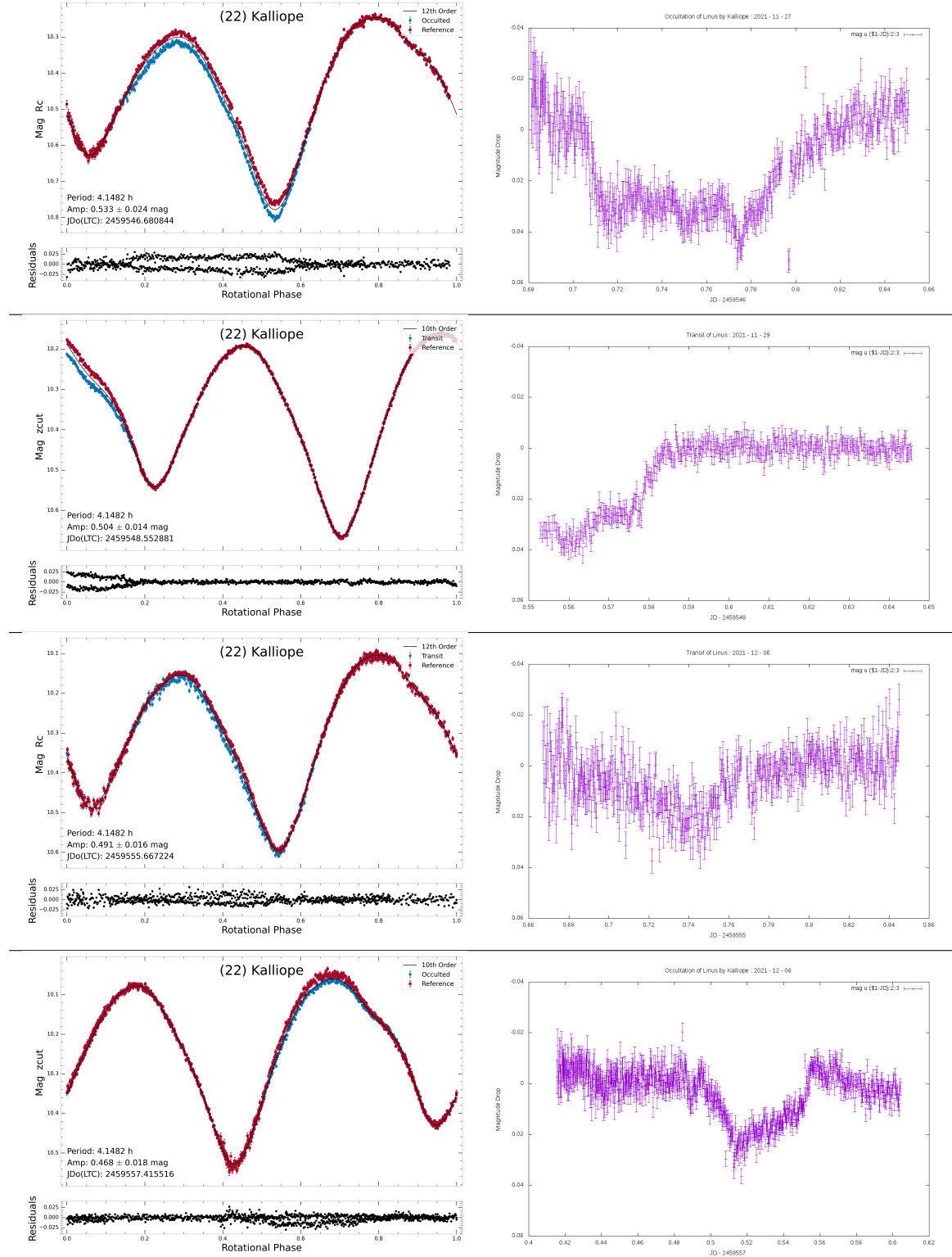


Figure 4.14.: Results of the observation of mutual events between Kalliope and Linus in November and December 2021 with TS and Artemis. The figures on the left show the rotational lightcurves during the events (in blue), along with reference curves (in red). Table 4.3 provides the dates, telescopes and types of event. The figures on the right are the corresponding drop curves.

## 5. Study of 42 large main belt asteroids

This chapter presents the results of the shape modeling of 42 large main belt asteroids with the MPCD methods as well as the contributions to the synthesis paper of the large program led by P. Vernazza. A description of the shape analysis performed on our 3D models is given with the main conclusions that could be drawn.

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## 5.1. 3D reconstruction with MPCD

In the last chapter, we focused on two particularly interesting targets of the ESO large program, Psyche and Kalliope, and we aimed at characterizing them as best as possible. The second part of the thesis was to also apply MPCD to the other members of the sample of large MBAs imaged by SPHERE. Then, a shape analysis could be applied to each of them in order to study the sample as a whole and to try to derive conclusions on the different classes.

Of the 42 targets of the ESO large program, we reconstructed the 3D shape of 40 of them with MPCD. The number of epochs observed for (48) Doris and (145) Adeona (see Table 1.3) was too small for MPCD really improve their shapes. Two additional asteroids were also later observed with SPHERE, following the successful individual proposals of M. Marsset and P. Vernazza that aimed to take advantages of the particularly bright apparitions of (65) Cybele and (121) Hermione. Two MPCD shape models were produced for these targets as well. The 3D shape models and the spin parameters produced for the large program, including the MPCD models, as well as the reduced and deconvolved SPHERE images are available at this address: <https://observations.lam.fr/astero/>

In total, MPCD was applied to 42 asteroids. Each time we used the ADAM model as input mesh to try to further refine it. SAGE models were also used in the case of Kalliope and Nemesis. We list the main parameters of the MPCD modeling of these objects in Table 5.1. We generated for each targets a mosaic displaying a comparison between the deconvolved SPHERE images (one per epoch), and the corresponding synthetic images for the different models, along with the residuals. These mosaics allow to easily visualize the quality of the fit of the model to the images. They are given in appendix of the synthesis paper of the large program (Vernazza et al., 2021), which is provided in Sect. 5.5.

The  $\chi^2$  values of the synthetic images produced by the ADAM model and the corresponding MPCD model are provided in Table 5.1. In almost cases, the  $\chi^2$  is improved by the MPCD model, indicating a better fit to the observed images. In average, the  $\chi^2$  was decreased by 20%.

To compare the modification that MPCD performed on the initial ADAM shapes, we computed for each asteroid the distribution of the distances measured along the normal direction between the two models and fitted Gaussian curves on them (as done for Kalliope, Fig. 4.8). The resulting means,  $R_{mean}$ , and standard deviations,  $R_{sigma}$ , are provided in Table 5.1. The largest mean differences are observed for the largest members of our sample, Ceres and Vesta, with 2 km and -2.1 km respectively. We then searched for a potential systematic difference in size between the ADAM and MPCD models. Such a systematic bias would not have been too surprising because of the difficulties that arise from the usage of deconvolved AO images by MPCD. The  $R_{mean}$  and  $R_{sigma}$  were used to generate Gaussian Probability Distribution Functions (PDFs) that were then multiplied together (Fig. 5.1). The resulting product PDF has a mean difference of  $0.2 \pm 0.3$ , indicating that they are no systematic difference between

## 5. Study of 42 large main belt asteroids – 5.1. 3D reconstruction with MPCD

the two methods.

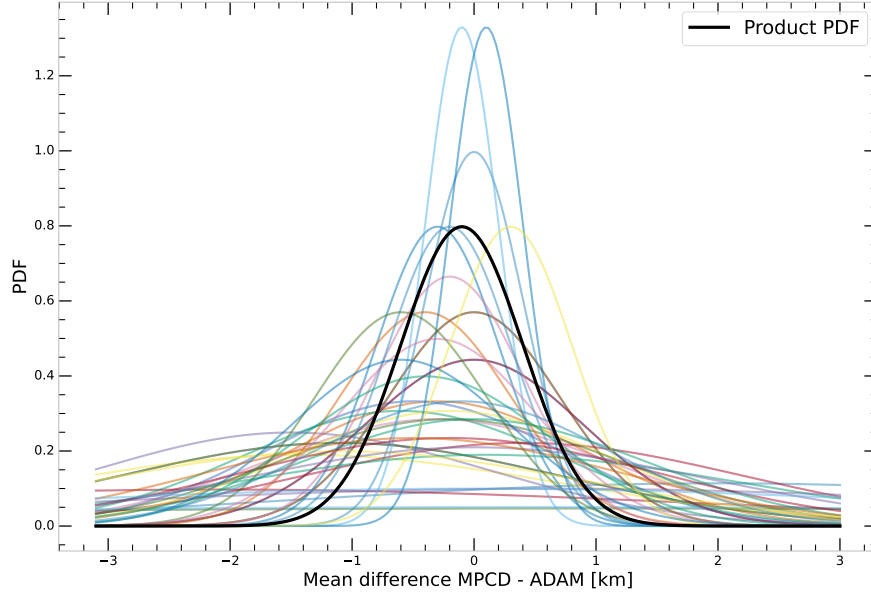


Figure 5.1.: Gaussian PDFs of the mean differences between the ADAM and MPCD models for the 42 asteroids reconstructed with MPCD. The product PDF is indicated by the black curve and has a mean of 0.2 km and a standard deviation of 0.3 km.

Table 5.1.: Synthesis of parameters concerning the shape reconstruction of 42 asteroids with MPCD.

| Number | Name       | $D_{mpcd}$<br>[km] | $N_{img}$ | $N'_{img}$ | Coverage<br>[%] | Aspect<br>[°] | Level | $N_{tri}$ | $\chi^2_{MPCD}$ | $\chi^2_{ADAM}$ | $R_{mean}$<br>[km] | $R_{sigma}$<br>[km] |
|--------|------------|--------------------|-----------|------------|-----------------|---------------|-------|-----------|-----------------|-----------------|--------------------|---------------------|
| 1      | Ceres      | $942 \pm 3$        | 25        | 17         | 100             | 97 - 89       | 5     | 114688    | 3               | 7               | 2.0                | 3.5                 |
| 2      | Pallas     | $508 \pm 4$        | 53        | 28         | 100             | 160 - 16      | 5     | 45056     | 35              | 44              | -2.1               | 4.1                 |
| 3      | Juno       | $252 \pm 3$        | 30        | 11         | 95              | 118           | 4     | 27008     | 34              | 53              | -1.1               | 1.8                 |
| 4      | Vesta      | $522 \pm 3$        | 30        | 22         | 97              | 108           | 5     | 86528     | 397             | 554             | 0.9                | 8.5                 |
| 6      | Hebe       | $194 \pm 5$        | 35        | 26         | 85              | 59            | 3     | 11136     | 25              | 45              | -0.3               | 1.2                 |
| 7      | Iris       | $204 \pm 10$       | 32        | 15         | 100             | 156 - 15      | 3-4   | 27936     | 61              | 99              | -0.5               | 1.2                 |
| 8      | Flora      | $142 \pm 5$        | 20        | 9          | 94              | 54 - 76       | 2-3   | 8000      | 55              | 90              | -0.5               | 1.2                 |
| 9      | Metis      | $172 \pm 4$        | 30        | 30         | 100             | 95            | 3     | 5920      | 32              | 45              | -0.6               | 1.3                 |
| 10     | Hygiea     | $431 \pm 6$        | 54        | 35         | 97              | 142 - 113     | 4     | 17664     | 21              | 26              | -1.4               | 2.1                 |
| 11     | Parthenope | $148 \pm 3$        | 25        | 15         | 100             | 19 - 108      | 3     | 4928      | 28              | 50              | 0.0                | 0.7                 |
| 12     | Victoria   | $116 \pm 2$        | 20        | 9          | 98              | 70            | 2     | 2864      | 48              | 63              | 0.0                | 0.9                 |
| 13     | Egeria     | $203 \pm 6$        | 30        | 28         | 79              | 34            | 3     | 7808      | 65              | 105             | 0.4                | 1.8                 |
| 15     | Eunomia    | $268 \pm 5$        | 80        | 40         | 100             | 93 - 99       | 3-4   | 11648     | 43              | 43              | -1.5               | 1.6                 |
| 16     | Psyche     | $222 \pm 4$        | 60        | 35         | 100             | 11 - 101      | 3     | 6464      | 43              | 54              | -1.1               | 1.8                 |
| 18     | Melpomene  | $141 \pm 5$        | 30        | 16         | 96              | 34 - 95       | 2-3   | 4320      | 44              | 41              | 0.0                | 0.7                 |

*Continued on next page*

## 5. Study of 42 large main belt asteroids – 5.2. Shape analysis

Table 5.1 – Continued from previous page

| Number | Name       | $D_{mpcd}$<br>[km] | $N_{img}$ | $N'_{img}$ | Coverage<br>[%] | Aspect<br>[–1.4°] | Level | $N_{tri}$ | $\chi^2_{MPCD}$ | $\chi^2_{ADAM}$ | $R_{mean}$<br>[km] | $R_{sigma}$<br>[km] |
|--------|------------|--------------------|-----------|------------|-----------------|-------------------|-------|-----------|-----------------|-----------------|--------------------|---------------------|
| 19     | Fortuna    | $211 \pm 3$        | 30        | 30         | 97              | 112               | 3     | 9280      | 28              | 27              | -0.3               | 1.4                 |
| 21     | Lutetia    | $98 \pm 2$         | 36        | 36         | 75              | 138               | 3     | 21838     | 26              | 30              | 0.5                | 7.9                 |
| 22     | Kalliope   | $151 \pm 4$        | 35        | 35         | 77              | 167 - 110         | 3     | 2568      | 114             | 171             | 0.1                | 2.1                 |
| 24     | Themis     | $208 \pm 5$        | 30        | 24         | 95              | 106               | 3     | 5952      | 25              | 35              | -0.2               | 1.3                 |
| 29     | Amphitrite | $203 \pm 3$        | 60        | 36         | 100             | 33 - 123 - 112    | 2     | 1360      | 23              | 20              | -0.3               | 0.5                 |
| 30     | Urania     | $89 \pm 4$         | 20        | 8          | 89              | 71                | 2     | 2760      | 51              | 65              | 0.0                | 0.4                 |
| 31     | Euphrosyne | $268 \pm 6$        | 34        | 34         | 10              | 88                | 3     | 6460      | 42              | 41              | 0.0                | 0.9                 |
| 41     | Daphne     | $186 \pm 13$       | 35        | 35         | 77              | 130 - 38          | 3     | 5818      | 28              | 30              | 0.6                | 4.0                 |
| 45     | Eugenia    | $187 \pm 3$        | 54        | 37         | 99              | 123 - 31          | 3     | 7264      | 23              | 24              | -0.2               | 1.4                 |
| 51     | Nemausa    | $149 \pm 3$        | 30        | 22         | 89              | 115               | 3     | 4512      | 20              | 20              | -0.4               | 0.7                 |
| 52     | Europa     | $318 \pm 4$        | 53        | 37         | 100             | 128 - 66          | 3     | 7328      | 36              | 35              | -0.2               | 0.6                 |
| 63     | Ausonia    | $93 \pm 3$         | 25        | 15         | 90              | 74                | 2     | 1760      | 56              | 67              | -0.1               | 0.3                 |
| 65     | Cybele     | $262 \pm 3$        | 35        | 35         | 100             | 93                | 3     | 6528      | 33              | 45              | 0.0                | 1.4                 |
| 87     | Sylvia     | $271 \pm 5$        | 38        | 15         | 95              | 110               | 3     | 5792      | 44              | 62              | -1.1               | 2.0                 |
| 88     | Thisbe     | $218 \pm 5$        | 30        | 30         | 99              | 74                | 3     | 12256     | 27              | 27              | 0.1                | 0.3                 |
| 89     | Julia      | $138 \pm 4$        | 40        | 24         | 85              | 163               | 3     | 6048      | 23              | 30              | -0.2               | 0.5                 |
| 121    | Hermione   | $181 \pm 6$        | 30        | 30         | 61              | 155               | 3     | 4896      | 50              | 62              | -0.2               | 1.7                 |
| 128    | Nemesis    | $164 \pm 5$        | 25        | 5          | 97              | 62                | 3     | 5472      | 30              | 20              | 0.0                | 1.9                 |
| 130    | Elektra    | $198 \pm 3$        | 30        | 30         | 100             | 93                | 3     | 5280      | 29              | 34              | -0.6               | 0.7                 |
| 173    | Ino        | $145 \pm 6$        | 25        | 25         | 62              | 146               | 3     | 3528      | 45              | 118             | -0.5               | 1.7                 |
| 187    | Lamberta   | $140 \pm 4$        | 25        | 19         | 95              | 91                | 3     | 6942      | 23              | 32              | -0.3               | 0.8                 |
| 216    | Kleopatra  | $118 \pm 3$        | 55        | 33         | 100             | 59 - 126          | 3     | 3168      | 51              | 135             | 0.0                | 4.0                 |
| 230    | Athamantis | $118 \pm 7$        | 13        | 6          | 88              | 85                | 2     | 2992      | 31              | 77              | -0.4               | 1.0                 |
| 324    | Bamberga   | $227 \pm 3$        | 38        | 25         | 100             | 95 - 71           | 3     | 8992      | 22              | 32              | 0.3                | 0.5                 |
| 354    | Eleonora   | $164 \pm 5$        | 35        | 35         | 99              | 96                | 3     | 4000      | 80              | 68              | -0.6               | 0.9                 |
| 511    | Davida     | $298 \pm 6$        | 33        | 30         | 94              | 103               | 3     | 8576      | 31              | 43              | -0.1               | 1.2                 |
| 704    | Interamnia | $332 \pm 4$        | 46        | 34         | 98              | 121 - 109         | 3     | 13024     | 24              | 24              | -0.1               | 0.5                 |

**Note:**  $D_{mpcd}$  is the volume-equivalent diameter of the MPCD models.  $N_{img}$  is the total number of SPHERE images available and  $N'_{img}$  is the number of images used by MPCD. Coverage indicates the percentage of the surface imaged. Aspect indicates the aspect angle for each apparition. Level is the number of resolution levels used by MPCD, and  $N_{tri}$  is the number of facets of the highest resolution model.  $\chi^2_{MPCD}$  and  $\chi^2_{ADAM}$  are the  $\chi^2$  values of the synthetic images obtained with the MPCD and ADAM model, respectively.  $R_{mean}$  and  $R_{sigma}$  are the mean and standard deviation of the distribution of the difference between the MPCD and ADAM models along the normal direction.

## 5.2. Shape analysis

### 5.2.1. Deviation to an ellipsoid

Our shape analysis consisted first to determine quantitatively how close to an ellipsoid and to a sphere are the shape of our targets. The deviation to an ellipsoid was obtained by computing the radial differences between the shape models of our targets and their

best-fitting ellipsoid. This gave us the (model – ellipsoid) average residuals relative to the mean radius. The resulting values are listed in Table 5.3. Smaller values indicate more ellipsoidal shapes than for larger values.

### 5.2.2. Asphericity

We then computed the asphericity of all targets to measure how different to a sphere are their shapes, in the same way as for Hygiea and Kalliope (Ferrais et al., 2020b; Vernazza et al., 2020). The sphericity index is a function of the surface area  $A$  and of the volume  $V$  (Wadell, 1935):

$$\Psi = \frac{\pi^{1/3} (6V)^{2/3}}{A}. \quad (5.1)$$

The asphericity is then defined as  $1 - \Psi$ .

However, the surface area is very sensitive to the surface topography and to the resolution of the 3D shape model. Therefore, a direct comparison of our shape models would lead to incorrect results because of the large range of model resolutions and the different topographies in our data set. This problem can be overcome by computing the real spherical harmonic expansion coefficients of each 3D model. We arbitrarily chose to compute the coefficients up to the tenth order. This method allows to obtain new shape models that reproduce well the overall shape of the original models but ignore the small-scale topographic variations. Therefore, applying the sphericity formula on these spherical harmonics provides a self-consistent comparison.

### 5.2.3. Relations between size and shape

Asteroids can have very irregular shapes, but this strongly depends on the size. Indeed, the more massive an asteroid is, the more ellipsoidal or spherical it becomes because of its own gravity. This effect appears very clearly when plotting the asphericity as well as the ellipsoid deviation as a function of their volume-equivalent radius. Fig. 5.2 shows a strong correlation for both quantities.

While the size, thus the mass, is the main parameter determining the global 3D shape of an asteroid, we noticed that the distribution of the asphericity of our sample appears to be bimodal at first order. We separated our sample in two groups, depending on their positions above or below the global linear fit (Fig. 5.2, black line with  $r = -0.76$ ). These two groups correspond to more spherical bodies (lower asphericity) and more elongated bodies (higher asphericity), relatively to their sizes. The asphericities of the groups fitted separately show an even improved correlation ( $r = -0.94$  for the more elongated bodies, and  $r = -0.96$  for the more spherical bodies). We also applied the DIP test (Hartigan and Hartigan, 1985) to the distribution of the log of the asphericity minus the distance to the global fit in order to measure its multimodality (Fig. 5.3). The resulting 99.4% confidence level against unimodality allows to reject the unimodality of the distribution.

## 5. Study of 42 large main belt asteroids – 5.2. Shape analysis

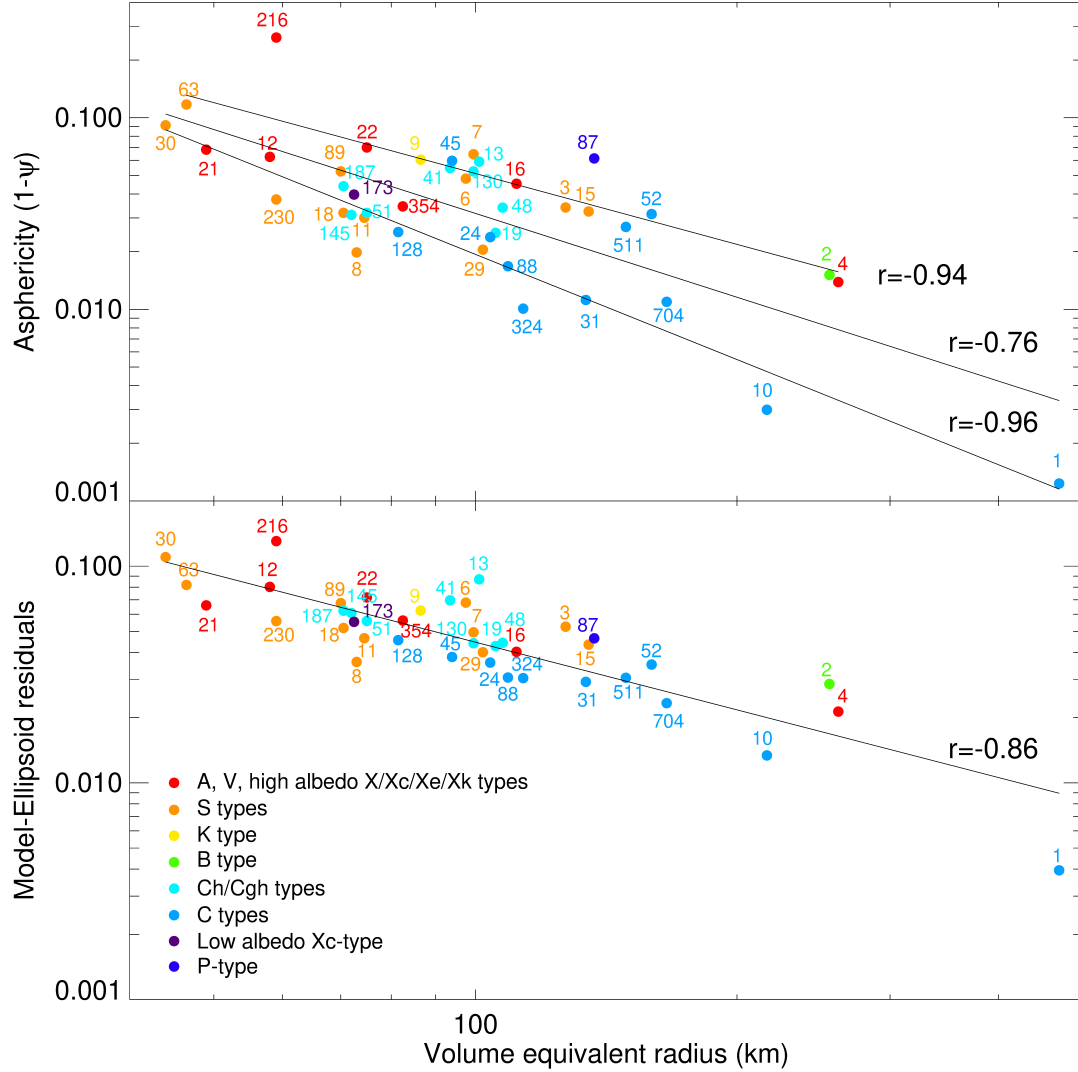


Figure 5.2.: *Upper panel:* Asphericity of the large program targets as a function of their volume-equivalent radius. *Lower panel:* Ellipsoid deviation as a function of the volume equivalent-radius. Both quantities appear highly correlated. In the case of the asphericity, fitting separately subsamples of more spherical and more elongated bodies increases further the correlation coefficients. Figure produced by P. Vernazza.



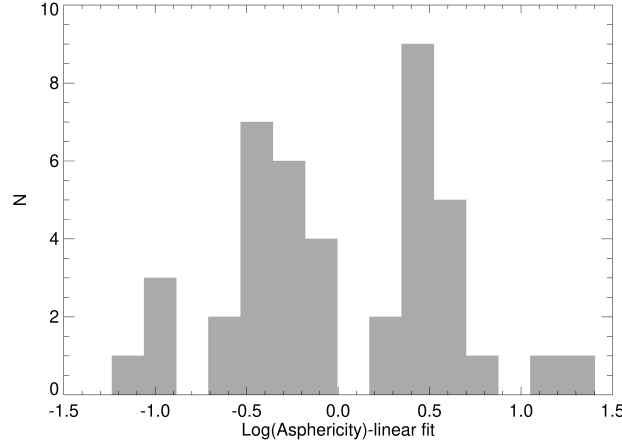


Figure 5.3.: Histogram of the distance between the asphericity of our targets and the linear best fit to the whole sample. The distribution appears bimodal at first order, and a DIP test rejects unimodality. Figure produced by P. Vernazza.

#### 5.2.4. Global shape

We saw in the previous section that the larger an asteroid is, the more its shape approach that of a sphere or an ellipsoid. Large asteroids can even, under some conditions, reach hydrostatic equilibrium. A self-gravitating and rotating body in hydrostatic equilibrium will naturally adapt the shape of an equilibrium figure, such as the Maclaurin's ellipsoid (Moritz, 1990). For an homogeneous body with rotational velocity  $\Omega$  and bulk density  $\rho$ , the Maclaurin's equation is given by (Chandrasekhar, 1969):

$$\frac{\Omega^2}{\pi G \rho} = \frac{2\sqrt{1-e^2}}{e^3} (3 - 2e^2) \arcsin(e) - 6 \frac{1-e^2}{e^2}, \quad (5.2)$$

where  $G$  is the gravitational constant and  $e$  is the ellipticity of the body shape defined as:

$$e^2 = 1 - \left(\frac{c}{a}\right)^2. \quad (5.3)$$

Finally,  $a$  and  $c$  are the equatorial and polar radii, which can be compared to the values of the observed shape. The Maclaurin's ellipsoid is not the only possible figure of equilibrium. For instance, C. G. Jacobi demonstrated that rotating triaxial ellipsoids with unequal axes, called Jacobi ellipsoids, can also be in equilibrium. The question of hydrostatic equilibrium for an asteroid has implications on its formation and internal structure but also on its primordial shape and collisional history.

The different figures of equilibrium can be characterized by their specific angular momentum  $H$ , and normalized angular velocity  $\Omega$  (Descamps, 2015). The different families of equilibrium figures form sequences in this parameters space (Chan-

drasekhar, 1969). The specific angular momentum is given by:

$$H = \frac{L}{\sqrt{G M^3 R}}, \quad (5.4)$$

where  $L$  denotes the angular momentum of the body,  $M$  its mass and  $R$  its volume-equivalent radius,  $G$  is the gravitational constant. The normalized angular velocity is defined as:

$$\Omega = \frac{\omega}{\sqrt{\frac{4}{3} \pi \rho G}}, \quad (5.5)$$

with  $\omega$  the actual angular velocity of the body, and  $\rho$  its bulk density.

We compared the specific angular momentum and the normalized angular velocity of our targets (Descamps, 2015) with the expected values for Maclaurin and Jacobi ellipsoids as well as dumb-bell shapes (Fig. 5.4). It appears that all bodies fall along the Maclaurin sequence, except for (216) Kleopatra who is found on the dumb-bell sequence. Then, the mean distance and the reduced  $\chi^2$  were computed for different sub-populations. It results that spherical bodies are closer to the Maclaurin sequence than elongated bodies, as well as the volatile-rich with respect to the volatile-poor bodies and the larger bodies ( $D > 200$  km) with respect to the smaller one.

### 5.3. Density

The densities of all targets were computed by combining an average of available mass estimates provided by B. Carry with our derived volume-equivalent diameters. To compute the diameters, we had at our disposal both the ADAM and the MPCD models, leaving the possibility to use one or the other, or to combined them. Because MPCD uses solely the AO images, we decided to rely on the ADAM diameter values only if the coverage was lower than 80% (9 asteroids out of 42). Otherwise, we reported the average of the ADAM and MPCD diameters. The distribution of the density for all of our targets shown in Fig. 5.5 reveals a strong bimodality between the volatile-poor bodies on the left, and the volatile-rich bodies on the right.

Table 5.2.: Results of the shape analysis of our asteroids.

| N  | $D$<br>[km] | $\rho$<br>[g cm <sup>-3</sup> ] | Albedo | Asph   | Ell. dev. | $H$   | $\Omega$ | $a$<br>[km] | $b$<br>[km] | $c$<br>[km] | $c/a$         |
|----|-------------|---------------------------------|--------|--------|-----------|-------|----------|-------------|-------------|-------------|---------------|
| 1* | 939.4±0.2   | 2.161±0.001                     | 0.096  | 0.0012 | 0.0039    | 0.104 | 0.247    | 964.4±0.2   | 964.2±0.2   | 891.8±0.2   | 0.9247±0.0003 |
| 2  | 511±4       | 2.92±0.08                       | 0.155  | 0.0151 | 0.0286    | 0.114 | 0.247    | 568±12      | 530±12      | 450±12      | 0.79±0.03     |
| 3  | 254±2       | 3.15±0.28                       | 0.202  | 0.034  | 0.0526    | 0.117 | 0.258    | 288±5       | 250±5       | 225±5       | 0.78±0.02     |
| 4* | 523.2±0.2   | 3.453±0.004                     | 0.38   | 0.0139 | 0.0213    | 0.154 | 0.332    | 572.6±0.2   | 557.2±0.2   | 446.4±0.2   | 0.7769±0.0004 |
| 6  | 195±3       | 3.18±0.64                       | 0.268  | 0.0481 | 0.0679    | 0.122 | 0.254    | 220±9       | 205±8       | 166±7       | 0.75±0.04     |

*Continued on next page*

## 5. Study of 42 large main belt asteroids – 5.3. Density

Table 5.2 – *Continued from previous page*

| N   | $D$<br>[km] | $\rho$<br>[g cm <sup>-3</sup> ] | Albedo | Asph   | Ell. dev. | $H$   | $\Omega$ | $a$<br>[km] | $b$<br>[km] | $c$<br>[km] | $c/a$     |
|-----|-------------|---------------------------------|--------|--------|-----------|-------|----------|-------------|-------------|-------------|-----------|
| 7   | 199±10      | 3.26±0.74                       | 0.279  | 0.0645 | 0.0495    | 0.151 | 0.256    | 260±5       | 225±4       | 150±18      | 0.58±0.07 |
| 8   | 146±2       | 2.4±1.0                         | 0.224  | 0.0198 | 0.0361    | 0.07  | 0.165    | 154±7       | 148±6       | 127±4       | 0.82±0.05 |
| 9   | 173±2       | 2.94±0.70                       | 0.18   | 0.0604 | 0.0624    | 0.201 | 0.379    | 218±10      | 176±10      | 133±8       | 0.61±0.05 |
| 10  | 433±8       | 2.06±0.20                       | 0.063  | 0.003  | 0.0134    | 0.068 | 0.166    | 450±10      | 430±10      | 424±20      | 0.94±0.05 |
| 11  | 149±2       | 3.20±0.27                       | 0.187  | 0.0301 | 0.0465    | 0.058 | 0.134    | 156±6       | 152±6       | 138±6       | 0.88±0.05 |
| 12  | 116±2       | 3.4±1.7                         | 0.167  | 0.0625 | 0.0802    | 0.108 | 0.208    | 140±4       | 116±3       | 96±3        | 0.69±0.03 |
| 13  | 202±3       | 2.13±0.49                       | 0.087  | 0.059  | 0.0869    | 0.154 | 0.321    | 238±12      | 199±11      | 182±10      | 0.76±0.06 |
| 15  | 270±3       | 2.96±0.21                       | 0.187  | 0.0324 | 0.0434    | 0.154 | 0.315    | 340±14      | 248±13      | 229±14      | 0.67±0.05 |
| 16  | 223±3       | 3.89±0.53                       | 0.155  | 0.0452 | 0.0402    | 0.211 | 0.399    | 277±5       | 238±6       | 164±4       | 0.59±0.02 |
| 18  | 141±2       | 3.06±0.62                       | 0.221  | 0.0319 | 0.0518    | 0.073 | 0.163    | 161±8       | 135±8       | 131±7       | 0.81±0.06 |
| 19  | 211±2       | 1.80±0.29                       | 0.056  | 0.0251 | 0.0428    | 0.148 | 0.331    | 242±10      | 203±10      | 192±10      | 0.79±0.05 |
| 21* | 98±2        | 3.45±0.21                       | 0.194  | 0.0682 | 0.0659    | 0.114 | 0.218    | 125±4       | 98±3        | 81±2        | 0.65±0.03 |
| 22  | 150±5       | 4.36±0.50                       | 0.198  | 0.07   | 0.0717    | 0.223 | 0.381    | 207±5       | 145±4       | 122±4       | 0.59±0.02 |
| 24  | 208±3       | 1.31±0.62                       | 0.06   | 0.0238 | 0.0359    | 0.163 | 0.344    | 232±14      | 220±14      | 176±14      | 0.76±0.08 |
| 29  | 204±2       | 2.86±0.45                       | 0.194  | 0.0205 | 0.0401    | 0.161 | 0.362    | 222±6       | 209±6       | 183±5       | 0.82±0.03 |
| 30  | 88±2        | 3.7±2.7                         | 0.214  | 0.0913 | 0.1101    | 0.067 | 0.125    | 112±5       | 84±5        | 76±4        | 0.68±0.05 |
| 31  | 268±4       | 1.64±0.27                       | 0.05   | 0.0112 | 0.0292    | 0.205 | 0.467    | 286±16      | 274±14      | 247±15      | 0.86±0.07 |
| 41  | 187±13      | 1.78±0.45                       | 0.052  | 0.0546 | 0.0696    | 0.211 | 0.413    | 235±17      | 183±16      | 153±14      | 0.65±0.08 |
| 45  | 188±2       | 1.66±0.07                       | 0.065  | 0.0596 | 0.0381    | 0.257 | 0.45     | 252±9       | 191±9       | 138±7       | 0.55±0.03 |
| 48  | 215±3       | 1.32±0.55                       | 0.066  | 0.0339 | 0.0443    | 0.116 | 0.241    | 257±3       | 211±3       | 185±3       | 0.72±0.01 |
| 51  | 150±3       | 2.2±0.9                         | 0.09   | 0.0319 | 0.0559    | 0.134 | 0.285    | 167±6       | 158±5       | 128±4       | 0.77±0.04 |
| 52  | 319±4       | 1.41±0.23                       | 0.052  | 0.0314 | 0.0352    | 0.249 | 0.495    | 378±14      | 336±14      | 255±12      | 0.67±0.04 |
| 63  | 93±3        | 2.96±0.61                       | 0.195  | 0.1172 | 0.0819    | 0.142 | 0.206    | 152±4       | 77±4        | 69±3        | 0.45±0.02 |
| 65  | 263±3       | 1.43±0.33                       | 0.058  | 0.0254 | 0.0266    | 0.224 | 0.454    | 296±5       | 290±5       | 213±5       | 0.72±0.02 |
| 87  | 274±4       | 1.33±0.07                       | 0.04   | 0.0613 | 0.0464    | 0.308 | 0.553    | 363±5       | 249±5       | 191±5       | 0.53±0.02 |
| 88  | 218±3       | 2.14±0.42                       | 0.057  | 0.0168 | 0.0306    | 0.169 | 0.374    | 241±13      | 221±12      | 195±12      | 0.81±0.07 |
| 89  | 140±3       | 3.0±2.2                         | 0.216  | 0.0525 | 0.0675    | 0.082 | 0.168    | 165±4       | 142±5       | 115±4       | 0.7±0.03  |
| 121 | 181±6       | 1.67±0.22                       | 0.056  | 0.0837 | 0.1028    | 0.3   | 0.46     | 245±5       | 177±5       | 116±5       | 0.47±0.02 |
| 128 | 163±5       | 1.5±0.8                         | 0.067  | 0.0253 | 0.0456    | 0.03  | 0.069    | 178±5       | 163±5       | 147±5       | 0.83±0.04 |
| 130 | 199±2       | 1.55±0.07                       | 0.067  | 0.0525 | 0.0441    | 0.283 | 0.507    | 268±8       | 195±9       | 153±9       | 0.57±0.04 |
| 145 | 144±3       | 1.52±0.21                       | 0.048  | 0.0311 | 0.0608    | 0.075 | 0.178    | 153±3       | 142±3       | 141±3       | 0.92±0.03 |
| 173 | 145±3       | 1.4±0.8                         | 0.061  | 0.0397 | 0.0553    | 0.219 | 0.461    | 162±8       | 152±8       | 123±8       | 0.76±0.06 |
| 187 | 141±2       | 1.28±0.22                       | 0.052  | 0.0439 | 0.0623    | 0.129 | 0.273    | 151±9       | 122±8       | 130±8       | 0.86±0.07 |
| 216 | 118±2       | 3.45±0.41                       | 0.152  | 0.2622 | 0.1305    | 0.559 | 0.33     | 267±6       | 61±6        | 48±6        | 0.18±0.02 |
| 230 | 118±2       | 2.7±1.3                         | 0.146  | 0.0374 | 0.0558    | 0.039 | 0.083    | 136±9       | 120±7       | 103±7       | 0.76±0.07 |
| 324 | 227±3       | 1.67±0.16                       | 0.06   | 0.0101 | 0.0304    | 0.036 | 0.087    | 234±9       | 224±9       | 225±7       | 0.96±0.05 |
| 354 | 165±3       | 3.18±1.14                       | 0.172  | 0.0345 | 0.0561    | 0.201 | 0.433    | 191±14      | 162±12      | 144±12      | 0.75±0.08 |
| 511 | 298±4       | 1.92±0.53                       | 0.063  | 0.0269 | 0.0305    | 0.224 | 0.464    | 359±18      | 293±20      | 253±17      | 0.7±0.06  |
| 704 | 332±5       | 1.84±0.28                       | 0.067  | 0.0109 | 0.0233    | 0.123 | 0.279    | 354±9       | 343±8       | 303±7       | 0.86±0.03 |

**Note:** N indicates the asteroid number,  $D$  is the volume-equivalent diameter,  $\rho$  is the bulk density. The geometric albedo, asphericity, ellipsoid deviation, specific angular momentum ( $H$ ) and normalized angular velocity ( $\Omega$ ) are then provided. Finally, we list the dimensions along the major axis of the best-fit triaxial ellipsoids ( $a > b > c$ ) as well as the  $c/a$  ratio. We also highlight the bodies that were visited by spacecrafts (\*) and from which some values are used.

## 5. Study of 42 large main belt asteroids – 5.3. Density

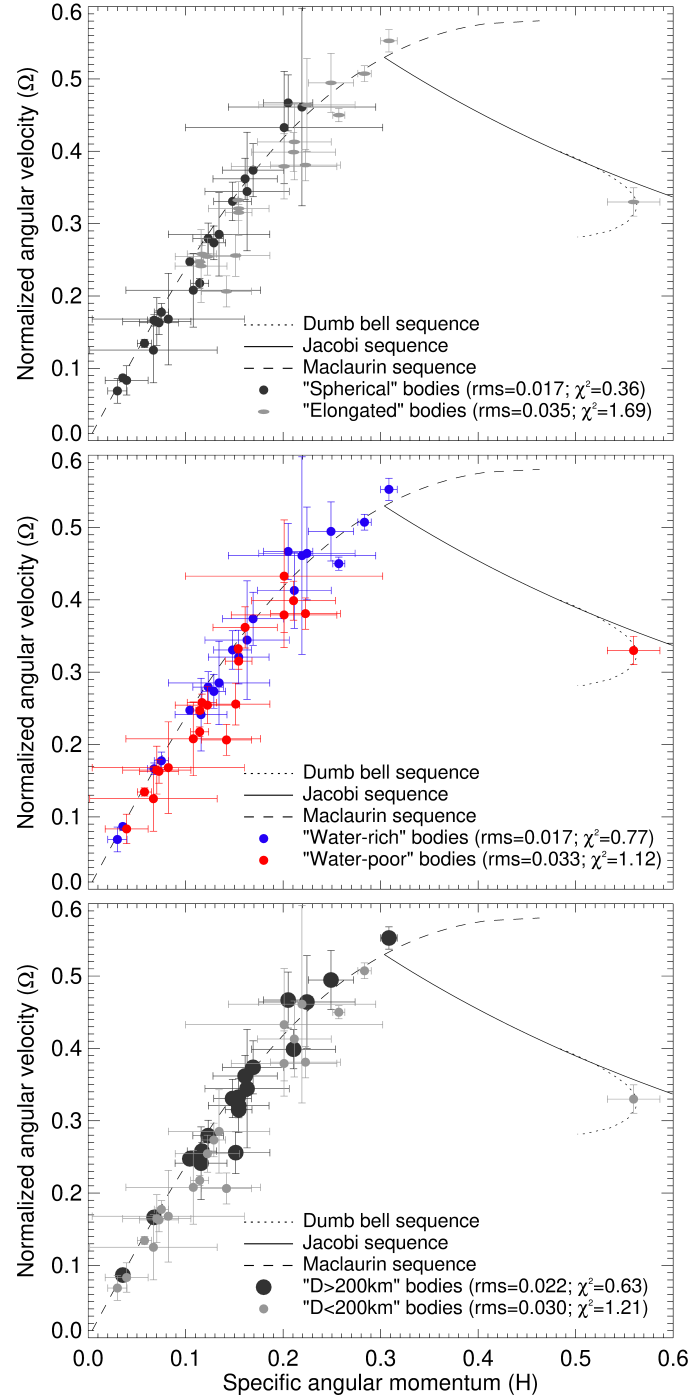


Figure 5.4.: Comparison of the specific angular momentum and the normalized angular velocity of our targets with the expected values for Maclaurin and Jacobi ellipsoids as well as dumb-bell shapes. *Upper panel:* Comparison between spherical and elongated bodies. *Middle panel:* Comparison between volatile-rich and -poor bodies. *Lower panel:* Comparison between the larger and the smaller bodies. Figure produced by P. Vernazza.

## 5. Study of 42 large main belt asteroids – 5.4. Conclusions

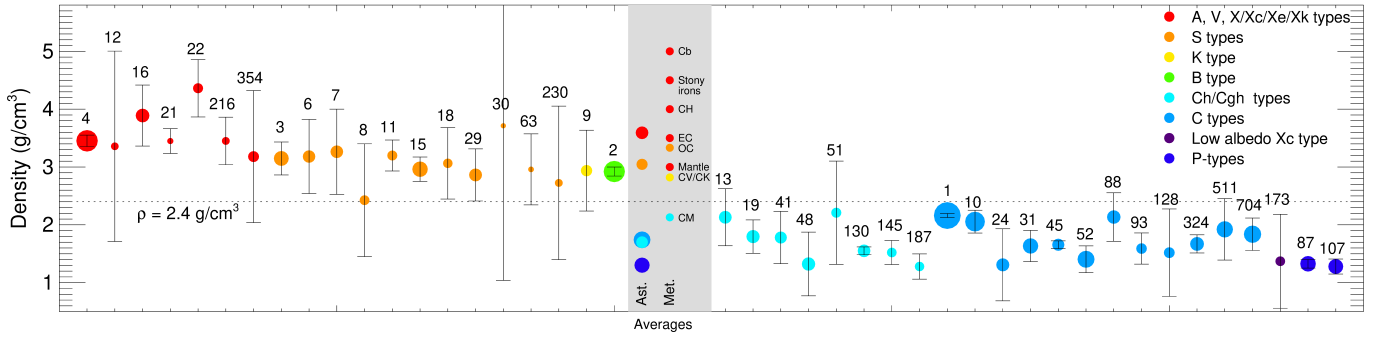


Figure 5.5.: Density distribution of the large program asteroid targets. Asteroids are grouped following their spectral classification, and their average density is compared to their likely meteoritic analogs in the center of the figure. Error bars correspond to one sigma values. Figure produced by P. Vernazza.

### 5.4. Conclusions

In this chapter we described the results of the application of the MPCD method to the SPHERE images obtained in the framework of the ESO large program imaging a sample of the largest MBAs, and the contributions that we brought to the analysis of the 3D shape of the objects.

MPCD 3D shape models were produced for 42 asteroids and compared to the ADAM models. Whereas the MPCD models fit better the observed images, the resulting volume-equivalent diameters are close to the ADAM values. Using the diameters from both methods, we derived new estimations of the bulk densities of all targets of the large program.

The shapes of our asteroid sample were analyzed. First, the measurement of the asphericity and the departure to an ellipsoid has highlighted a separation in two groups composed of more spherical bodies on the one hand, and of more elongated bodies in the other hand. Then, we computed the specific angular momentum and the normalized angular velocity of our targets. The results were then compared to the expected values for Maclaurin and Jacobi ellipsoids.

These results were further discussed in the synthesis paper of the large program (Vernazza et al., 2021, provided below), and used to better constrain the formation and evolution of the different compositional classes represented in our sample.

## 5.5. Final results and synthesis paper

### **VLT/SPHERE imaging survey of the largest main-belt asteroids: Final results and synthesis**

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# VLT/SPHERE imaging survey of the largest main-belt asteroids: Final results and synthesis<sup>★,★★,★★★</sup>

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## ABSTRACT

**Context.** Until recently, the 3D shape, and therefore density (when combining the volume estimate with available mass estimates), and surface topography of the vast majority of the largest ( $D \geq 100$  km) main-belt asteroids have remained poorly constrained. The improved capabilities of the SPHERE/ZIMPOL instrument have opened new doors into ground-based asteroid exploration.

**Aims.** To constrain the formation and evolution of a representative sample of large asteroids, we conducted a high-angular-resolution imaging survey of 42 large main-belt asteroids with VLT/SPHERE/ZIMPOL. Our asteroid sample comprises 39 bodies with  $D \geq 100$  km and in particular most  $D \geq 200$  km main-belt asteroids (20/23). Furthermore, it nicely reflects the compositional diversity present in the main belt as the sampled bodies belong to the following taxonomic classes: A, B, C, Ch/Cgh, E/M/X, K, P/T, S, and V.

**Methods.** The SPHERE/ZIMPOL images were first used to reconstruct the 3D shape of all targets with both the ADAM and MPCD reconstruction methods. We subsequently performed a detailed shape analysis and constrained the density of each target using available mass estimates including our own mass estimates in the case of multiple systems.

**Results.** The analysis of the reconstructed shapes allowed us to identify two families of objects as a function of their diameters, namely “spherical” and “elongated” bodies. A difference in rotation period appears to be the main origin of this bimodality. In addition, all but one object (216 Kleopatra) are located along the Maclaurin sequence with large volatile-rich bodies being the closest to the latter. Our results further reveal that the primaries of most multiple systems possess a rotation period of shorter than 6 h and an elongated shape ( $c/a \leq 0.65$ ). Densities in our sample range from  $\sim 1.3$  g cm<sup>-3</sup> (87 Sylvia) to  $\sim 4.3$  g cm<sup>-3</sup> (22 Kalliope). Furthermore, the density distribution appears to be strongly bimodal with volatile-poor ( $\rho \geq 2.7$  g cm<sup>-3</sup>) and volatile-rich ( $\rho \leq 2.2$  g cm<sup>-3</sup>) bodies. Finally, our survey along with previous observations provides evidence in support of the possibility that some C-complex bodies could be intrinsically related to IDP-like P- and D-type asteroids, representing different layers of a same body (C: core; P/D: outer shell). We therefore propose that P/D-types and some C-types may have the same origin in the primordial trans-Neptunian disk.

**Key words.** minor planets, asteroids: general – methods: observational – techniques: high angular resolution

## 1. Introduction

Before the advent of the SPHERE/ZIMPOL instrument at the VLT (Beuzit et al. 2019), only a handful of the largest main-belt asteroids (e.g., (1) Ceres, (2) Pallas, (4) Vesta, (52) Europa, (511) Davida) had been the subject of in-depth studies using the first-generation high-angular-resolution imaging systems operating in

the optical (HST) or in the near-infrared (NIR; VLT/NACO, Keck/NIRC2) (e.g., Thomas et al. 1997, 2005; Conrad et al. 2007; Carry et al. 2008, 2010; Schmidt et al. 2009; Merline et al. 2013). Although sparse, VLT/NACO and Keck/NIRC2 imaging data had been collected for many  $D \geq 100$  km asteroids, these data were rarely acquired with excellent seeing conditions and/or when the targets were at opposition, leading to suboptimal resolution for the observations of these bodies (Hanus et al. 2017). It follows that until recently, the 3D shape, and therefore density, (when combining the volume estimate with available mass estimates) and surface topography of the vast majority of the largest ( $D \geq 100$  km) main-belt asteroids have remained poorly constrained. The improved capabilities of the SPHERE/ZIMPOL instrument operating at the diffraction limit in the optical (angular resolution of  $\sim 20$  mas at 600 nm) have opened new doors into

\* Tables A.2 and A.3 are only available at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](https://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/654/A56>

\*\* Based on observations made with ESO Telescopes at the Paranal Observatory under programme ID 199.C-0074 (PI: P. Vernazza).

\*\*\* The reduced and deconvolved images as well as the 3D shape models are available at <https://observations.lam.fr/astero/>

<sup>†</sup> Deceased.



ground-based asteroid exploration, enabling investigation of the following fundamental questions:

- What is the diversity in shape among large asteroids and are the shapes close to equilibrium?
- How do large impacts affect asteroid shape?
- What is the bulk density of large asteroids and is there a relationship with their surface composition? Is there any evidence of differentiation among those bodies?
- Is the density of those bodies that are predicted to be implanted bodies from the outer Solar System (P/D-types) compatible with that of small ( $D \leq 300$  km) trans-Neptunian objects?
- What physical properties drive the formation of companions around large asteroids?

To shed some light on these questions, as part of an ESO large programme (199.C-0074; PI: P. Vernazza) conducted between May 2017 and September 2019, we have been carrying out disk-resolved observations with SPHERE/ZIMPOL of a substantial fraction of all  $D \geq 200$  km main-belt asteroids (20 of 23 objects) throughout their rotation. The three  $D \geq 200$  km asteroids absent from our list are 65 Cybele, 107 Camilla (already observed with SPHERE by Pajuelo et al. 2018), and 451 Patientia. Our survey also comprised 19 asteroids with  $100 \text{ km} \leq D \leq 200 \text{ km}$  and 3 objects with  $85 \text{ km} \leq D \leq 100 \text{ km}$ . Importantly, our survey covered the main compositional classes present in the main belt (A, B, C, Ch/Cgh, E/M/X, K, P/T, S, V; DeMeo et al. 2009).

So far, several targets of our observing program have already been the subject of dedicated papers (Vernazza et al. 2018; Viikinkoski et al. 2018; Fétick et al. 2019; Carry et al. 2019, 2021; Hanuš et al. 2019, 2020; Yang et al. 2020b; Ferrais et al. 2020; Marsset et al. 2020; Dudziński et al. 2020; Marchis et al. 2021; Brož et al. 2021) and we briefly summarize some of these findings below.

Our observations of (4) Vesta have allowed us to recover most of the main topographic features present across its surface, unveiled by the NASA Dawn mission (Fétick et al. 2019). This includes the south pole impact basin and its prominent central peak, several  $D \geq 25$  km-sized craters, and also Matronalia Rupes, including its steep scarp and its small and large arcs. Observations of (2) Pallas have revealed a heavily cratered “golf ball-like” surface that is most likely the consequence of its high inclination and eccentricity, which imply high-impact velocities on that body (Marsset et al. 2020). (10) Hygiea observations have revealed a basin-free spherical shape while it suffered a catastrophic disruption, which is at the origin of one of the largest asteroid families (Vernazza et al. 2020). Observations of (16) Psyche, the target of a forthcoming NASA discovery mission, imply a primordial shape close to that of a Jacobi ellipsoid and a density compatible with that of stony-iron meteorites (Viikinkoski et al. 2018; Ferrais et al. 2020). Observations of (31) Euphrosyne, the tenth largest asteroid, allowed the discovery of a satellite (Yang et al. 2020b) and observations of (41) Daphne and (87) Sylvia, two multiple systems, imply a homogeneous internal structure in the first case and a differentiated interior for Sylvia (Carry et al. 2019, 2021). Observations of (89) Julia, a  $D \sim 140$  km S-type asteroid and the parent body of a small collisional family that consists of 66 known members with  $D < 2.5$  km, have revealed the presence of an impact crater ( $\sim 75$  km wide) that could be the origin of this family (Vernazza et al. 2018). This particular case illustrates the progress made since the discovery by HST of Vesta’s south pole impact basin at the origin of its family. Finally, (216) Kleopatra observations

have allowed us to substantially revise its mass and volume estimates (Marchis et al. 2021; Brož et al. 2021). Furthermore, we showed that Kleopatra is the largest critically rotating asteroid, with the surface corresponding to the L1 equipotential.

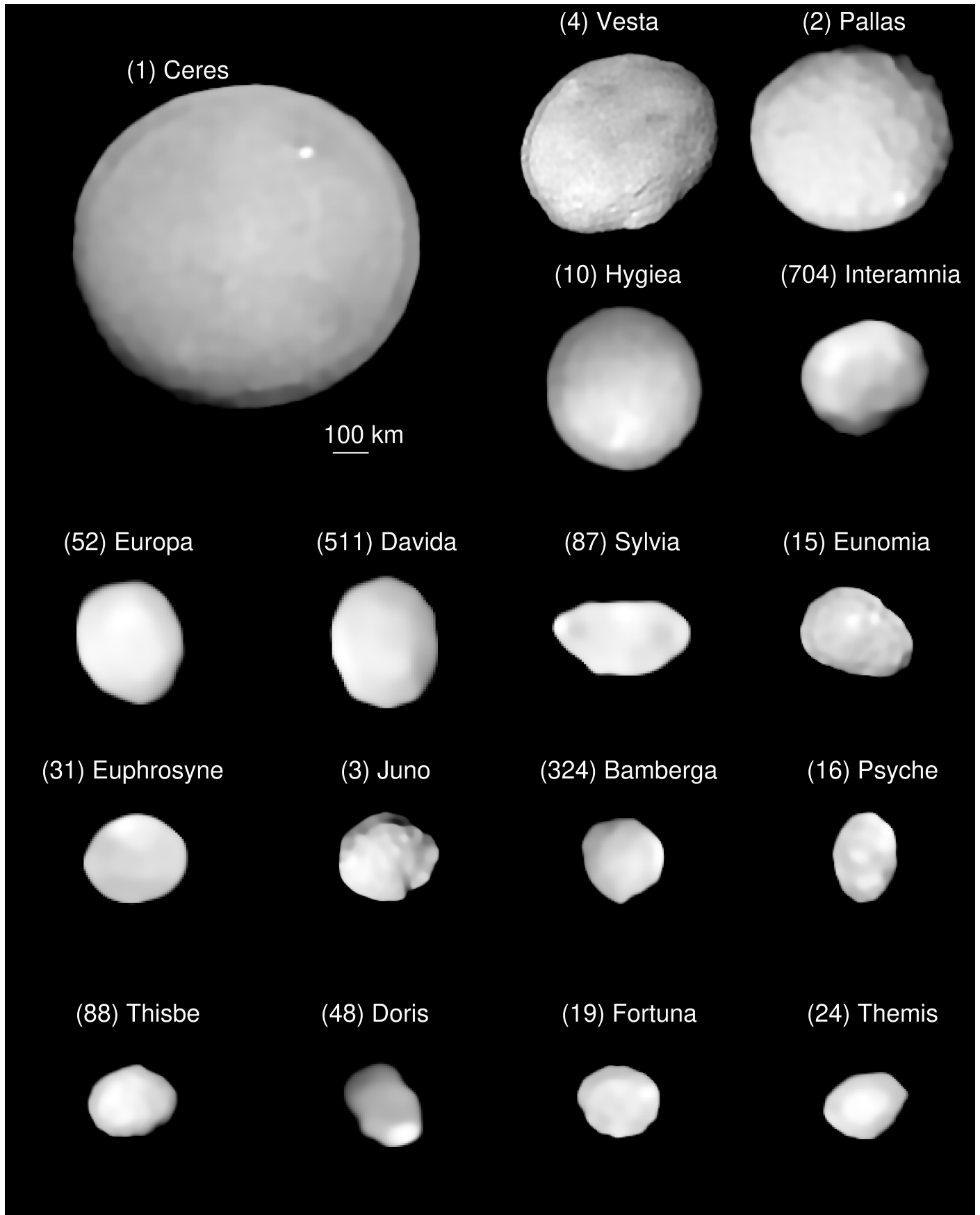
Here, we report all the data that have been acquired by our large programme, namely SPHERE/ZIMPOL images for 42 targets. These images have been used to reconstruct the 3D shape of all targets with both the All-Data Asteroid Modeling (ADAM) and the Multi-resolution PhotoClinometry by Deformation (MPCD) reconstruction methods (Capanna et al. 2013; Viikinkoski et al. 2015a; Jorda et al. 2016). We then present a shape analysis of our target sample as well as our best estimate of the density of our targets. Finally, we use these constraints to provide partial answers to the questions listed above.

## 2. Observations

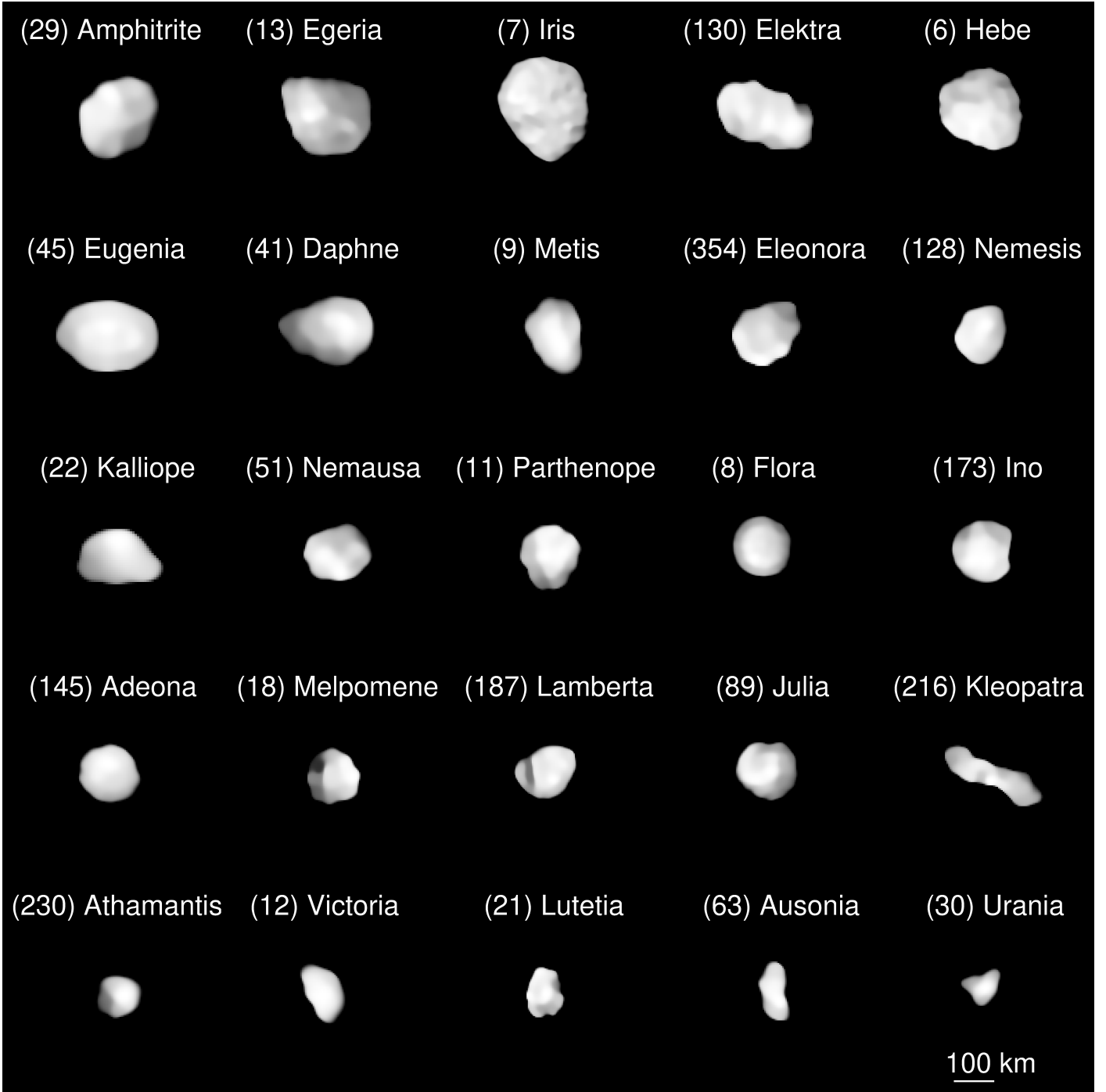
The baseline observational strategy adopted for our large programme has been to image each target with SPHERE/ZIMPOL (i) around opposition to ensure an optimal spatial resolution (we restricted the observing period so that its angular diameter remained greater than at least 85% of that at opposition), (ii) every  $\sim 60^\circ$  in rotation phase in order to obtain a satisfactory surface coverage, and (iii) with seeing conditions of better than  $0.8''$  and an airmass of below 1.6 in order to ensure great observing conditions and thus high-quality data. To fulfil these criteria and given that large programmes have the highest priority at ESO, we performed our large programme entirely in service mode. We would like to stress that this strategy has been key to the success of our programme.

Our full set of images provides a satisfactory rotational coverage (at least four epochs per target, with the objective being six epochs per target) for 39 asteroids (see Table A.2 for a complete list of all observations). All ZIMPOL observations were obtained in the narrowband imaging configuration ( $N_R$  filter; filter central wavelength = 645.9 nm, width = 56.7 nm). The observing strategy has been the same for all targets within our ESO large programme, namely the asteroid target was used as a natural guide star for AO correction during each series of images (five images per epoch).

These images were subsequently reduced (see Vernazza et al. 2018 for a description of the data-reduction steps) and deconvolved with the MISTRAL algorithm (Fusco et al. 2003; Mugnier et al. 2004) using a point-spread function (PSF). At the beginning of our observing programme, we were observing a stellar PSF either before or just after every asteroid observation. However, because the deconvolution with the stellar PSF was not systematically producing satisfactory results, we investigated alternative methods to increase the sharpness of the image. We noticed that in several cases, we reached a better result by using stellar PSFs acquired on different nights. We therefore tested the deconvolution process with synthetic PSFs modeled by a 2D Moffat function. The deconvolution always converged towards an acceptable solution by varying the Moffat parameters (Fétick et al. 2019). We therefore switched to a systematically parametric PSF to deconvolve our images (e.g., Fétick et al. 2019; Viikinkoski et al. 2018). Notably, the case of Vesta has confirmed the accuracy of our image-deconvolution algorithm (Fétick et al. 2019). Overall, the use of a parametric PSF has been highly beneficial for our programme as it left more observing time for our asteroid targets. In Fig. 1, we show one deconvolved image of every large programme target whereas Fig. A.1 shows one image per epoch for each target.



**Fig. 1.** (A) VLT/SPHERE images of all  $D > 210$  km asteroid targets deconvolved with the MISTRAL algorithm (Fusco et al. 2003). The relative sizes are respected, and the scale is indicated on the plot. The objects are ordered according to decreasing values of their volume equivalent diameter.



**Fig. 1.** continued. (B) VLT/SPHERE deconvolved images of all  $D < 210$  km asteroid targets with the MISTRAL algorithm (Fusco et al. 2003).

### 3. Determination of the 3D shape

Reconstruction of the 3D shape of our targets has always followed a well-defined scheme. Our SPHERE data along with light curve data have been used to constrain the rotational parameters (spin axis and period) and have allowed us to reconstruct a first 3D shape of every target with the ADAM model (Viikinkoski et al. 2015a). We used all available “dense-in-time” light curves from the DAMIT<sup>1</sup> database (Durech et al. 2010) and supplemented them with additional data either from a different source

(such as ALCDEF<sup>2</sup>) or based on our new observations. All light-curve data that were used for the reconstruction and that are not included in DAMIT are listed in Table A.3. We excluded the “sparse-in-time” data from surveys such as the Catalina Sky Survey for their redundancy as rich dense datasets are usually available. A large fraction of the listed data are based on observations from the SuperWASP survey that were processed by Grice et al. (2017). Photometry for several asteroids was obtained by the TRAPPIST telescopes (Jehin et al. 2011) and through the

<sup>1</sup> <https://astro.troja.mff.cuni.cz/projects/damit/>

<sup>2</sup> <https://minplanobs.org/alcddef/>

Gaia-GOSA<sup>3</sup> observing campaign. The strength of the ADAM model is that it makes use of all types of data (light curves but also stellar occultations when available), not just AO data. Given that the SPHERE data provide only a partial surface coverage for most of our targets, light-curve data were often necessary to constrain the uncovered aspect angles. We note that the SAGE model (Bartczak & Dudziński 2018), improved over the course of our large programme, has now the same type of strength as the ADAM model as it can constrain the spin axis and reconstruct the 3D shape of an asteroid using not only light curves but also AO data (Dudziński et al. 2020). We note that the SAGE model was key in constraining the rotational parameters of two targets (128 Nemesis and 324 Bamberga), illustrating the benefit of having multiple reconstruction methods.

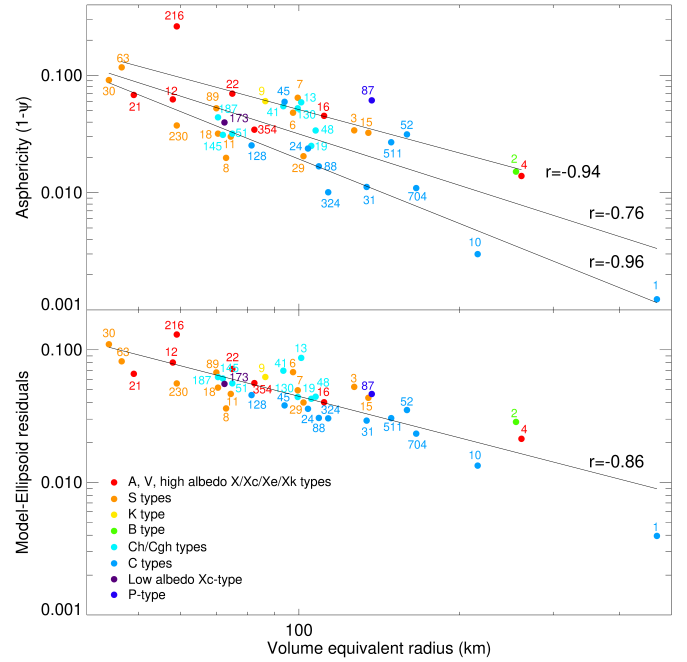
The 3D shape produced with the ADAM model was subsequently used as input to the MPCD model (Capanna et al. 2013). The strength of the MPCD method with respect to the ADAM or SAGE models is that it tries to capture small topographic details from the high-resolution SPHERE images. Unlike the ADAM and SAGE approaches, the MPCD method was designed for space missions and uses only SPHERE data along with a decimated version of the ADAM model as input. It is therefore not surprising that the images generated with the MPCD models using the OASIS software (Jorda et al. 2010) usually show the smallest residuals with respect to the SPHERE images (Appendix B). Nonetheless, the ADAM and MPCD models are systematically very close to each other and the rms residuals between the volume equivalent diameters estimated with both methods amounts to 1.6 km (0.8%). We also calculated the difference between the ADAM and MPCD equivalent diameters of all our targets to search for a possible bias between the two methods. The result amounts to  $\sim 1.0$  km, excluding a significant bias.

Importantly, our VLT/SPHERE observations of (1) Ceres (5 epochs) and (4) Vesta (6 epochs), targets of the Dawn mission, provide a direct demonstration of the accuracy of our approach. Despite the limited number of images for both objects, our inferred dimensions ( $a$ ,  $b$ ,  $c$  and the volume equivalent diameter) are accurate to within less than 3% and our derived volumes are accurate to within less than 0.4% of those derived from the Dawn observations (Russell et al. 2012, 2016). Although Ceres and Vesta are the two main-belt asteroids with the largest angular diameter, we are confident that our volume estimates for the remaining large programme targets should reach uncertainties of a few percent at most ( $\leq 10\%$ ). Indeed, our inferred values for the volume equivalent diameter of (21) Lutetia (one of the smallest targets within our observing programme) with the ADAM ( $D = 100 \pm 2$  km) and MPCD ( $D = 98 \pm 2$  km) models are compatible with that derived from the Rosetta observations ( $D = 98 \pm 2$  km) (Sierks et al. 2011).

Finally, we computed the geometric albedo of our targets using our diameter estimates in tandem with the most recent estimates of the absolute magnitude of these bodies (see Table 1).

#### 4. Shape analysis

The analysis of the shape of our targets was performed in the same way as described in Vernazza et al. (2020) and Ferrais et al. (2020). First, we calculated the sphericity index (Wadell 1935) of all targets, the latter being a function of the surface area and of



**Fig. 2.** *Upper panel:* asphericity of our large programme targets as a function of their volume equivalent radius. Both quantities appear highly correlated whereas the distribution of the asphericity as a function of target radius appears bimodal at first order (see Fig. 3). The correlation coefficient increases significantly when each subsample is considered separately. *Lower panel:* departure of the shape of our targets from their best-fit ellipsoid as a function of their volume equivalent radius. As in the case of the asphericity, both quantities appear highly correlated.

the volume. Second, we computed the radial differences between the shape models of our targets and their best-fitting ellipsoid, and derived the (model – ellipsoid) average residual relative to the mean radius (in %) for every object. The sphericity index as well as the (model – ellipsoid) average residual are reported for every target as a function of their volume equivalent radius in Fig. 2. A very strong correlation appears between both quantities and the volume equivalent radius of our targets ( $r = -0.76$  and  $r = -0.86$  for  $N = 42$  implying a  $>99.95\%$  confidence level that these correlations are not random). These correlations demonstrate that the size, and therefore the mass, is a key factor in determining the main aspects of the 3D shape of an asteroid (for the considered range of diameters).

Furthermore, the distribution of the sphericity index of our asteroid sample as a function of the volume equivalent radius appears to be bimodal at first order (see Fig. 3) and not continuous or unimodal. For each size bin, there appears to be a group of more spherical bodies and a group of more elongated objects (hereafter “spherical” and “elongated”). The dip test (Hartigan & Hartigan 1985), which measures multimodality in a sample by the maximum difference, over all sample points between the empirical distribution function and the unimodal distribution function that minimizes that maximum difference gives a 99.4% confidence level against unimodality. Of importance, all objects that are the largest remnants of a catastrophic disruption and thus likely formed via reaccumulation ((8) Flora, (10) Hygiea, (31) Euphrosyne) belong to the spherical group.

As the angular momentum is the determining factor of the oblateness of an object provided that it formed as a fluid (likely the case for many of our targets; see discussion), we first compared the  $c/a$  axes ratio of all targets to their rotation period. It

<sup>3</sup> <http://www.gaiagosa.eu/>

**Table 1.** Taxonomic type, volume-equivalent diameter ( $D$ ), mass ( $m$ ), density ( $\rho$ ), geometric albedo, and  $c/a$  ratio of our large programme targets.

| Asteroid       | Class | Family (F)<br>Satellite (S) | $D$<br>[km]     | $m$<br>[ $10^{18}$ kg] | $\rho$<br>[g cm $^{-3}$ ] | Albedo | $c/a$               |
|----------------|-------|-----------------------------|-----------------|------------------------|---------------------------|--------|---------------------|
| 1 Ceres (*)    | C     |                             | $939.4 \pm 0.2$ | $938.40 \pm 0.01$      | $2.161 \pm 0.001$         | 0.096  | $0.9247 \pm 0.0003$ |
| 2 Pallas       | B     | F                           | $511 \pm 4$     | $204.2 \pm 2.7$        | $2.92 \pm 0.08$           | 0.155  | $0.79 \pm 0.03$     |
| 3 Juno         | S     | F                           | $254 \pm 2$     | $27.0 \pm 2.4$         | $3.15 \pm 0.28$           | 0.202  | $0.78 \pm 0.02$     |
| 4 Vesta (*)    | V     | F                           | $523.2 \pm 0.2$ | $259.0 \pm 0.1$        | $3.453 \pm 0.004$         | 0.38   | $0.7769 \pm 0.0004$ |
| 6 Hebe         | S     |                             | $195 \pm 3$     | $12.4 \pm 2.4$         | $3.18 \pm 0.64$           | 0.268  | $0.75 \pm 0.04$     |
| 7 Iris         | S     |                             | $199 \pm 10$    | $13.5 \pm 2.3$         | $3.26 \pm 0.74$           | 0.279  | $0.58 \pm 0.07$     |
| 8 Flora        | S     | F                           | $146 \pm 2$     | $4.0 \pm 1.6$          | $2.4 \pm 1.0$             | 0.224  | $0.82 \pm 0.05$     |
| 9 Metis        | K     |                             | $173 \pm 2$     | $8.0 \pm 1.9$          | $2.94 \pm 0.70$           | 0.18   | $0.61 \pm 0.05$     |
| 10 Hygiea      | C     | F                           | $433 \pm 8$     | $87.4 \pm 6.9$         | $2.06 \pm 0.20$           | 0.063  | $0.94 \pm 0.05$     |
| 11 Parthenope  | S     | F                           | $149 \pm 2$     | $5.5 \pm 0.4$          | $3.20 \pm 0.27$           | 0.187  | $0.88 \pm 0.05$     |
| 12 Victoria    | A     |                             | $116 \pm 2$     | $2.7 \pm 1.3$          | $3.4 \pm 1.7$             | 0.167  | $0.69 \pm 0.03$     |
| 13 Egeria      | Ch    |                             | $202 \pm 3$     | $9.2 \pm 2.1$          | $2.13 \pm 0.49$           | 0.087  | $0.76 \pm 0.06$     |
| 15 Eunomia     | S     |                             | $270 \pm 3$     | $30.5 \pm 1.9$         | $2.96 \pm 0.21$           | 0.187  | $0.67 \pm 0.05$     |
| 16 Psyche      | M/Xk  |                             | $223 \pm 3$     | $22.6 \pm 2.9$         | $3.89 \pm 0.53$           | 0.155  | $0.59 \pm 0.02$     |
| 18 Melpomene   | S     |                             | $141 \pm 2$     | $4.5 \pm 0.9$          | $3.06 \pm 0.62$           | 0.221  | $0.81 \pm 0.06$     |
| 19 Fortuna     | Ch    |                             | $211 \pm 2$     | $8.8 \pm 1.4$          | $1.80 \pm 0.29$           | 0.056  | $0.79 \pm 0.05$     |
| 21 Lutetia (*) | M/Xc  |                             | $98 \pm 2$      | $1.70 \pm 0.02$        | $3.45 \pm 0.21$           | 0.194  | $0.65 \pm 0.03$     |
| 22 Kalliope    | M/X   | S                           | $150 \pm 5$     | $7.7 \pm 0.4$          | $4.36 \pm 0.50$           | 0.198  | $0.59 \pm 0.02$     |
| 24 Themis      | C     | F                           | $208 \pm 3$     | $6.2 \pm 2.9$          | $1.31 \pm 0.62$           | 0.06   | $0.76 \pm 0.08$     |
| 29 Amphitrite  | S     |                             | $204 \pm 2$     | $12.7 \pm 2.0$         | $2.86 \pm 0.45$           | 0.194  | $0.82 \pm 0.03$     |
| 30 Urania      | S     |                             | $88 \pm 2$      | $1.3 \pm 0.9$          | $3.7 \pm 2.7$             | 0.214  | $0.68 \pm 0.05$     |
| 31 Euphrosyne  | C     | F/S                         | $268 \pm 4$     | $16.5 \pm 2.6$         | $1.64 \pm 0.27$           | 0.05   | $0.86 \pm 0.07$     |
| 41 Daphne      | Ch    | S                           | $187 \pm 13$    | $6.1 \pm 0.9$          | $1.78 \pm 0.45$           | 0.052  | $0.65 \pm 0.08$     |
| 45 Eugenia     | C     | S                           | $188 \pm 2$     | $5.8 \pm 0.1$          | $1.66 \pm 0.07$           | 0.065  | $0.55 \pm 0.03$     |
| 48 Doris       | Ch    |                             | $215 \pm 3$     | $6.9 \pm 2.9$          | $1.32 \pm 0.55$           | 0.066  | $0.72 \pm 0.01$     |
| 51 Nemausa     | Cgh   |                             | $150 \pm 3$     | $3.9 \pm 1.6$          | $2.2 \pm 0.9$             | 0.09   | $0.77 \pm 0.04$     |
| 52 Europa      | C     |                             | $319 \pm 4$     | $23.9 \pm 3.8$         | $1.41 \pm 0.23$           | 0.052  | $0.67 \pm 0.04$     |
| 63 Ausonia     | S     |                             | $93 \pm 3$      | $1.2 \pm 0.2$          | $2.96 \pm 0.61$           | 0.195  | $0.45 \pm 0.02$     |
| 87 Sylvia      | X/P   | F/S                         | $274 \pm 4$     | $14.3 \pm 0.5$         | $1.33 \pm 0.07$           | 0.04   | $0.53 \pm 0.02$     |
| 88 Thisbe      | C     |                             | $218 \pm 3$     | $11.6 \pm 2.2$         | $2.14 \pm 0.42$           | 0.057  | $0.81 \pm 0.07$     |
| 89 Julia       | S     | F                           | $140 \pm 3$     | $4.3 \pm 3.2$          | $3.0 \pm 2.2$             | 0.216  | $0.7 \pm 0.03$      |
| 128 Nemesis    | C     | F                           | $163 \pm 5$     | $3.4 \pm 1.7$          | $1.5 \pm 0.8$             | 0.067  | $0.83 \pm 0.04$     |
| 130 Elektra    | Ch    | S                           | $199 \pm 2$     | $6.4 \pm 0.2$          | $1.55 \pm 0.07$           | 0.067  | $0.57 \pm 0.04$     |
| 145 Adeona     | Ch    | F                           | $144 \pm 3$     | $2.4 \pm 0.3$          | $1.52 \pm 0.21$           | 0.048  | $0.92 \pm 0.03$     |
| 173 Ino        | Xc    |                             | $145 \pm 3$     | $2.2 \pm 1.3$          | $1.4 \pm 0.8$             | 0.061  | $0.76 \pm 0.06$     |
| 187 Lambertia  | Ch    |                             | $141 \pm 2$     | $1.9 \pm 0.3$          | $1.28 \pm 0.22$           | 0.052  | $0.86 \pm 0.07$     |
| 216 Kleopatra  | M/Xe  | S                           | $118 \pm 2$     | $3.0 \pm 0.3$          | $3.45 \pm 0.41$           | 0.152  | $0.18 \pm 0.02$     |
| 230 Athamantis | S     |                             | $118 \pm 2$     | $2.3 \pm 1.1$          | $2.7 \pm 1.3$             | 0.146  | $0.76 \pm 0.07$     |
| 324 Bamberga   | C     |                             | $227 \pm 3$     | $10.2 \pm 0.9$         | $1.67 \pm 0.16$           | 0.06   | $0.96 \pm 0.05$     |
| 354 Eleonora   | A     |                             | $165 \pm 3$     | $7.5 \pm 2.7$          | $3.18 \pm 1.14$           | 0.172  | $0.75 \pm 0.08$     |
| 511 Davida     | C     |                             | $298 \pm 4$     | $26.6 \pm 7.3$         | $1.92 \pm 0.53$           | 0.063  | $0.7 \pm 0.06$      |
| 704 Interamnia | C     |                             | $332 \pm 5$     | $35.2 \pm 5.1$         | $1.84 \pm 0.28$           | 0.067  | $0.86 \pm 0.03$     |

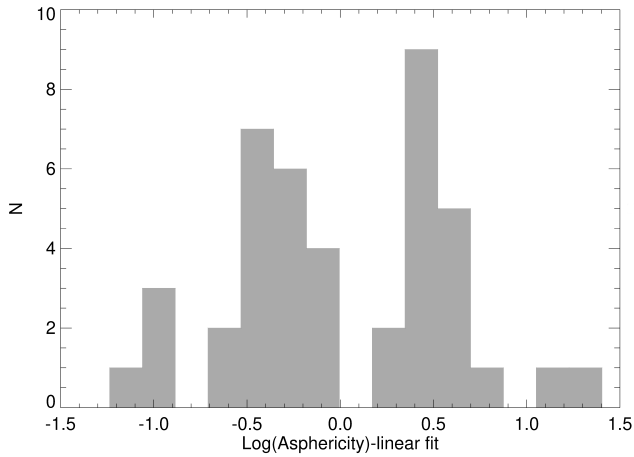
**Notes.** Uncertainties correspond to  $1\sigma$  values. We also highlight the bodies visited by spacecraft (\*), that are members of a collisional family (F) or that possess one or two satellites (S). Apart from the three targets visited by a space mission (Ceres, Vesta and Lutetia), all reported values were derived in the present study.

appears that both quantities are correlated ( $r=0.48$  for  $N=42$ , a 99.7% confidence level that this correlation is not random; Fig. 4). We notice that multiple systems tend to possess a rotation period below 6 h and a  $c/a$  axis ratio  $\leq 0.65$  (except 31 Euphrosyne). We also compared the distribution of the rotation period within the two groups of the bimodality (Fig. 5). It appears that on average, elongated objects possess a shorter rotation period (average: 6.4 h) with respect to more spherical bodies (average: 12.2 h). In particular, 16 out of the 18 (~89%) more elongated objects possess a rotation period of shorter than 8 h. However, the distribution of the more spherical bodies appears

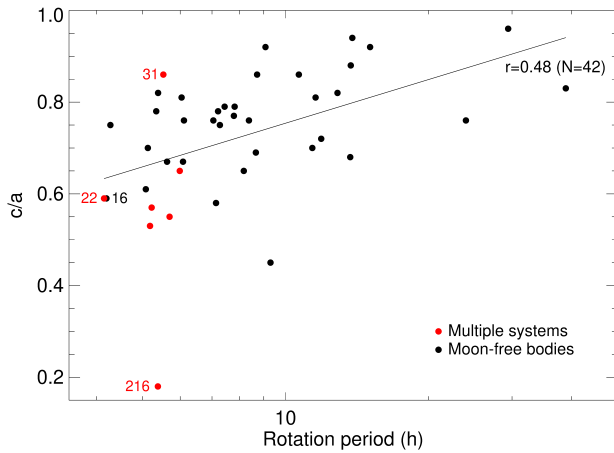
to be flat. This raises some questions regarding the origin of the spherical shape of some rapidly rotating bodies as for example in the case of (31) Euphrosyne (Yang et al. 2020b).

Finally, we compare the specific angular momentum and the normalized angular velocity of our targets (Descamps 2015) with the expected values for Maclaurin and Jacobi ellipsoids as well as dumb-bell shapes (Fig. 6). It appears that all but one of the bodies fall along the Maclaurin sequence. The only body falling onto the dumb-bell sequence is 216 Kleopatra. Next, we computed both the mean distance in the H and  $\Omega$  space (md) and the reduced chi-square to evaluate the impact of the





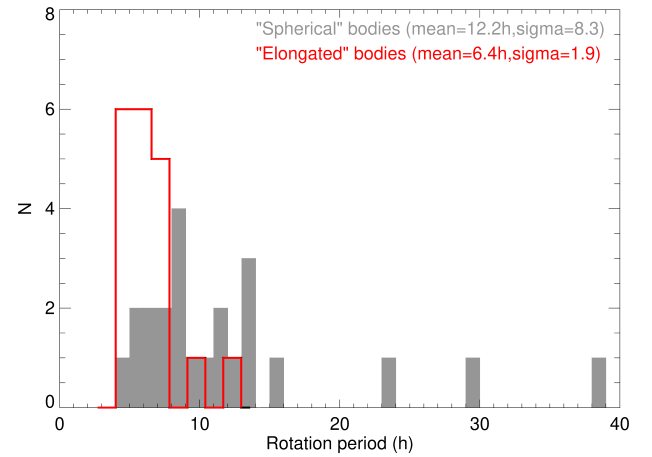
**Fig. 3.** Histogram of the distance between the asphericity of our targets and the linear best fit to the whole sample. The distribution appears bimodal at first order and the dip test rejects the unimodality of the distribution with a 99% confidence level.



**Fig. 4.** Relationship between the rotation period of large asteroids and their oblateness ( $c/a$  ratio). We observe a linear relation between both physical properties with a correlation coefficient of  $r=0.48$  ( $N=42$ ), a 99.8% confidence level that this correlation is not random. All multiple systems observed within our programme possess a rotation period of below 6h and a  $c/a$  axis ratio of below 0.65 except (31) Euphrosyne).

shape, bulk composition (density), and size on the distance of the bodies to the Maclaurin sequence. Concerning the calculation of the reduced chi-square, we removed both Ceres and Vesta from the computation because of their extremely small error bars compared to the other objects. It is interesting to note that:

- Spherical bodies ( $md=0.017$ ;  $\chi^2=0.36$ ) tend to be closer to the Maclaurin sequence than elongated bodies ( $md=0.035$ ;  $\chi^2=1.69$ ).
- Low-density ( $\rho \leq 2.2 \text{ g cm}^{-3}$ ) volatile-rich bodies ( $md=0.017$ ;  $\chi^2=0.77$ ) tend to be closer to the Maclaurin sequence than volatile-poor bodies with  $\rho \geq 2.7 \text{ g cm}^{-3}$  ( $md=0.033$ ;  $\chi^2=1.12$ ).
- Bodies with volume-equivalent diameters above 200 km ( $md=0.022$ ;  $\chi^2=0.63$ ) tend to be closer to the Maclaurin sequence than bodies with a volume-equivalent diameter of less than 200 km ( $md=0.030$ ;  $\chi^2=1.21$ ).

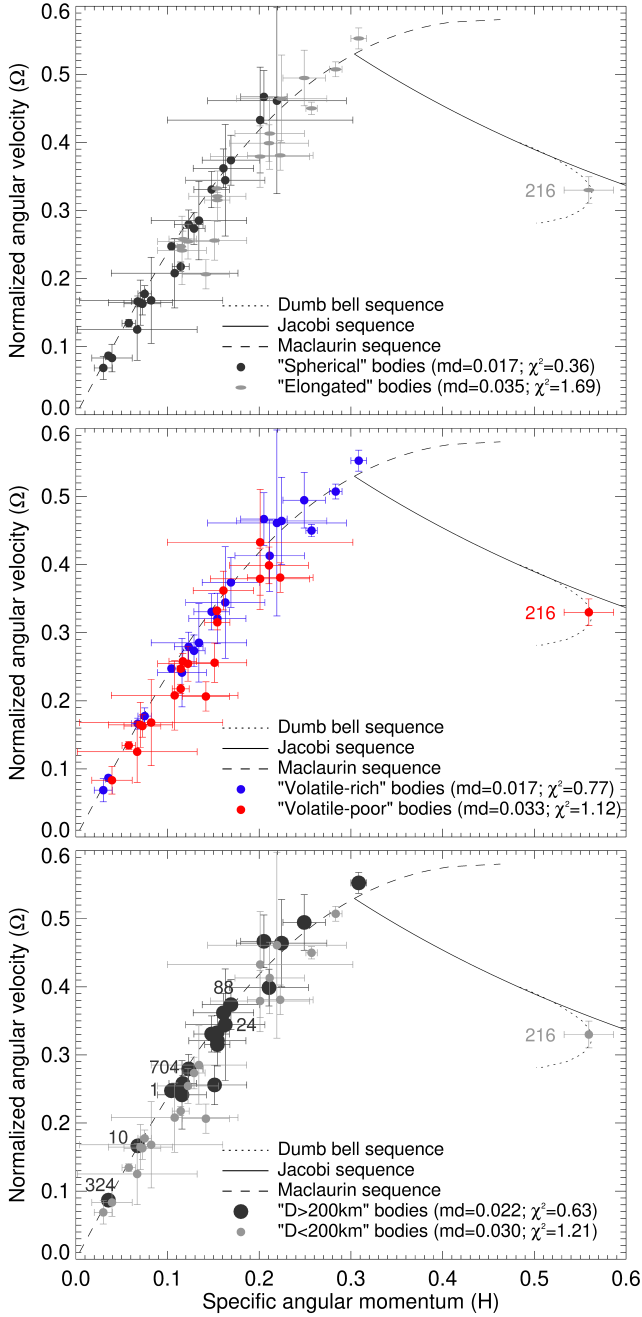


**Fig. 5.** Distribution of the rotation period of “elongated” and “spherical” bodies (see text). All but two “elongated” bodies possess a rotation period shorter than 8 h.

– In spite of large error bars, it appears that most objects in our sample (31/41) fall below the Maclaurin equilibrium curve. To ascertain that the bulk composition (density) and mass are both determining factors in the distance to the Maclaurin sequence, we computed the chi-square for  $D \geq 200$  km bodies ( $N=18$ ) by first removing four volatile-poor ( $\rho \geq 2.7 \text{ g cm}^{-3}$ ) bodies and then four volatile-rich ( $\rho \leq 2.2 \text{ g cm}^{-3}$ ) bodies. In the first case, the chi-square decreases to  $\sim 0.21$ , a value three times lower than that of the whole sample. In the second case, the chi-square increases to  $\sim 0.80$ , a value  $\sim 1.27$  times greater than that of the whole sample. This highlights the small contribution of volatile-rich bodies to the overall chi-square and the large contribution of volatile-poor bodies to the latter. Of great interest, there is a small fraction of bodies that appear the closest ( $\chi^2=0.0064$ ) to the Maclaurin sequence, namely large ( $D \geq 220$  km) volatile-rich bodies (excluding 31 Euphrosyne from the sample which is an odd case). This subpopulation (10 Hygiea, 24 Themis, 88 Thisbe, 324 Bamberga, 704 Interamnia), which only comprises spherical bodies, appears to be the main origin of the  $md$  and chi-square differences illustrated in the three panels of Fig. 6. In conclusion, both the bulk density (hence composition) and the mass of a body appear to be determining factors in its distance to the Maclaurin equilibrium figure with large volatile-rich bodies being by far the closest to the sequence.

## 5. Density

We computed the density of all targets using an average of available mass estimates and our derived volume equivalent diameters (Fig. 7). The volume equivalent diameters were determined as follows. For those targets whose surface coverage was lower than 80%, we relied on the ADAM diameter value only, whereas for the remaining cases (coverage  $\geq 80\%$ ) we computed the average of the ADAM and MPCD diameters. The mass estimates were determined as follows. For those objects with a large number of available mass estimates ( $\geq 10$ ), we included only the values within two sigma of the mean. For those objects with fewer estimates, we removed outlier values. In the case of three targets ((8) Flora, (128) Nemesis, (173) Ino) with mass estimates following a bimodal distribution, we selected the peak corresponding to the most meaningful density rather than the average value.



**Fig. 6.** Comparison of the specific angular momentum and the normalized angular velocity of our targets with the expected values for Maclaurin and Jacobi ellipsoids as well as dumb-bell shapes. Our targets are successively grouped as a function of their oblateness (*upper panel*), volatile content (*middle panel*), and size (*lower panel*). Both the mean distance (md) and chi-square of each group with respect to the Maclaurin sequence are indicated in each panel. We note that (216) Kleopatra is not included in these calculations. Large volatile-rich spherical bodies that fall very close to the Maclaurin sequence are highlighted in the bottom panel.

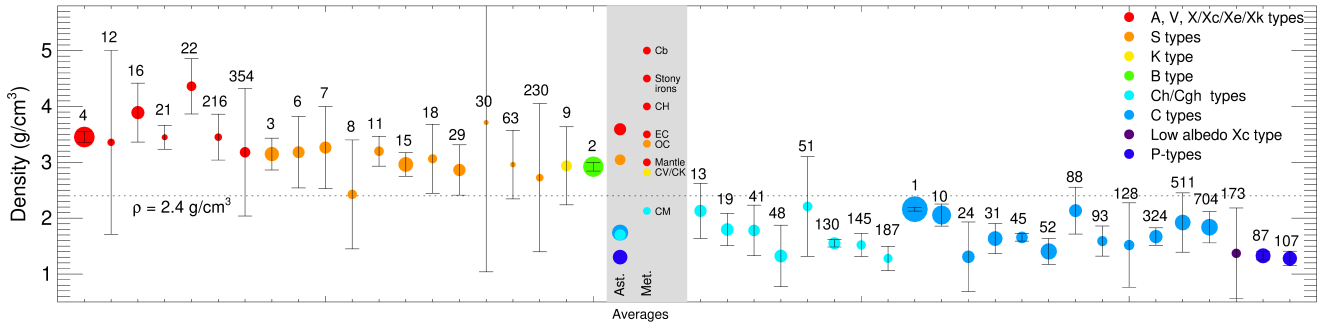
In most cases (asteroids without a companion), the error in density is largely dominated by the uncertainty of the mass estimate. We note that we added two  $D \geq 150$  km targets that are not part of the large programme (C-type (93) Minerva and P-type (107) Camilla; Marchis et al. 2013; Hanuš et al. 2017; Pajuelo et al. 2018) to Fig. 7 to slightly improve the statistics. The

density values for these two objects are robust given that they are multiple systems with well-defined masses and volumes.

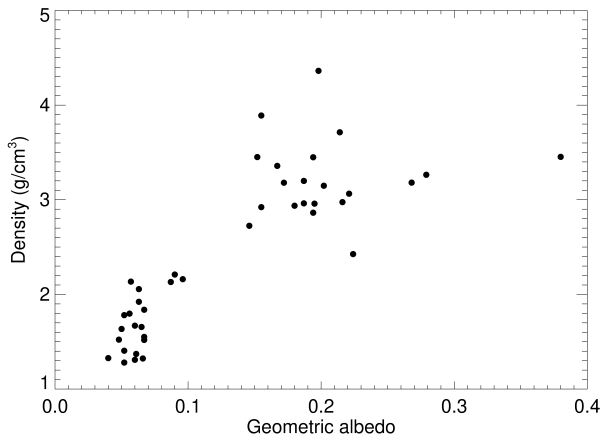
Densities in our sample range from  $\sim 1.3 \text{ g cm}^{-3}$  (P-type asteroids (87) Sylvia and (107) Camilla) to  $\sim 4.3 \text{ g cm}^{-3}$  (M/X-type asteroid (22) Kalliope), highlighting the wide diversity in composition of the asteroid belt. Notably, there is a clear difference in density (nearly a factor of two) between bodies affiliated to volatile-poor meteorites ( $\rho_{\text{mean}} = 3.26 \text{ g cm}^{-3}$  for A-, V-, high albedo X-, Xc-, Xe-, Xk- and S-type asteroids that are related to achondrites, stony iron meteorites, CB, CH, enstatite, and ordinary chondrites; Vernazza & Beck 2017) and bodies related to volatile-rich meteorites (CI/CM chondrites) and/or interplanetary dust particles ( $\rho_{\text{mean}} = 1.69 \text{ g cm}^{-3}$  for C-, Cgh-/Ch- and P-type asteroids; Vernazza et al. 2015a; Vernazza & Beck 2017). This dichotomy in density is confirmed by applying the dip test to our sample which gives a 99.1% confidence level against unimodality. Given that asteroid albedos also follow a bimodal distribution (Masiero et al. 2011), two main groups of asteroids emerge (Fig. 8), namely (a) asteroids with a geometric albedo below 0.1 and a density below  $2.2 \text{ g cm}^{-3}$  and (b) asteroids with a geometric albedo higher than 0.145 and a density greater than  $2.7 \text{ g cm}^{-3}$ . A simple explanation for this dichotomy may be the chondrule versus matrix content of these bodies. Indeed, low-albedo asteroids (C, P, D) have been mostly associated (based on spectroscopic observations) with chondrule-poor matrix-rich extra-terrestrial materials (CI and CM chondrites, Tagish Lake, IDPs) whose bulk density is significantly lower than that of chondrule-rich meteorites. Conversely, chondrule-rich extra-terrestrial materials (ordinary chondrites, enstatite chondrites, but also CV/CK chondrites) have been associated with asteroid types (S, E, M, K) that usually possess a geometric albedo of greater than 0.14. In short, the relative abundance of matrix and chondrules is perhaps the main origin of the observed dichotomy in addition to the carbon and volatile content.

As a next step, we computed the average and rms density of the main compositional classes (see Fig. 7). To estimate the amount of macroporosity within large asteroids, we restricted ourselves to the mean density of two major compositional classes (S and Ch/Cgh) that possess a well-identified meteoritic analog and that supposedly did not differentiate (Vernazza et al. 2014; Carry et al. 2019). Specifically, we assumed that ordinary chondrites are the meteoritic analogs of S-type asteroids (Vernazza et al. 2014, 2015b) and CM chondrites those of Ch/Cgh-types (Vernazza et al. 2016) and references therein). Asteroid densities appear systematically lower than those of their meteoritic analogs ( $\rho_S = 3.05 \text{ g cm}^{-3}$  versus  $\rho_{\text{OC}} = 3.33 \text{ g cm}^{-3}$ ,  $\rho_{\text{Ch/Cgh}} = 1.7 \text{ g cm}^{-3}$  versus  $\rho_{\text{CM}} = 2.13 \text{ g cm}^{-3}$ ; regarding meteorites, the bulk density is provided throughout the manuscript), implying the presence of some amount of macroporosity ( $\sim 8\%$  for S-types and  $\sim 20\%$  for Ch/Cgh-types) within these bodies. Furthermore, there is a small density trend within two major compositional classes (S and C types) where larger bodies (median diameters for large S and C-types: 204 km and 332 km respectively) possess higher densities on average with respect to smaller ones (median diameters for small S and C-types: 141 and 208 km respectively) ( $\rho_{\text{largeS}} = 3.08 \text{ g cm}^{-3}$ ,  $\rho_{\text{smallS}} = 3.01 \text{ g cm}^{-3}$ ,  $\rho_{\text{largeC}} = 1.84 \text{ g cm}^{-3}$ ,  $\rho_{\text{smallC}} = 1.65 \text{ g cm}^{-3}$ ). We note that the small variation in diameter within our Ch/Cgh sample in tandem with the large uncertainty of our mass estimates may explain why such a trend is not seen in that group. Overall, both a higher macroporosity value for Ch/Cgh-type bodies with respect to the more massive S-type bodies and the aforementioned





**Fig. 7.** Density distribution of our large programme asteroid targets. The density distribution appears strongly bimodal (see text) with volatile-poor bodies on the left of the gray zone and volatile-rich bodies on its right. Two multiple systems (93 Minerva and 107 Camilla; Marchis et al. 2013; Pajuelo et al. 2018) imaged outside of our observing program were also added because of their accurate density determination. Asteroids are grouped following their spectral classification. The relative sizes of the dots follow the relative diameters of the bodies in logarithmic scale. Error bars are one sigma. In the center of the figure, the gray zone shows the average density of the main asteroid groups (left) and of their likely meteoritic analogs (right).



**Fig. 8.** Relationship between the geometric albedo of large asteroids and their density. We observe two groups of objects: those with high albedos ( $\geq 0.14$ ) and densities ( $\geq 2.7 \text{ g cm}^{-3}$ ) and those with low albedos ( $\leq 0.1$ ) and densities ( $\leq 2.2 \text{ g cm}^{-3}$ ).

density trend between larger and smaller S- and C-type bodies suggest that the amount of macroporosity decreases with increasing size, and therefore mass, in agreement with the findings of Carry (2012). Finally, it appears that macroporosity is minimal ( $\leq 5\text{--}10\%$ ) for objects with masses  $\geq 10^{19} \text{ kg}$ .

## 6. Surface topography

As expected, the main topographic features observed in the images are impact craters and basins. Thanks to the unprecedented resolution of SPHERE/ZIMPOL, craters with minimum diameters of  $D \sim 25\text{--}70 \text{ km}$  (depending on the geocentric distance during the observations) could be detected from the ground for the first time. The most prominent ones are also captured in the reconstructed shape models (see Appendix B).

As outlined in Vernazza et al. (2020) in the cases of (10) Hygiea and (1) Ceres, there appears to be a crater dichotomy between volatile-poor and volatile-rich bodies which cannot solely be explained by the difference in heliocentric distance. As a matter of fact, volatile-rich bodies are located on average further away from the Sun than volatile-poor ones (typically a factor of 2 in geocentric distance and therefore surface resolution).

We interpret this dichotomy as a consequence of different crater morphologies on volatile-rich versus volatile-poor bodies. Whereas bowl-shaped craters are easily identifiable from the

ground, leading to a clear contrast between the crater floor and walls and the crater rim, the same is not true in the case of complex craters with a flat floor. Notably, impacts in volatile-poor surfaces form bowl-shaped craters up to much larger diameters than in the case of volatile-rich surfaces (e.g., Hiesinger et al. 2016). In the case of Ceres for example (Schenk et al. 2021), all craters with diameters above  $\sim 12 \text{ km}$  are complex (flat floored) which explains why craters can hardly be recognized in our images although Ceres' surface is saturated in craters. In contrast, several craters with diameters in the  $24\text{--}45 \text{ km}$  range could be easily identified in our images of (4) Vesta (Fétick et al. 2019) using observations from the Dawn mission as benchmark (Marchi et al. 2012).

Finally, the case of (2) Pallas (Marsset et al. 2020) has taught us that the inclination of the orbit of a body is a key parameter driving its collisional history (the higher the inclination, the more violent the collisional history because of higher mean impact velocities). A dedicated paper presenting an in-depth analysis of all impact craters detected by our survey is in preparation.

## 7. Discussion

In this section, we attempt to provide partial answers to the questions listed in the introduction based on data from our large programme.

### 7.1. What is the diversity in shapes among large asteroids and are the shapes close to equilibrium?

Apart from (216) Kleopatra and its dumb-bell shape (Marchis et al. 2021), all our targets with  $D > 100 \text{ km}$  possess shapes compatible with that of an ellipsoid and whose departure from a perfect ellipsoid strongly increases with decreasing size. Furthermore, the rotation period appears in most cases to be a determining factor in the resulting shape, with faster rotating bodies being more elongated than slower rotating objects. Along these lines, the rotation period is a key factor in the observed bimodality of the shapes (particularly true for objects with diameters above  $\sim 140 \text{ km}$ ), and separates increasingly spherical bodies from those that are more elongated. Except (216) Kleopatra, the shapes of all of the bodies are compatible with a Maclaurin equilibrium figure. We note that we cannot exclude that some bodies formed as Jacobi ellipsoids, as suggested in the case of (16) Psyche (Ferrais et al. 2020).

**Table 2.** Overview of the current knowledge regarding the surface and bulk composition of large asteroids ( $D > 100$  km) belonging to the main taxonomic classes.

| Asteroid type | Surface composition             | Families        | Bulk density        | Differentiated (yes/no)             |
|---------------|---------------------------------|-----------------|---------------------|-------------------------------------|
| S             | Ordinary chondrites             | Homogeneous     | Ordinary chondrites | No                                  |
| Ch/Cgh        | CM chondrites                   | Homogeneous     | CM chondrites       | No                                  |
| C/Cb/Cg       | Chondritic smooth IDPs ?        | Heterogeneous ? | <CM chondrites      | ?                                   |
| P             | Chondritic porous IDPs          | Heterogeneous   | <CI/TL              | Likely yes                          |
| M/X           | ECs, CB/CH, unsampled material? | ?               | <CB, >CH, >>EC      | Likely yes (21, 22)<br>16, 216: TBD |

However, only a handful of bodies are really close to the Maclaurin sequence ( $\chi^2 = 0.0064$ ). These are all large ( $D \geq 220$  km) volatile-rich ( $\rho \leq 2.2$  g cm $^{-3}$ ) bodies. The “equilibrium” shapes of large volatile-rich bodies may suggest that the interiors of these bodies had a fluid-like behavior until recent times, a likely consequence of their high content of volatiles and of thermal heating due to the decay of long-lived radionuclides (e.g., [Carry et al. 2021](#)) leading to continuous relaxation. The evolutionary history of these bodies may therefore have followed that of Ceres for which a paucity of large impact basins has been observed ([Marchi et al. 2016](#)), suggesting that the interiors and/or outer shells of these bodies have behaved like fluids (i.e., significantly relaxed) over long timescales. The fact that large volatile-poor bodies such as (2) Pallas and (4) Vesta depart from equilibrium can be understood as a direct consequence of an absence of recent relaxation and that they may no longer be geologically active. In their cases, late major impacts have excavated a fraction of their volume without affecting the rest of the overall shape, leading them to depart from the equilibrium figure. For smaller volatile-poor bodies, this mechanism is in competition with re-accumulation following a large catastrophic impact ([Vernazza et al. 2020](#); [Yang et al. 2020b](#)) which brings them closer to the Maclaurin equilibrium figure.

## 7.2. How do large impacts affect asteroid shape?

All objects in our survey ((8) Flora, (10) Hygiea, (31) Euphrosyne) that are members of a large collisional family that formed following a catastrophic disruption belong to the “spherical” group. Numerical simulations of such impact events ([Vernazza et al. 2020](#); [Yang et al. 2020b,a](#)) imply that the parent bodies were entirely disrupted and that the largest remnants formed via re-accumulation and that their shapes should be rather spherical, exactly as observed. In the case of smaller yet major impacts (e.g., (2) Pallas, (3) Juno, (4) Vesta), the shape is modified by the formation of large impact basins.

In summary, extremely large impacts reset the shapes of large asteroids and cause the shape to become roughly spherical and close to that of an ellipsoid. Conversely, smaller impacts cause the shape to become less spherical and to increase its departure from that of an ellipsoid.

## 7.3. What is the bulk density of large asteroids and is there a relationship with their surface composition? Is there any evidence of differentiation among those bodies?

Characterizing the density of the largest asteroids has been one of the main science objectives of our large programme. Indeed, density is the physical property that best constrains the bulk

composition of asteroids provided that their interiors contain a minimal fraction (<20%) of macroporosity. This is likely the case for the largest ( $D \geq 100$  km) asteroids whereas the interiors of smaller bodies ( $D \leq 100$  km) may be largely occupied by voids (reaching up to 50–60% in the case of the smallest bodies; e.g., [Carry 2012](#); [Scheeres et al. 2015](#)).

Our programme has confirmed the presence of a low level of macroporosity (<20%) in the interior of the largest asteroids with the latter becoming almost negligible ( $\leq 5\%$ ) in the interiors of the most massive bodies (with  $m \geq 10^{19}$  kg). However, this assumes that the bulk density of meteorites is representative of that of their parent bodies. Most importantly, our analysis reveals a strong dichotomy in density between volatile-poor ( $\rho = 3.26$  g cm $^{-3}$ ) and volatile-rich ( $\rho_S = 1.69$  g cm $^{-3}$ ) bodies.

Hereafter, we summarize the constraints delivered by our large programme regarding the bulk composition of the main taxonomic classes. Specifically, we combine our density measurements with previous spectroscopic observations of the surfaces of main-belt asteroids (including asteroid families) to constrain the formation and evolution of the main taxonomic classes (Table 2). We note that we do not discuss the case of our single V-type target Vesta here (see instead a review of the Dawn mission results by [Russell et al. 2015](#)) nor those of A- and K-type asteroids given the large uncertainties on their density estimates.

### 7.3.1. X, Xc, and Xe types

High-albedo ( $\rho_v \geq 0.15$ ) X/Xc/Xe-complex asteroids (which is the case of our four targets: (16) Psyche, (21) Lutetia, (22) Kalliope, (216) Kleopatra) likely comprise the parent bodies of (1) iron meteorites (e.g., [Cloutis et al. 1990](#); [Shepard et al. 2015](#) and references therein), (2) enstatite chondrites (ECs), and aubrites (e.g., [Vernazza et al. 2009, 2011](#); [Ockert-Bell et al. 2010](#); [Shepard et al. 2015](#)), (3) CB and CH chondrites (e.g., [Hardersen et al. 2011](#); [Shepard et al. 2015](#); [Krämer Ruggiu et al. 2021](#)), and (4) anomalous metal-rich chondrites (e.g., [Reddy et al. 2019](#)). While stony-iron meteorites (mesosiderites, pallasites) could be plausible analogs for these asteroid types because of their similarity in density, their spectral properties appear to be at odds with those of these asteroid types (Ferrais et al., in prep.). We therefore consider it highly unlikely that these meteorites are analogs of these asteroid types. Pallasites are likely analogs of A-type asteroids ([Cruikshank & Hartmann 1984](#); [Sunshine et al. 2007](#)), whereas mesosiderites may be analogs of V-type asteroids (e.g., [Burbine et al. 2007](#), Ferrais et al., in prep.).

Besides Lutetia, which has been associated with enstatite chondrites ([Vernazza et al. 2009, 2011](#)), none of the remaining

asteroids possess a well-identified meteoritic analog in terms of surface composition (we note that the Lutetia-EC association cannot be considered as unquestionable). However, the densities derived by our survey are strong evidence at this stage that iron is neither the representative material of the surfaces of these asteroids, as implied by radar observations (Shepard et al. 2015, 2017, 2018) nor of their bulk composition. In addition, there is great variability in the metal content of the surfaces of these objects. Specifically, two of our X-complex targets possess a low radar albedo (Lutetia and Kalliope have a radar albedo in the 0.18–0.24 range; Shepard et al. 2015) whereas the remaining two targets possess a high radar albedo (Psyche and Kleopatra have a radar albedo in the 0.37–0.43 range; Shepard et al. 2017, 2018). Finally, three of these bodies show evidence of a  $\sim 0.9$  micron and/or  $\sim 3$  micron feature (Psyche, Kalliope and Kleopatra; Hardersen et al. 2011; Usui et al. 2019) whereas Lutetia is featureless in the visible and NIR range (e.g., Vernazza et al. 2011).

Our density estimates for our four X-complex targets are amongst the highest measured so far for main-belt asteroids, with both Kalliope and Psyche being the two densest bodies known so far after the telluric planets. If one considers that the amount of porosity of a high-density  $D \sim 100$  km body (Lutetia, Kleopatra) should be in the 15–25% range whereas it should be below 10% for a  $D \geq 150$  km body (Psyche, Kalliope), then the average density of the materials making up these bodies should be in the  $\sim 4.0$ – $4.8$  g cm $^{-3}$  range. In the case of Lutetia, assuming an EC-like surface composition ( $\rho_{EC} = 3.45$ – $3.80$  g cm $^{-3}$ ; Macke et al. 2010), a denser interior may be implied, and therefore a thermal history including differentiation (Vernazza et al. 2011; Weiss & Elkins-Tanton 2013). A similar thermal history has also been proposed in the case of Kalliope (Ferrais et al., in prep.). For the remaining bodies, CH chondrites or a mixture of CH and CB chondrites (Ferrais et al., in prep.) may be plausible analogs, whereas CB chondrites alone seem excluded given their high density ( $\rho_{CB} \sim 5$  g cm $^{-3}$ ; Macke et al. 2011). It might also be the case that no representative meteorites are available in our collections for these bodies. We therefore cannot presently exclude that both Kleopatra and Psyche are undifferentiated bodies.

Regarding the formation location of our four X-complex targets, the latter may be diverse. The connection between Lutetia and enstatite chondrites favors an origin in the terrestrial planet region (Vernazza et al. 2011). However, most large M-types, including (16) Psyche and (22) Kalliope, are located in the outer part of the asteroid belt (Gradie & Tedesco 1982; DeMeo & Carry 2013, 2014). Yet, the bodies scattered from the terrestrial planet region into the main belt are preferentially implanted in the inner and middle belt (Raymond & Izidoro 2017), likely precluding an inner Solar System origin for most large metal-rich bodies.

Finally, laboratory analyses of CB/CH chondrites and anomalous metal-rich chondrites should be a main focus in the near future for a more accurate understanding of the composition and overall thermal history of these bodies.

### 7.3.2. S-types

S-type asteroids comprise the parent bodies of the most common type of meteorites, namely ordinary chondrites ( $\sim 80\%$  of the falls), and also possibly those of some rare types of differentiated meteorites such as lodranites and acapulcoites (see Vernazza et al. 2015b for a detailed review on this topic). Vernazza et al. (2014) analyzed the visible and NIR spectral properties of nearly 100 S-type asteroids among which all our S-type targets are

found. These authors discovered that the surface composition of these bodies is compatible with that of H, L, and LL ordinary chondrites. Furthermore, they reported little compositional variation amongst the largest S-type collisional families, suggesting a rather homogeneous internal structure for the largest S-type asteroids.

Our derived densities for the largest S-type asteroids are consistent with those of ordinary chondrites and some level of macroporosity ( $\leq 10\%$ ; see also Viikinkoski et al. 2015b; Marsset et al. 2017; Hanuš et al. 2019; Dudziński et al. 2020), implying – contrary to asteroid (4) Vesta – the absence of large-scale differentiation for these bodies, which is in agreement with both spectroscopic observations (Vernazza et al. 2014) and the thermal history of ordinary chondrites (Huss et al. 2006; Monnereau et al. 2013).

### 7.3.3. B-type (2) Pallas

The true nature and origin of (2) Pallas remains a mystery despite the breathtaking images acquired for that object within our large programme (Marsset et al. 2020). Its spectral properties in the visible and NIR, including its  $\sim 2.7$   $\mu$ m hydration feature (e.g., Takir & Emery 2012; Usui et al. 2019), are unlike those of any meteorite in our collection but suggest a connection to low albedo C-complex asteroids. In contrast, both its geometric albedo (0.155) and its density ( $2.92$  g cm $^{-3}$ ) bring Pallas closer to rocky bodies (Marsset et al. 2020), in particular S-type asteroids.

A sample return mission to that object or to one of its family members currently appears to be a necessary future step for deciphering its formation and evolution unless a meteorite originating from Pallas is recovered in the coming years.

### 7.3.4. Ch/Cgh-types

Ch- and Cgh-type asteroids comprise the parent bodies of CM chondrites (Vilas & Gaffey 1989; Vernazza et al. 2016 and references therein). An analysis of the visible and NIR spectral properties of 70 of these bodies was reported by Vernazza et al. (2016), among which all our Ch/Cgh targets are found, as well as the members of some of the largest collisional families. These latter authors showed that the spectral variation observed among these bodies is mostly due to variations in the average regolith grain size. In addition, they showed that the spectral properties of the vast majority (unheated) of CM chondrites resemble those of both the surfaces of the largest bodies and those of the smaller family members, implying a homogeneous internal structure and a “low” temperature ( $< 300^\circ\text{C}$ ) thermal evolution of the CM parent body(ies) (Vernazza et al. 2016).

Our derived densities for the largest CM-like bodies are consistent with those of CM chondrites and some level of macroporosity (15–20%), suggesting a homogeneous internal structure for these bodies (Carry et al. 2019), in agreement with spectroscopic observations and numerical simulations of the thermal history of CM chondrite parent bodies (Bland & Travis 2017; Neveu & Vernazza 2019).

### 7.3.5. C-types

The surfaces of C-type asteroids, including Ceres, appear unsampled by our meteorite collections, similar to P- and D-type asteroids (Vernazza et al. 2015a, 2017). Notably, these abundant asteroid types (DeMeo & Carry 2013) comprise – similarly to S-types – a high number of large asteroid families such as the Hygiea, Themis, Euphrosyne, Nemesis, and Polana-Eulalia



families (see Brož et al. 2013; Nesvorný et al. 2015 for further information on asteroid families). Considering that asteroid families are a major source of meteorites (this is well supported by the connection between the Vesta family and the HED meteorites), we should be receiving plenty of fragments from these bodies. Nevertheless, this seems not to be the case for their surface material, at least not under the form of consolidated meteorites. We note that metamorphosed CI/CM chondrites have been proposed in the past as analogs of C-, Cb-, and Cg-type surfaces (Hiroi et al. 1993). However, such a possibility presently appears untenable (Vernazza et al. 2015a).

Vernazza et al. (2015a) proposed that these asteroid types might (at least their surfaces and/or outer shells) consist largely of friable materials unlikely to survive atmospheric entry as macroscopic bodies. It may therefore not be surprising that these asteroid types are not well represented by the cohesive meteorites in our collections. Vernazza et al. (2015a) proposed that interplanetary dust particles (IDPs) as well as volatiles may, similarly to comets, be more appropriate analogs for these bodies (at least their surfaces and/or outer shells).

Given the lack of well-identified extra-terrestrial analogs for these bodies, it follows that most of our knowledge regarding the origin, formation, and evolution of these bodies is rather limited and so far comes from remote-sensing observations only. Spectroscopic observations of these bodies in the  $3\mu\text{m}$  region (Takir & Emery 2012; Usui et al. 2019) have allowed their surface compositions and thermal histories to be refined. It appears that most of the large C-type asteroids are found to possess a  $\sim 2.7\mu\text{m}$  feature associated with the presence of hydrated minerals at their surfaces (Usui et al. 2019). This implies that their present outer shell has witnessed aqueous alteration. Furthermore, visible and NIR spectroscopic observations of two major C-type collisional families (Themis and Euphrosyne; Marsset et al. 2016; Yang et al. 2020a) indicate some degree of spectral variation (from C to P/X) that may hint at a primordial heterogeneous internal structure of their parent bodies (Marsset et al. 2016).

Our derived average density for C-type asteroids ( $1.74\text{ g cm}^{-3}$ ) is the same within uncertainties as that of CM-like C-types ( $1.70\text{ g cm}^{-3}$ ). However, the average diameter of our C-type targets is 313 km, whereas this is 181 km for CM-like C-types, and the factor difference in average mass between the two C-type groups is  $\sim 5$ . It follows that the average macroporosity may be significantly reduced in the interiors of our C-type targets with respect to the 20% value inferred for our CM-like targets (see Sect. 5). Given that the average mass of our C-type targets is comparable to that of our S-type sample, we assume by direct analogy an average macroporosity of at most 10% for our C-type sample leading to a maximum density of the analog material of  $1.97\text{ g cm}^{-3}$ . This implies an average bulk composition for large C types that likely consists of material that is less dense than CM chondrites ( $\rho_{\text{CM}} = 2.13\text{ g cm}^{-3}$ ). Such material may contain (i) more microporosity due in some cases to more limited aqueous alteration of the interior, (ii) fewer chondrules by analogy with the less dense CI chondrites and/or the Tagish Lake meteorite (whose density amounts to  $\sim 1.6\text{ g cm}^{-3}$ ), and/or (iii) more volatiles and/or water. In any case, thermally metamorphosed volatile-poor CI/CM chondrites appear as unlikely analogs for these bodies based on our density estimates.

Notably, there are some major differences in density among the largest C-types (with  $D \geq 300\text{ km}$ ) with densities ranging between  $\sim 1.5\text{ g cm}^{-3}$  (52 Europa) and  $2.16\text{ g cm}^{-3}$  (1 Ceres) and for which the macroporosity may be negligible. We speculate that the thermal histories of these bodies may be an important

factor at the origin of these density differences and that the denser targets may have a more lithified (*cemented*) interior due to aqueous alteration. Indeed, all large C-types with higher densities (Ceres, Hygiea, Interamnia, Davida) possess a well-defined  $2.7\mu\text{m}$  band in their spectra (Usui et al. 2019) implying the presence of hydrated minerals at their surfaces, whereas such a band is nearly absent or significantly shallower in the spectrum of (52) Europa. This may imply that Europa may have a partially aqueously altered interior whereas the four other objects experienced significant aqueous alteration up to their current surface. Considering C/P-type objects with similar diameters and masses, both features (a lower density and a less hydrated surface) place (52) Europa in between P-type asteroid (87) Sylvia and C-complex asteroids Interamnia and Davida (see Sect. 7.4 for possible implications). Finally, Ceres' density is abnormally high ( $2.16\text{ g cm}^{-3}$ ; Russell et al. 2016) compared to the average density of Hygiea, Interamnia, and Davida ( $1.94\text{ g cm}^{-3}$ ) on the one hand, and that of Callisto, Ganymede, Pluto, and Charon (in the  $1.71\text{--}1.93\text{ g cm}^{-3}$  range) on the other hand. This suggests the possibility of loss of volatile material in the case of Ceres. The scenario in which Ceres once possessed an icy shell of  $\sim 30\text{--}50\text{ km}$  in thickness as a consequence of its early thermal evolution that was lost following its implantation in the asteroid belt (Castillo-Rogez et al. 2016) has some merit following our results. For instance, a 30 km icy shell would imply a primordial density of  $\sim 2.05\text{ g cm}^{-3}$  for Ceres, still higher than that of the other large C-types.

### 7.3.6. P-types

P- and D-type asteroids represent the vast majority of the Jupiter Trojans and about 10% of all main-belt asteroids (DeMeo & Carry 2013, 2014). Their visible, NIR, and MIR spectral properties resemble those of comets (Emery et al. 2006; Vernazza et al. 2015a; Vernazza & Beck 2017) implying a similar surface composition (at least for the silicate component). So far, chondritic porous interplanetary dust particles appear to be the most likely representative samples of the surface material of these bodies (Vernazza et al. 2015a; Vernazza & Beck 2017). In particular, the volatile-rich Tagish Lake meteorite appears to be non-representative of the surface composition of most P- and D-type asteroids with well-characterised NIR and MIR spectral properties as suggested earlier (Hiroi et al. 2001). So far, only one P-type asteroid has been tentatively linked to that meteorite, namely 368 Haidea (Vernazza et al. 2013). Spectroscopic observations in the  $3\mu\text{m}$  region have revealed that most P-type and all D-type asteroids possess an anhydrous surface composition (Takir & Emery 2012; Usui et al. 2019) which contrasts with the aqueously altered surfaces of C-complex asteroids. Notably, the spectral characterisation of the members of the Eurybates family, the largest collisional family among the Jupiter Trojans (P/D types), has revealed significant spectral variety (Fornasier et al. 2007; De Luise et al. 2010), with about half of the family members being C-types and the remaining objects being P-types. These observations could suggest that P-/D-type asteroids did differentiate and that their cores may consist of C-type-like material (Vernazza et al. 2017).

Our observations of triple P-type asteroid (87) Sylvia likely imply the presence of a core, and therefore a differentiated internal structure (Carry et al. 2021). Sylvia's low density and likely differentiated interior can be explained by partial melting and mass redistribution through water percolation. The outer shell would be composed of material similar to interplanetary dust particles (IDPs) and the core similar to aqueously altered IDPs or

carbonaceous chondrite meteorites. By analogy with the Eurybates family, the core may have spectral properties similar to those of C-type asteroids. In the case of (87) Sylvia, our density estimate for its  $D \sim 200$  km large core amounts to  $\sim 1.7 \text{ g cm}^{-3}$ , a value consistent with the density of C-type asteroids. Finally, a differentiated interior has also been advocated in the case of the second largest P-type asteroid (107) Camilla (Pajuelo et al. 2018).

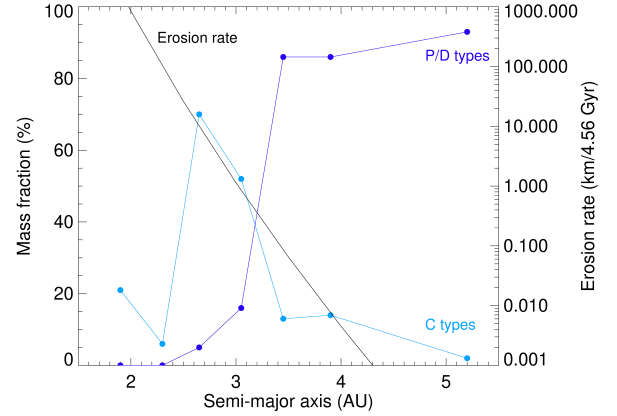
#### 7.4. Does the main asteroid belt comprise former trans-Neptunian objects and do we recognize all of them?

The Nice model, which invokes an outward migration of Uranus and Neptune (Tsiganis et al. 2005; Morbidelli et al. 2005; Levison et al. 2009), implies that the P/D- type main-belt asteroids (and thus P/D near-Earth asteroids) and the Trojans of Jupiter likely have the same origin as outer Solar System small bodies such as Centaurs, short-period comets, and small ( $D \leq 300$  km) trans-Neptunian objects. Available spectroscopic observations of these populations as well as the similarity in size distributions between the Jupiter Trojans and trans-Neptunian objects (Fraser et al. 2014) support such a hypothesis.

Our density estimate of P-type (87) Sylvia (Carry et al. 2021) as well as that of (107) Camilla (Pajuelo et al. 2018) appear compatible with those of several  $D \leq 300$  km TNOs (Brown 2013; Kovalenko et al. 2017) providing support for a direct link between P/D types and TNOs. However, the same applies for C-type asteroids. Based on our density estimates for all C-complex bodies, we cannot discard a link between these asteroid types and current TNOs. We note the existence of a few TNOs with extremely low densities (Brown 2013; Kovalenko et al. 2017) whose counterparts were not identified by our survey of main-belt asteroids.

Based on our density estimates and spectrophotometric observations, which we detail below, we speculate that many of the C-types could be former TNOs and that these C-types may simply represent the aqueously altered version of primordial P/D-type material. Here is a list of measurements that support such an idea:

- Large ( $D \geq 130$  km) P-types likely partially differentiated (Pajuelo et al. 2018; Carry et al. 2021) and their interior (core) may not simply have a C-type-like density (typically  $1.7 \text{ g cm}^{-3}$ ; Carry et al. 2021) but also C-type spectral properties as suggested by the spectroscopic observations of the Eurybates family (Fornasier et al. 2007; De Luise et al. 2010). We note that spectroscopic observations of two large C-type families in the outer belt (Themis, Euphrosyne) show a mix of C- and P-types bodies, and therefore a similar spectral heterogeneity as observed in the case of the Eurybates family (Marsset et al. 2016; Yang et al. 2020a).
- The compositional (spectral type) mass distribution throughout the asteroid belt shows a rather sharp transition from the C- to the P-types (DeMeo & Carry 2013, 2014 and Fig. 9). This transition occurs in the outer belt ( $\sim 2.8\text{--}3.3$  AU), which corresponds exactly to the heliocentric range where the sublimation of water ice starts (e.g., Schorghofer 2008). For bodies located beyond 3.3 AU from the Sun, water ice can persist within the top few meters of the surface over billions of years. At such distances, mostly P- and D-type asteroids (DeMeo & Carry 2013, 2014) with anhydrous surfaces are observed (Takir & Emery 2012; Usui et al. 2019). Large P- and D-type asteroids that were implanted inward of 3.3 AU would have lost their comet-like P/D type outer shell due

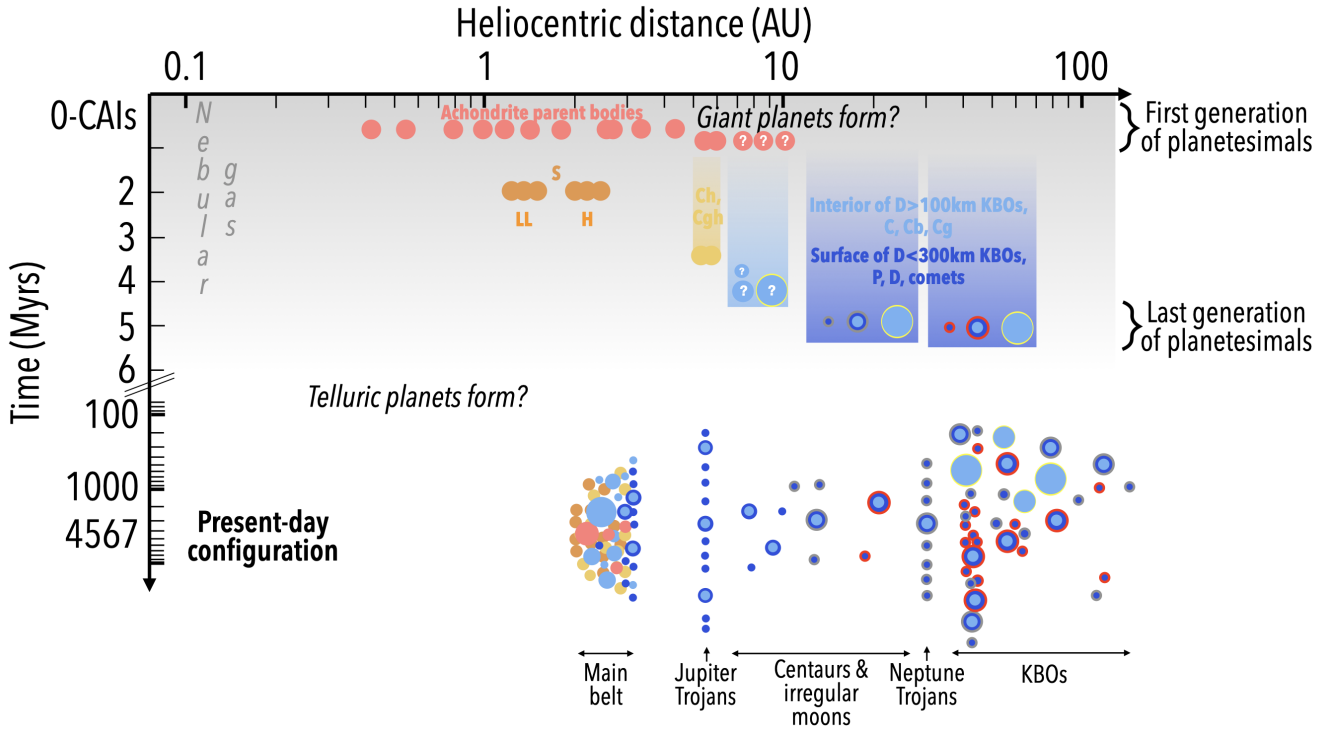


**Fig. 9.** Percentage of mass for C and P/D-type asteroids (DeMeo & Carry 2013) and the theoretical erosion rate due to the sublimation of water ice (Schorghofer 2008) as a function of the semi-major axis. For the calculation of the theoretical loss rate, we assumed a spherical shape, a geometric albedo of 0.05, zero obliquity, and an eccentricity of 0.145 (Morbidelli et al. 2015). The abrupt decrease in the fraction of P/D type asteroids (and conversely the abrupt increase in the fraction of C-types) occurs exactly where the erosion rate due to water sublimation becomes significant.

to water-ice sublimation (see Fig. 9 and Schorghofer 2008) in addition to collisional erosion, which would naturally explain why we are currently observing the exposed aqueously altered C-type-like interiors of these bodies. The same could apply for Ceres (see above) whose density appears higher ( $2.16 \text{ g cm}^{-3}$ ) than the typical density of large TNOs ( $1.8\text{--}2.0 \text{ g cm}^{-3}$ ; Kovalenko et al. 2017) and that may have lost a primordial  $\sim 30\text{--}50$  km thick icy shell following its implantation in the middle belt (see above).

- The size distribution of TNOs does not reach its maximum at  $\sim 270$  km which corresponds to the diameter of the largest inner Solar System P/D-type (namely 87 Sylvia). Instead, the current TNO population comprises a few hundred  $D \geq 300$  km bodies (Lawler et al. 2018; Bannister et al. 2018). It is therefore difficult to imagine that no  $D \geq 300$  km bodies were trapped in the asteroid belt following the outward migration of Uranus and Neptune as described in the Nice model. Considering C-complex bodies along with P/D-type asteroids as implanted TNOs would help to solve this issue. We note that in Vokrouhlický et al. (2016), the efficiency of TNO capture is too high in the main belt (by a factor of 10 in some parts). As a solution, they propose for example a weaker scaling law along with substantial collisional grinding, long-term dynamical removal by the Yarkovsky effect, or thermal destruction. Considering C-types along with P/D types (as proposed here) implies that the high capture efficiency may no longer be a problem.

In conclusion, we propose that some C-complex bodies (so-called IDP-like C-types) could be intrinsically related to IDP-like P- and D-type asteroids, representing different layers of a same body (C: core; P/D: outer shell). In this scenario, aqueously altered chondritic smooth IDPs appear as the most likely analogs of IDP-like C-types with anhydrous chondritic porous IDPs being the analogs of P/D-type asteroids. We thus highlight the possibility that P/D-types and some C-complex bodies may have the same origin in the primordial trans-Neptunian disk. We note that this suggestion is not incompatible with a different formation location for the remaining C-complex bodies (including



**Fig. 10.** Postulated sequence of events tracing the time, place, and duration of formation of the main compositional classes of small bodies (top) to present-day observed characteristics (bottom; vertical spread reproducing roughly the distribution of orbital inclinations). The accretion duration is shown as gradient boxes ending at the fully formed bodies. This graph is adapted from Vernazza & Beck (2017) and Neveu & Vernazza (2019) with the following novelty: we highlight the possibility that so-called IDP-like C-types could be intrinsically related to IDP-like P- and D-type asteroids, representing different layers of a same body (C: core; P/D: outer shell). Therefore, C, P, and D-types may all have the same origin in the primordial trans-Neptunian disk. Kuiper belt objects (KBOs) that were implanted inward of the snowline following giant planet migration may have lost their P/D outer shell due to water ice sublimation revealing their C-type interiors.

CM-like bodies; see Fig. 10) in regions between the giant planets (Raymond & Izidoro 2017). In particular, we speculate that chondrule-rich CM-like bodies, while sharing a similar density with other C-complex bodies, may have a different origin. As a matter of fact, chondritic porous IDPs (analogs of P/D types and comets) are chondrule-poor materials suggesting that CM-like bodies and P/D-types did not form in the same region of the Solar System.

#### 7.5. What physical properties drive the formation of companions around large asteroids?

At the time of writing the Asteroid III book, seven multiple systems were known among the largest ( $D \geq 90$  km) main-belt asteroids (Merline et al. 2002) and this number increased by a factor of two at the time of writing the Asteroid IV book (Margot et al. 2015). Since then, only one multiple system has been discovered among large main-belt asteroids ((31) Euphrosyne and its moon discovered via our observing programme; Yang et al. 2020b). Among these 15 multiple systems, six are triple systems, the first discovered being that of (87) Sylvia (Marchis et al. 2005). Two-thirds of these multiple systems belong to the C-complex while the remaining ones belong either to the P or M classes. Surprisingly, there are currently no large S-types with known companions. Whereas the observed S/CP type dichotomy may be interpreted as a consequence of compositional differences (hence different material strengths), implying a different response to impacts between the volatile-poor silicate-rich S-types and the volatile-rich CP-types, the existence of the dense metal- and silicate-rich Kalliope and Kleopatra systems renders this interpretation unlikely.

Instead of composition, the main physical properties that seem to favor the creation and/or long-term survival of moons appear to be rotation period and oblateness (Fig. 4). It appears that both of these physical quantities are lower than threshold values for most large asteroids with companions, namely  $P \leq 6$  h and  $c/a \leq 0.65$ . This also applies to large binary systems not covered by our large programme. Among our large programme targets, (31) Euphrosyne appears to be an exception as one of these two physical quantities ( $c/a$ ) appears much higher than the threshold value. Given the young age ( $\sim 0.3$  Gyr) of the Euphrosyne family (Yang et al. 2020b,a), and therefore of the moon, future studies should attempt to determine the long-term stability of the moon in order to reach a better overall understanding of moon formation and long-term survival.

As proposed in the extreme case of Kleopatra (Marchis et al. 2021), mass ejection at the edges of rapidly rotating elongated bodies, the gravity of which is significantly lower at such locations (up to  $\sim 50\%$  in the case of Kleopatra) than that of a spherical body of equivalent mass, might be a plausible explanation for the formation of some companions. The case of Euphrosyne might be different and may result from the large collision at the origin of its re-accumulation and the formation of its large family.

## 8. Conclusions and perspective

Here, we report the analysis of a high-angular-resolution imaging survey of 42 large main-belt asteroids conducted with VLT/SPHERE/ZIMPOL as an ESO large programme (199.C-0074; PI: P. Vernazza). Our asteroid sample comprises 39 bodies



with  $D \geq 100$  km and in particular most  $D \geq 200$  km main-belt asteroids (20/23). Furthermore, it reflects well the compositional diversity present in the main belt as the sampled bodies belong to the following taxonomic classes: A, B, C, Ch/Cgh, E/M/X, K, P/T, S, V.

The SPHERE/ZIMPOL images were first used to reconstruct the 3D shape of all targets with both the ADAM and MPCD reconstruction methods. We subsequently performed a detailed shape analysis and constrained the density of each target using available mass estimates including our own mass estimates in the case of multiple systems. We summarize the main results below.

- Size (and therefore mass) and the rotation period are the two main physical properties determining the shape of large asteroids. First, both the asphericity and the departure from an ellipsoid are highly anti-correlated with the size, and therefore the mass, of our targets. Second, the distribution of the asphericity values as a function of diameter appears bimodal with a group of “spherical” bodies and a group of “elongated” bodies. A difference in rotation period appears to be the main origin of such bimodality with more elongated bodies possessing a shorter rotation period with respect to more spherical ones. In addition, there is a statistically significant correlation between the rotation period and the  $c/a$  axis ratio of our targets. Finally, re-accumulation following large impacts completes the picture leading to the formation of rather spherical bodies.
- A comparison of the specific angular momentum and the normalized angular velocity of our targets with the expected values for Maclaurin and Jacobi ellipsoids as well as dumb-bell shapes shows that all bodies but one (Kleopatra) fall along the Maclaurin sequence. The only body falling onto the dumb-bell sequence is 216 Kleopatra. Furthermore, it appears that large ( $D \geq 220$  km) volatile-rich bodies (except 31 Euphrosyne which is an odd case) tend to be the closest to the Maclaurin sequence (in terms of chi-square). The equilibrium shapes of large volatile-rich bodies may suggest that the interiors and/or outer shells of these bodies behaved like fluids (i.e., significantly relaxed) until recent times, a likely consequence of their high content of volatile material and of thermal heating due to the decay of long lived radionuclides (e.g., [Carry et al. 2021](#)) leading to continuous relaxation. The evolutionary history of these bodies may therefore have followed that of Ceres for which a paucity of large impact basins has been observed, suggesting that large-scale relaxation has occurred for billions of years and may still be ongoing ([Marchi et al. 2016](#)).
- Five out of six multiple systems possess a rotation period of shorter than 6 h and a  $c/a$  axis ratio of less than 0.65. Hence, both the rotation period and the oblateness of a body appear to be key factors for the formation and/or long-term stability of companions. Mass ejection at the edges of rapidly rotating elongated bodies might be a plausible explanation for the formation of some multiple systems.
- Densities in our sample range from  $\sim 1.3$  g cm $^{-3}$  (P-type asteroids 87 Sylvia) to  $\sim 4.3$  g cm $^{-3}$  (M/X-type asteroids 22 Kalliope), highlighting the wide diversity in composition of the asteroid belt. Furthermore, the density distribution appears bimodal to first order with volatile-poor ( $\rho \geq 2.7$  g cm $^{-3}$ ) bodies and volatile-rich bodies ( $\rho \leq 2.2$  g cm $^{-3}$ ). Given that asteroid albedos also follow a bimodal distribution ([Masiero et al. 2011](#)), two main groups of asteroids emerge, namely (a) asteroids with a geometric albedo of below 0.1 and a density below 2.2 g cm $^{-3}$  and (b) asteroids with a geometric albedo of higher than 0.145 and a

density of greater than 2.7 g cm $^{-3}$ . Finally, our density estimates imply, in agreement with the findings of [Carry \(2012\)](#), that the amount of macroporosity decreases with increasing size, and therefore mass, and that macroporosity is minimal ( $\leq 5$ –10%) only in the case of the largest objects with masses  $\geq 10^{19}$  kg.

- Regarding the thermal evolution of the main compositional classes, our conclusions are as follows. Most ordinary chondrite-like and CM chondrite-like asteroids likely did not differentiate. However, this is not the case for large P-type asteroids and at least a fraction of X/M-type asteroids. The cores of P-type asteroids may consist of C-type material. This is well supported by our density estimate of these cores as well as spectroscopic observations of the Eurybates family. We speculate that a large fraction of nonCM-like C-type asteroids (Ch/Cgh types) may be genetically linked to P- and D-type asteroids and thus share a similar origin in the trans-Neptunian region.

Although our large programme has allowed us to make significant progress in our understanding of the formation and evolution of the largest asteroids, it has generated new questions for which future investigations should provide an answer. For example, the first pertains to whether or not our collections contain meteoritic analogs of high-density asteroids such as Kalliope, Psyche, and Kleopatra. If so, are these analogs CH or CB chondrites? An in depth characterization of these meteorite classes (spectroscopy, density) would help to make progress in this respect. Also, we do not know which asteroids are the parent bodies of metallic meteorites. Our density estimates for the largest M-types exclude a direct link between these objects and those meteorites, implying that the parent bodies could be found among smaller M-types. Also, thanks to our large programme, the volumes of  $\sim 40$  large asteroids are now constrained with high accuracy (2–10%). However, the same cannot be said for the mass estimates for about half of these bodies. Exploitation of the high-accuracy astrometry delivered by the ESA Gaia mission for these bodies will help in constraining their mass with an uncertainty in the 10%–30% range ([Mouret et al. 2008](#)).

Another unknown is the number of multiple systems comprised by large asteroids ( $D \geq 100$  km). Our program focused on  $\sim 40$  large asteroids but the main asteroid belt comprises  $\sim 230$  such bodies. High-angular-resolution imaging observations of the remaining  $D \geq 100$  km bodies should be of high priority in the near future to tackle this question.

Most large volatile-rich asteroids with  $D \geq 220$  km have shapes close to equilibrium. The slight deviation of their shapes from that of perfect ellipsoids is likely a consequence of the high collisional rate in the asteroid belt. Whether or not TNOs of similar sizes possess perfect equilibrium shapes is also unknown.

In the present work, we reveal the possibility that a fraction of C-complex asteroids (typically C-, Cb types) could be directly connected to P/D-type asteroids and TNOs. Several investigations should be conducted to prove or disprove this suggestion. These include: (1) the spectroscopic characterization of chondritic, smooth IDPs and a better understanding of their relation to chondritic, porous IDPs; (2) the spectroscopic characterization in the NIR and MIR (including the 3 micron region) of TNOs at all sizes and that of asteroid collisional families that show a mix of C and P-types (e.g., Eurybates); (3) a comparison of the size frequency distribution of C, P, and D-type asteroids with that of TNOs expanding previous investigations that focused on P/D type asteroids only (e.g., [Vokrouhlický et al. 2016](#)); and finally (4) dynamical simulations that should test the ability of the Nice



model to implant a Ceres-like and a Hygiea-like body in the asteroid belt along with a few  $D \sim 300$  km C-type asteroids.

Our imaging observations demonstrate in a striking manner how the gap between interplanetary missions and ground-based observations is getting narrower (Férick et al. 2019; Vernazza et al. 2020). With the advent of extremely large telescopes (ELT, GMT, TMT), the science objectives of future interplanetary missions to main-belt asteroids will have to be carefully thought out so that these missions will complement – and not duplicate – the achievements of Earth-based telescopic observations. For instance, first-generation ELT adaptive-optics NIR imaging observations of main-belt asteroids will allow the resolution of bodies with diameters down to 35–80 km (depending on their main-belt location) and craters down to  $\sim 10$ –25 km in size implying that we shall be able to characterize the global geological history of a much larger sample of main-belt asteroids from the ground. This implies that geological and geomorphological studies (based on high-angular-resolution imaging data) are likely to become – during the coming decade – the prime science objectives conducted from Earth in the case of  $D \geq 35$ –80 km asteroids, dethroning studies related to the nature and origin of these bodies deduced from the analysis of their spectra. Interplanetary missions to main-belt asteroids performing cosmochemistry experiments and/or a sample return should be given preference at the forefront of in situ exploration as these would ideally complement the investigations conducted from Earth. In particular, IDP-like asteroids as well as the rare B, L, Xc/Xe/Xk, and O types should be preferred targets as little is known regarding these bodies because of the paucity or absence of samples for these objects in our collections.

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## Appendix A: Additional table

**Table A.1:** Absolute magnitude  $H$ , Sidereal rotation period  $P$ , spin-axis ecliptic J2000 coordinates  $\lambda$  and  $\beta$ , obliquity, asphericity, ellipsoid deviation, and dimensions along the major axis of the best-fit triaxial ellipsoids ( $a > b > c$ ). Uncertainties correspond to  $1\sigma$  values.

| N   | H    | P<br>[h]                          | $\lambda$<br>[deg]  | $\beta$<br>[deg]   | Obl<br>[deg] | Asph   | Ell. dev. | a<br>[km]       | b<br>[km]       | c<br>[km]       |
|-----|------|-----------------------------------|---------------------|--------------------|--------------|--------|-----------|-----------------|-----------------|-----------------|
| *1  | 3.34 | $9.07417 \pm 1 \times 10^{-6}$    | $348.832 \pm 0.007$ | $81.553 \pm 0.002$ | 2            | 0.0012 | 0.0039    | $964.4 \pm 0.2$ | $964.2 \pm 0.2$ | $891.8 \pm 0.2$ |
| 2   | 4.09 | $7.81321 \pm 2 \times 10^{-5}$    | $42 \pm 3$          | $-15 \pm 3$        | 78           | 0.0151 | 0.0286    | $568 \pm 12$    | $530 \pm 12$    | $450 \pm 12$    |
| 3   | 5.31 | $7.209531 \pm 1 \times 10^{-6}$   | $105 \pm 3$         | $18 \pm 3$         | 60           | 0.0340 | 0.0526    | $288 \pm 5$     | $250 \pm 5$     | $225 \pm 5$     |
| *4  | 3.29 | $5.34212767 \pm 1 \times 10^{-8}$ | $330.82 \pm 0.01$   | $57.72 \pm 0.01$   | 27           | 0.0139 | 0.0213    | $572.6 \pm 0.2$ | $557.2 \pm 0.2$ | $446.4 \pm 0.2$ |
| 6   | 5.71 | $7.274467 \pm 1 \times 10^{-6}$   | $342 \pm 2$         | $50 \pm 1$         | 36           | 0.0481 | 0.0679    | $220 \pm 9$     | $205 \pm 8$     | $166 \pm 7$     |
| 7   | 5.51 | $7.138843 \pm 1 \times 10^{-6}$   | $20 \pm 3$          | $23 \pm 3$         | 72           | 0.0645 | 0.0495    | $260 \pm 5$     | $225 \pm 4$     | $150 \pm 18$    |
| 8   | 6.54 | $12.86667 \pm 1 \times 10^{-5}$   | $337 \pm 2$         | $-1 \pm 3$         | 87           | 0.0198 | 0.0361    | $154 \pm 7$     | $148 \pm 6$     | $127 \pm 4$     |
| 9   | 6.31 | $5.079176 \pm 1 \times 10^{-6}$   | $181 \pm 2$         | $22 \pm 2$         | 73           | 0.0604 | 0.0624    | $218 \pm 10$    | $176 \pm 10$    | $133 \pm 8$     |
| 10  | 5.43 | $13.82559 \pm 5 \times 10^{-5}$   | $306 \pm 3$         | $-29 \pm 3$        | 120          | 0.0030 | 0.0134    | $450 \pm 10$    | $430 \pm 10$    | $424 \pm 20$    |
| 11  | 6.55 | $13.72204 \pm 1 \times 10^{-5}$   | $312 \pm 2$         | $17 \pm 4$         | 73           | 0.0301 | 0.0465    | $156 \pm 6$     | $152 \pm 6$     | $138 \pm 6$     |
| 12  | 7.24 | $8.660345 \pm 5 \times 10^{-6}$   | $177 \pm 2$         | $-27 \pm 3$        | 110          | 0.0625 | 0.0802    | $140 \pm 4$     | $116 \pm 3$     | $96 \pm 3$      |
| 13  | 6.74 | $7.046664 \pm 3 \times 10^{-6}$   | $38 \pm 5$          | $31 \pm 5$         | 59           | 0.0590 | 0.0869    | $238 \pm 12$    | $199 \pm 11$    | $182 \pm 10$    |
| 15  | 5.28 | $6.082753 \pm 1 \times 10^{-6}$   | $355 \pm 2$         | $-70 \pm 2$        | 169          | 0.0324 | 0.0434    | $340 \pm 14$    | $248 \pm 13$    | $229 \pm 14$    |
| 16  | 5.90 | $4.195948 \pm 1 \times 10^{-6}$   | $35 \pm 2$          | $-9 \pm 2$         | 96           | 0.0452 | 0.0402    | $277 \pm 5$     | $238 \pm 6$     | $164 \pm 4$     |
| 18  | 6.51 | $11.570306 \pm 5 \times 10^{-6}$  | $12 \pm 2$          | $19 \pm 2$         | 64           | 0.0319 | 0.0518    | $161 \pm 8$     | $135 \pm 8$     | $131 \pm 7$     |
| 19  | 7.13 | $7.443224 \pm 1 \times 10^{-6}$   | $103 \pm 3$         | $60 \pm 3$         | 29           | 0.0251 | 0.0428    | $242 \pm 10$    | $203 \pm 10$    | $192 \pm 10$    |
| *21 | 7.35 | $8.168271 \pm 1 \times 10^{-6}$   | $52 \pm 1$          | $-8 \pm 1$         | 97           | 0.0682 | 0.0659    | $125 \pm 4$     | $98 \pm 3$      | $81 \pm 2$      |
| 22  | 6.45 | $4.1482 \pm 1 \times 10^{-6}$     | $195 \pm 3$         | $4 \pm 3$          | 97           | 0.0700 | 0.0717    | $207 \pm 5$     | $145 \pm 4$     | $122 \pm 4$     |
| 24  | 7.08 | $8.374187 \pm 1 \times 10^{-6}$   | $146 \pm 3$         | $73 \pm 3$         | 18           | 0.0238 | 0.0359    | $232 \pm 14$    | $220 \pm 14$    | $176 \pm 14$    |
| 29  | 5.85 | $5.390119 \pm 1 \times 10^{-6}$   | $323 \pm 2$         | $-29 \pm 2$        | 116          | 0.0205 | 0.0401    | $222 \pm 6$     | $209 \pm 6$     | $183 \pm 5$     |
| 30  | 7.57 | $13.68717 \pm 5 \times 10^{-6}$   | $106 \pm 2$         | $19 \pm 2$         | 72           | 0.0913 | 0.1101    | $112 \pm 5$     | $84 \pm 5$      | $76 \pm 4$      |
| 31  | 6.74 | $5.529595 \pm 1 \times 10^{-6}$   | $94 \pm 5$          | $67 \pm 3$         | 48           | 0.0112 | 0.0292    | $286 \pm 16$    | $274 \pm 14$    | $247 \pm 15$    |
| 41  | 7.12 | $5.98798 \pm 6 \times 10^{-5}$    | $199 \pm 5$         | $-32 \pm 5$        | 126          | 0.0546 | 0.0696    | $235 \pm 17$    | $183 \pm 16$    | $153 \pm 14$    |
| 45  | 7.46 | $5.699151 \pm 1 \times 10^{-6}$   | $128 \pm 2$         | $-35 \pm 2$        | 123          | 0.0596 | 0.0381    | $252 \pm 9$     | $191 \pm 9$     | $138 \pm 7$     |
| 48  | 6.90 | $11.890105 \pm 1 \times 10^{-6}$  | $294 \pm 2$         | $51 \pm 2$         | 45           | 0.0339 | 0.0443    | $257 \pm 3$     | $211 \pm 3$     | $185 \pm 3$     |
| 51  | 7.35 | $7.78484 \pm 1 \times 10^{-6}$    | $170 \pm 4$         | $-66 \pm 4$        | 153          | 0.0319 | 0.0559    | $167 \pm 6$     | $158 \pm 5$     | $128 \pm 4$     |
| 52  | 6.31 | $5.629954 \pm 1 \times 10^{-6}$   | $255 \pm 2$         | $40 \pm 2$         | 56           | 0.0314 | 0.0352    | $378 \pm 14$    | $336 \pm 14$    | $255 \pm 12$    |
| 63  | 7.55 | $9.297587 \pm 1 \times 10^{-6}$   | $121 \pm 2$         | $-27 \pm 2$        | 120          | 0.1172 | 0.0819    | $152 \pm 4$     | $77 \pm 4$      | $69 \pm 3$      |
| 87  | 6.94 | $5.18364 \pm 4 \times 10^{-5}$    | $75 \pm 5$          | $64 \pm 5$         | 28           | 0.0613 | 0.0464    | $363 \pm 5$     | $249 \pm 5$     | $191 \pm 5$     |
| 88  | 7.04 | $6.041321 \pm 1 \times 10^{-6}$   | $350 \pm 3$         | $116 \pm 3$        | 21           | 0.0168 | 0.0306    | $241 \pm 13$    | $221 \pm 12$    | $195 \pm 12$    |
| 89  | 6.60 | $11.388336 \pm 1 \times 10^{-6}$  | $14 \pm 2$          | $-24 \pm 2$        | 128          | 0.0525 | 0.0675    | $165 \pm 4$     | $142 \pm 5$     | $115 \pm 4$     |
| 128 | 7.49 | $38.9325 \pm 1 \times 10^{-4}$    | $313 \pm 2$         | $-19 \pm 1$        | 104          | 0.0253 | 0.0456    | $178 \pm 5$     | $163 \pm 5$     | $147 \pm 5$     |
| 130 | 7.05 | $5.224663 \pm 1 \times 10^{-6}$   | $68 \pm 180$        | $-89 \pm 1$        | 156          | 0.0525 | 0.0441    | $268 \pm 8$     | $195 \pm 9$     | $153 \pm 9$     |
| 145 | 8.13 | $15.07081 \pm 1 \times 10^{-5}$   | $101 \pm 4$         | $48 \pm 3$         | 48           | 0.0311 | 0.0608    | $153 \pm 3$     | $142 \pm 3$     | $141 \pm 3$     |
| 173 | 7.80 | $6.110939 \pm 1 \times 10^{-6}$   | $28 \pm 2$          | $-17 \pm 2$        | 95           | 0.0397 | 0.0553    | $162 \pm 8$     | $152 \pm 8$     | $123 \pm 8$     |
| 187 | 7.98 | $10.667033 \pm 2 \times 10^{-6}$  | $115 \pm 2$         | $-79 \pm 2$        | 179          | 0.0439 | 0.0623    | $151 \pm 9$     | $122 \pm 8$     | $130 \pm 8$     |
| 216 | 7.30 | $5.3852824 \pm 1 \times 10^{-7}$  | $74 \pm 0$          | $22 \pm 0$         | 61           | 0.2622 | 0.1305    | $267 \pm 6$     | $61 \pm 6$      | $48 \pm 6$      |
| 230 | 7.35 | $23.98475 \pm 1 \times 10^{-5}$   | $111 \pm 2$         | $66 \pm 2$         | 18           | 0.0374 | 0.0558    | $136 \pm 9$     | $120 \pm 7$     | $103 \pm 7$     |
| 324 | 6.82 | $29.4403 \pm 5 \times 10^{-5}$    | $17 \pm 4$          | $-57 \pm 5$        | 154          | 0.0101 | 0.0304    | $234 \pm 9$     | $224 \pm 9$     | $225 \pm 7$     |
| 354 | 6.44 | $4.277185 \pm 1 \times 10^{-6}$   | $154 \pm 2$         | $24 \pm 2$         | 71           | 0.0345 | 0.0561    | $191 \pm 14$    | $162 \pm 12$    | $144 \pm 12$    |
| 511 | 6.22 | $5.129365 \pm 1 \times 10^{-6}$   | $300 \pm 2$         | $26 \pm 2$         | 62           | 0.0269 | 0.0305    | $359 \pm 18$    | $293 \pm 20$    | $253 \pm 17$    |
| 704 | 5.94 | $8.71234 \pm 1 \times 10^{-5}$    | $87 \pm 5$          | $62 \pm 5$         | 36           | 0.0109 | 0.0233    | $354 \pm 9$     | $343 \pm 8$     | $303 \pm 7$     |

**Notes.** \* Values for Ceres, Vesta and Lutetia are derived using shape models from the NASA Dawn and ESA Rosetta space missions.

## Appendix B: Individual mosaics

Comparison between VLT/SPHERE/ZIMPOL deconvolved images of our targets (top row) and the corresponding synthetic images generated by OASIS of our MPCD (second row) and ADAM (third row) shape models. The red arrows indicate the direction of the spin axis. Fourth and fifth rows: residuals in units of instrumental noise between the observed images and the synthetic images of the MPCD and ADAM shape models, respectively.

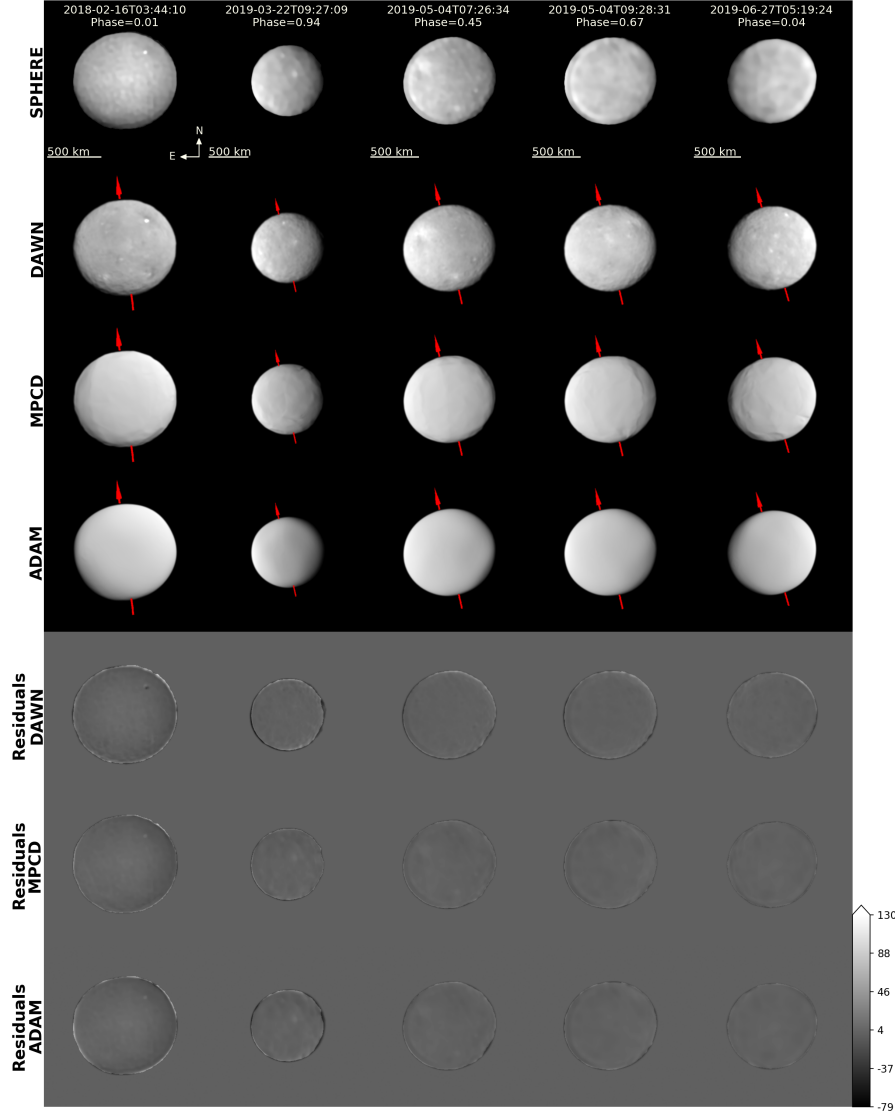


Fig. B.1: (1) Ceres.

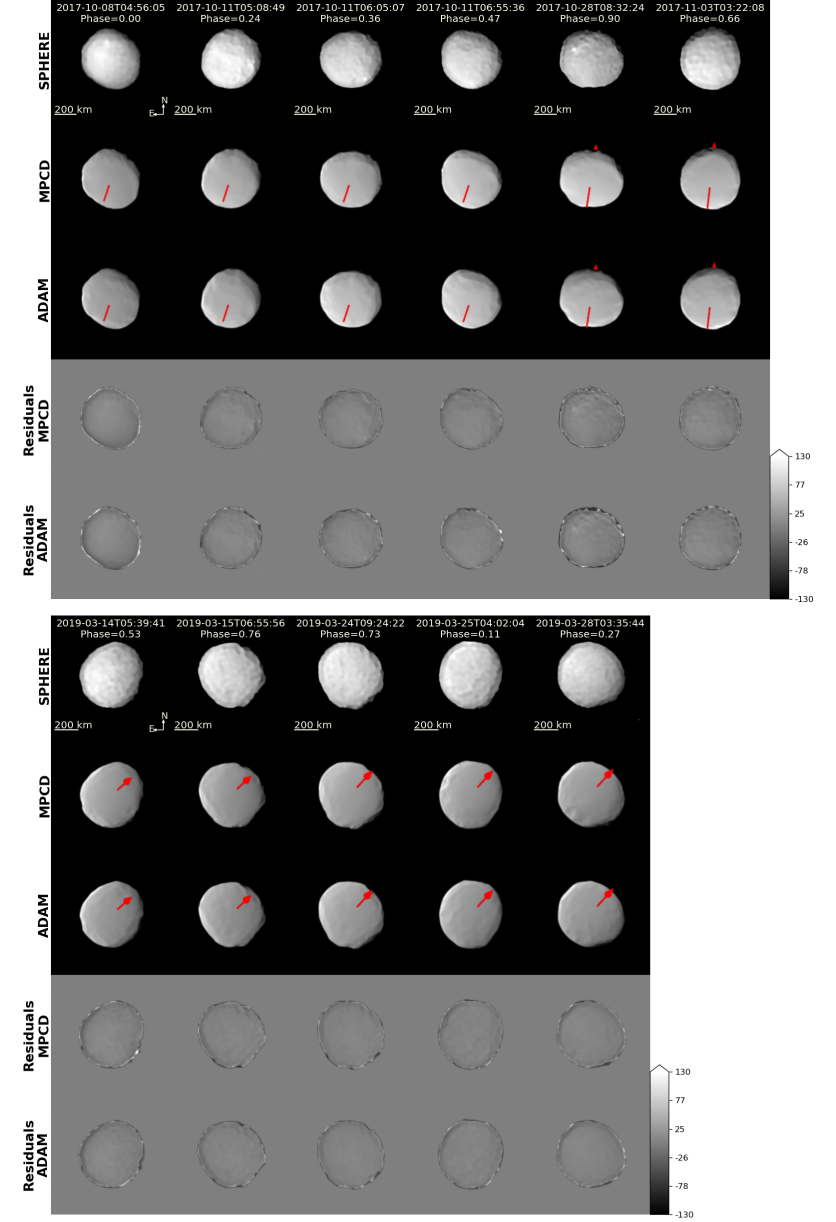


Fig. B.2: (2) Pallas.



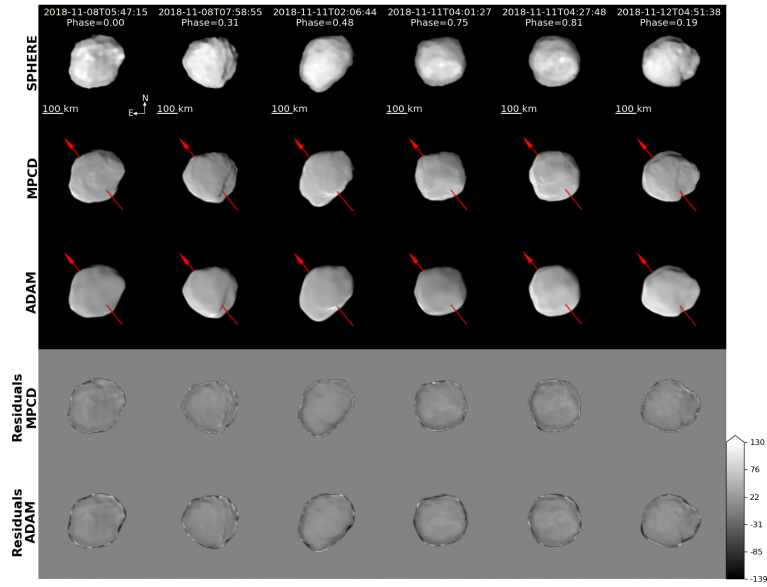


Fig. B.3: (3) Juno.

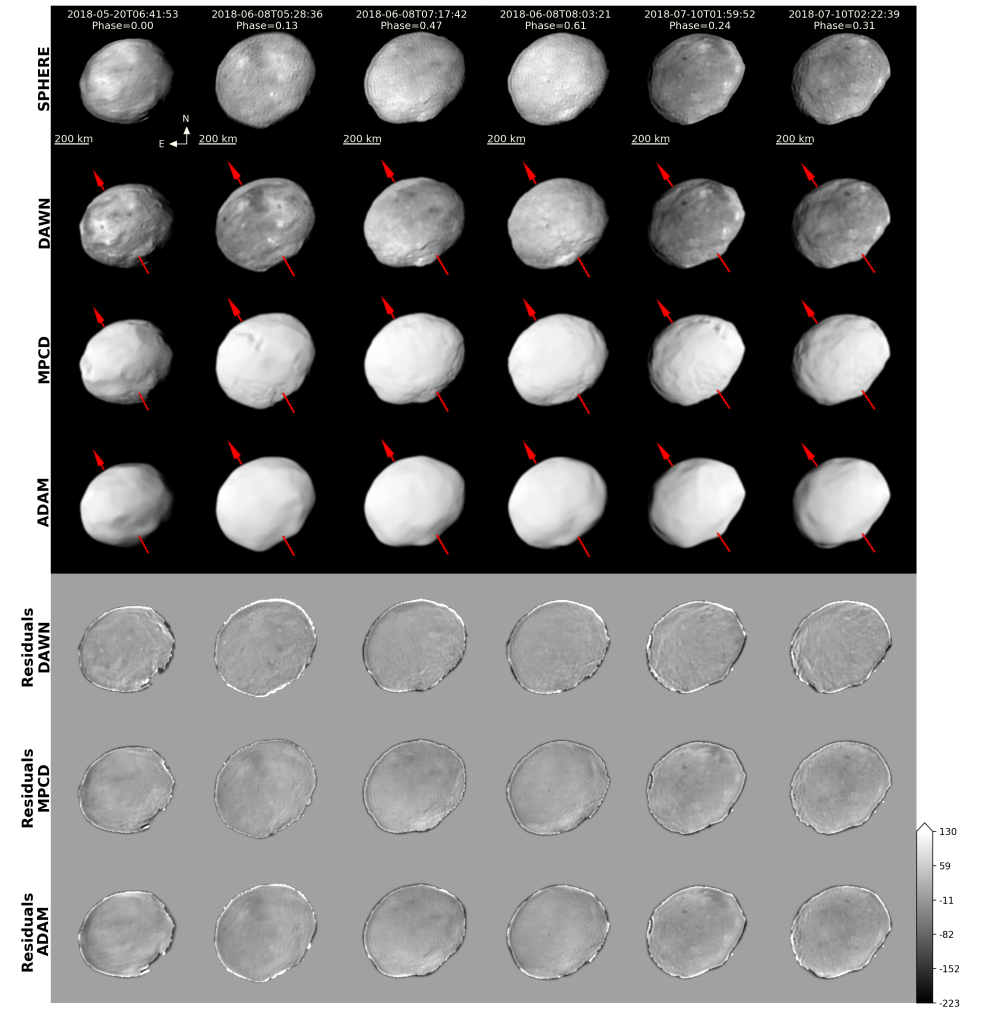


Fig. B.4: (4) Vesta.

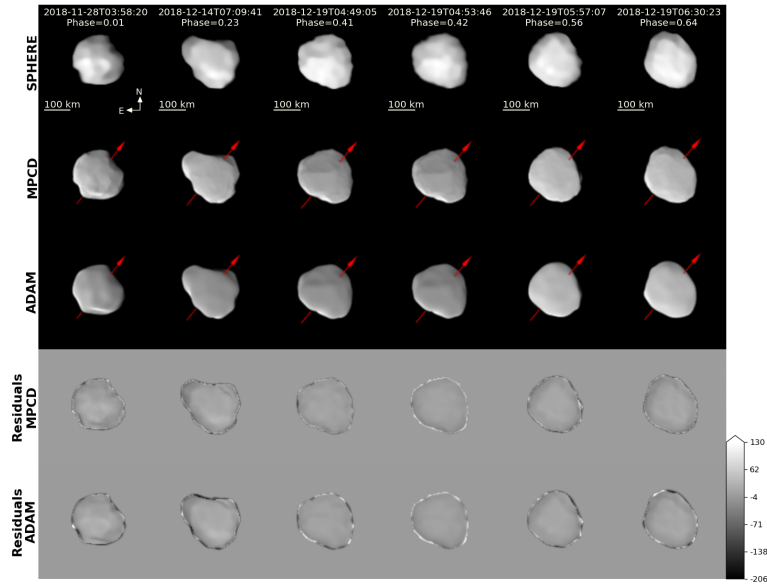


Fig. B.5: (6) Hebe.

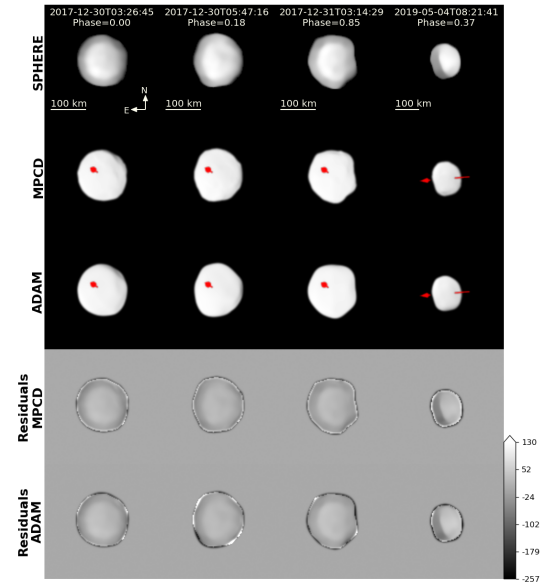


Fig. B.7: (8) Flora.

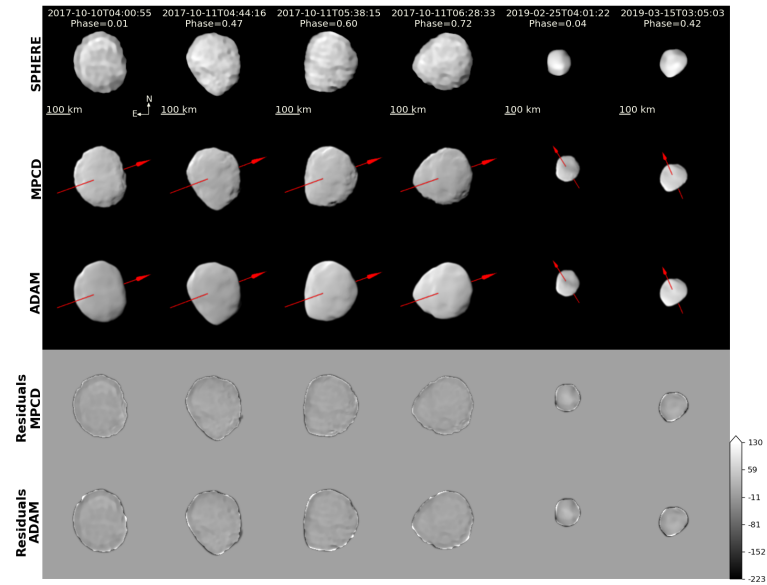


Fig. B.6: (7) Iris.

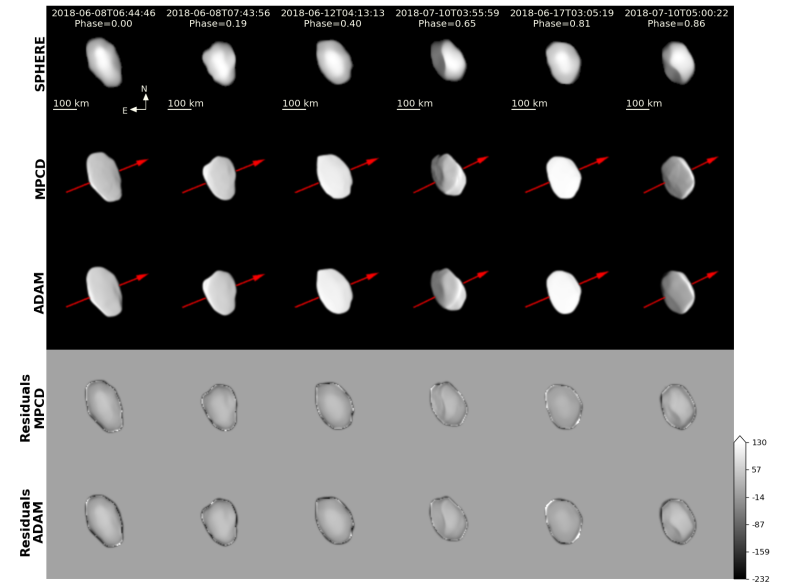


Fig. B.8: (9) Metis.

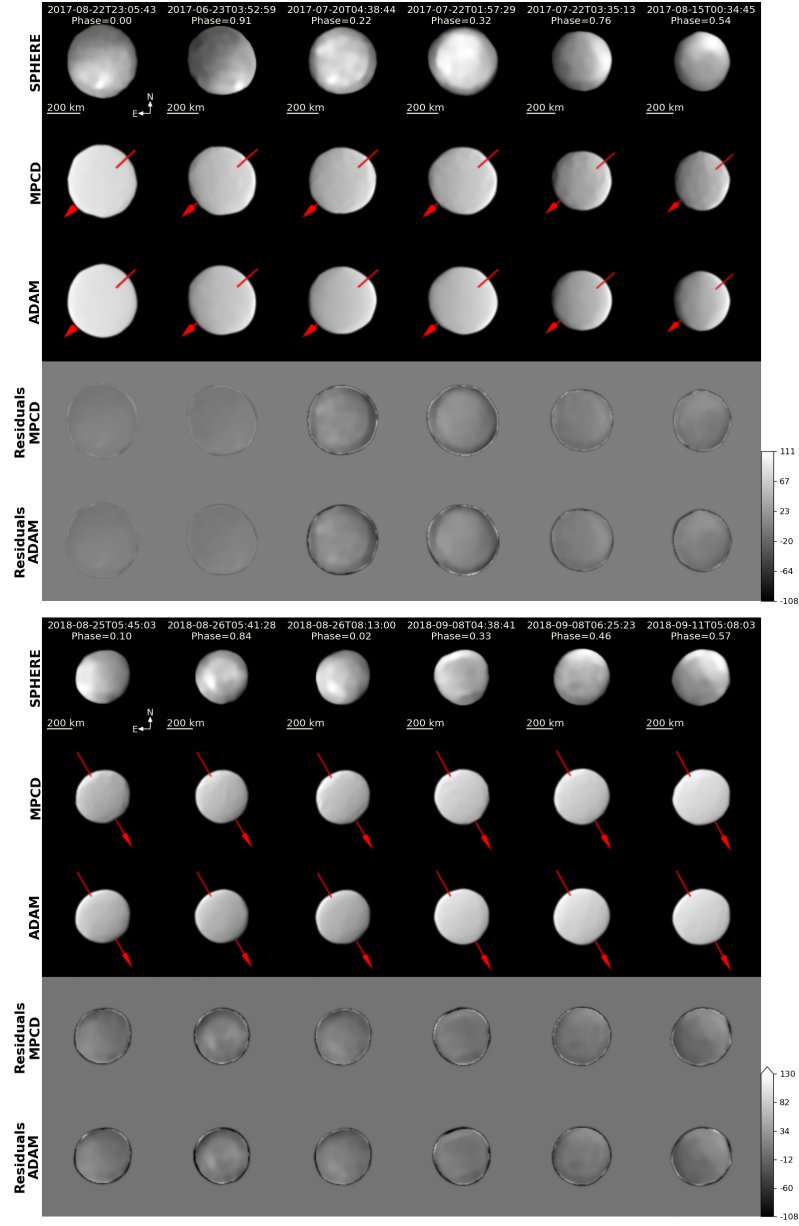


Fig. B.9: (10) Hygiea.

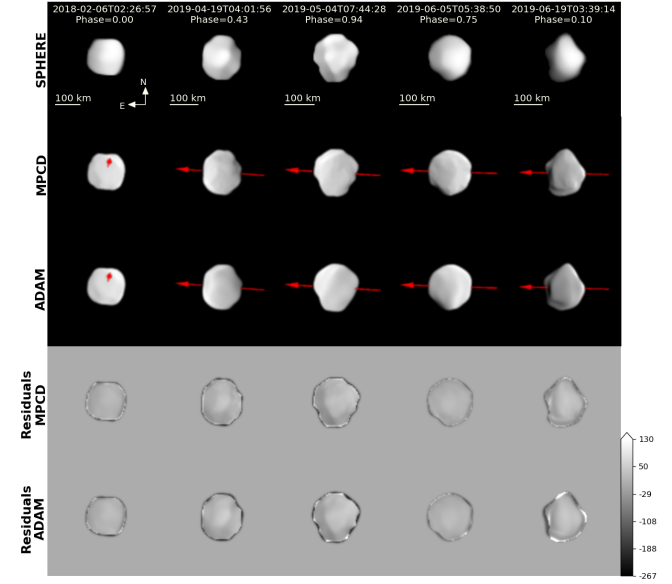


Fig. B.10: (11) Parthenope.

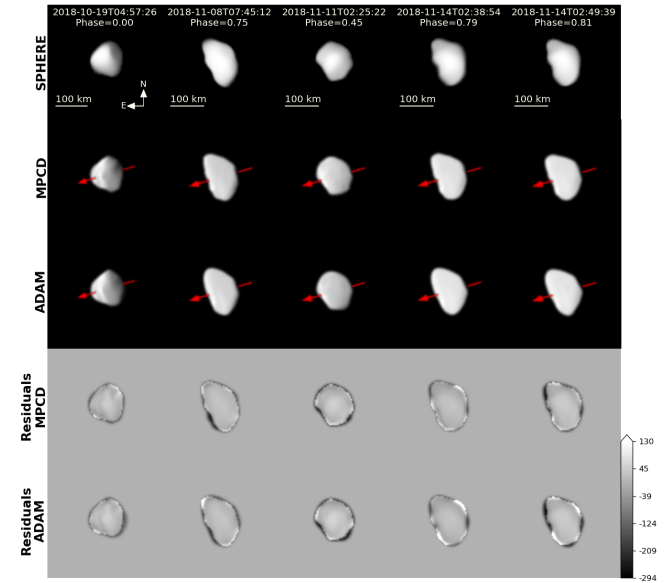


Fig. B.11: (12) Victoria.



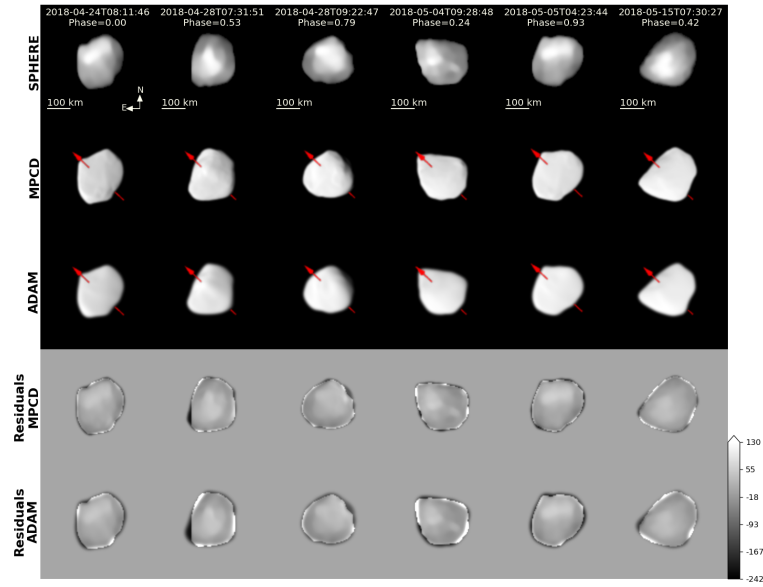


Fig. B.12: (13) Egeria.

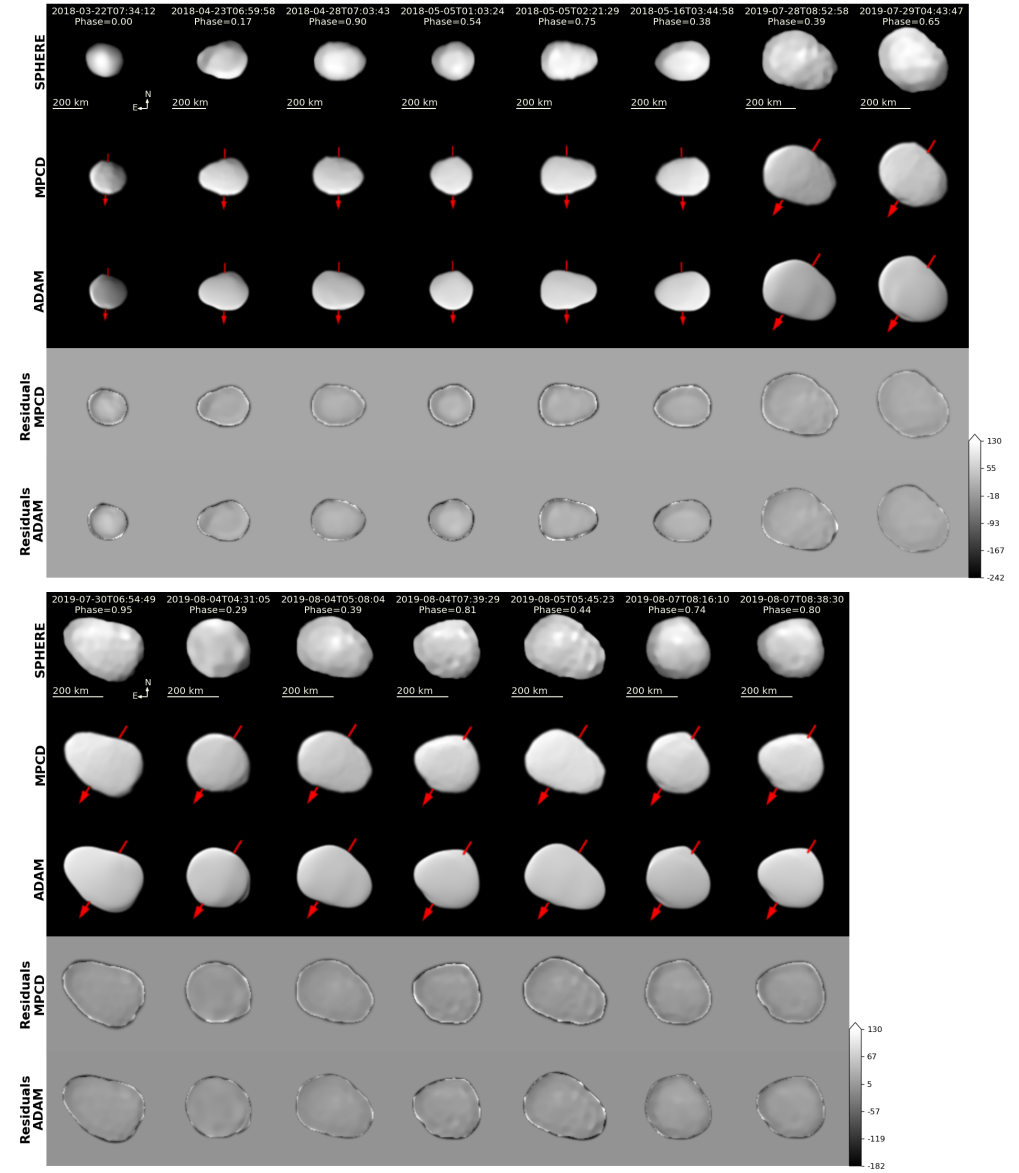


Fig. B.13: (15) Eunomia.

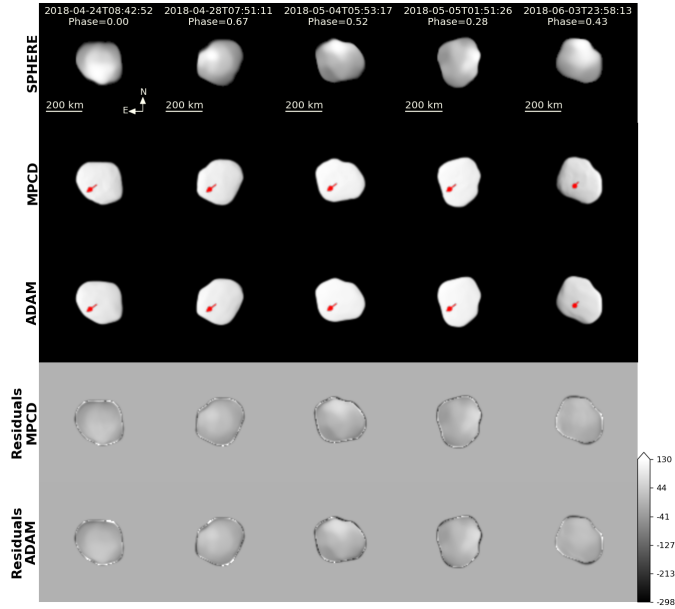


Fig. B.14: (16) Psyche.

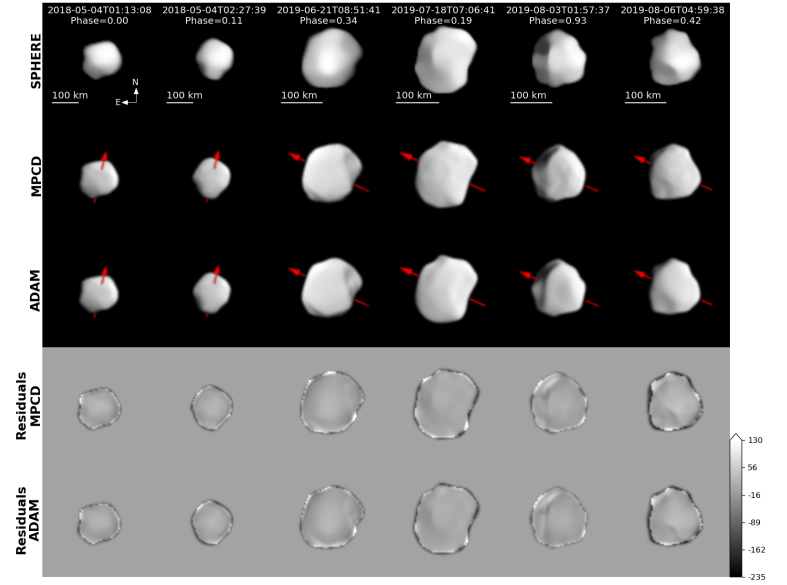


Fig. B.15: (18) Melpomene.

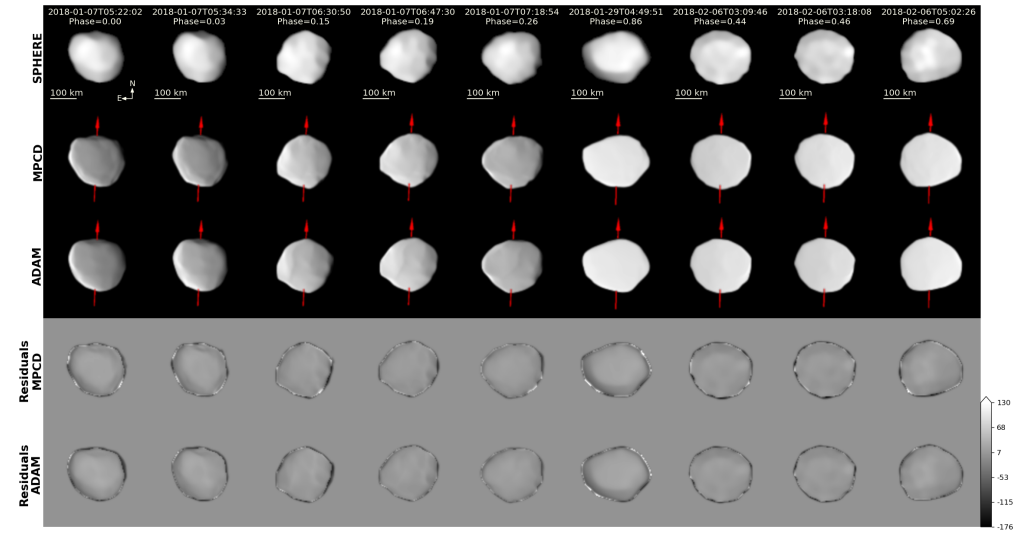
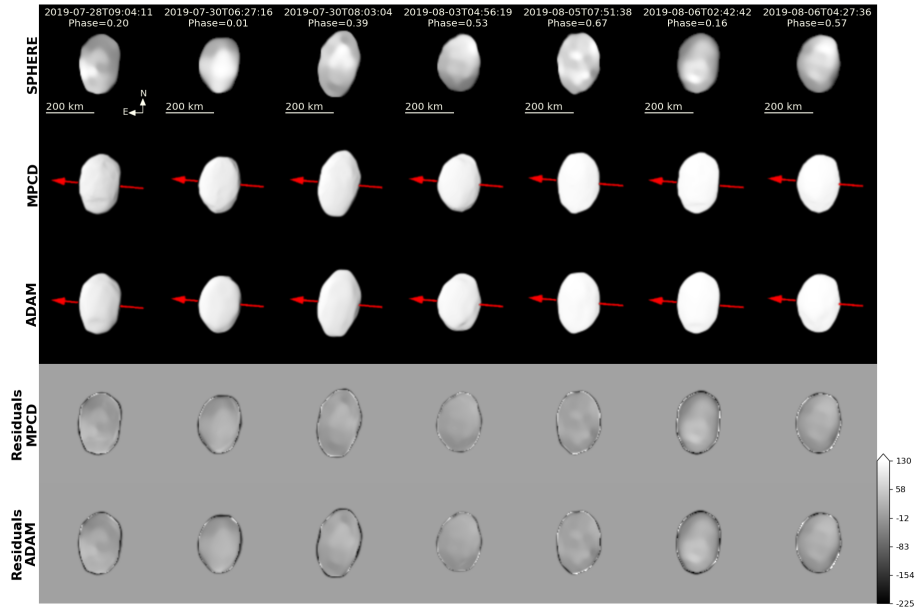


Fig. B.16: (19) Fortuna.

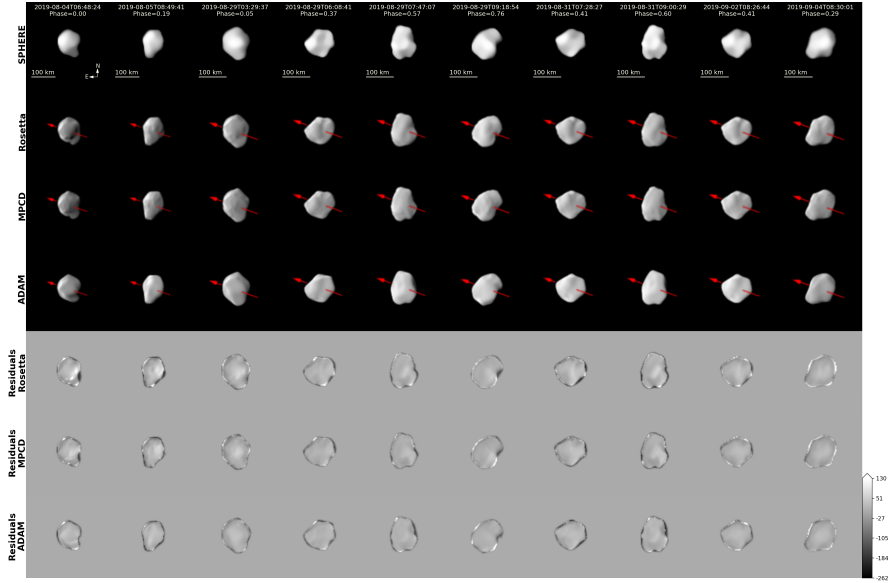


Fig. B.17: (21) Lutetia.

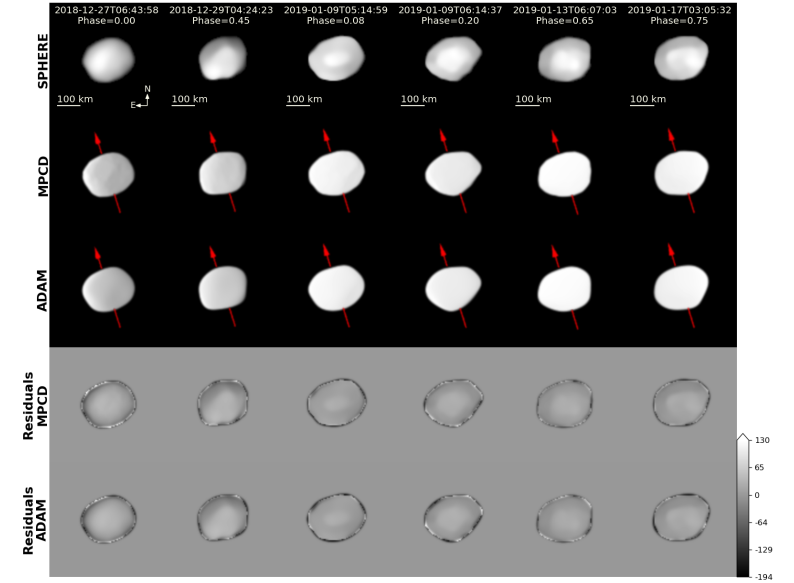


Fig. B.19: (24) Themis.

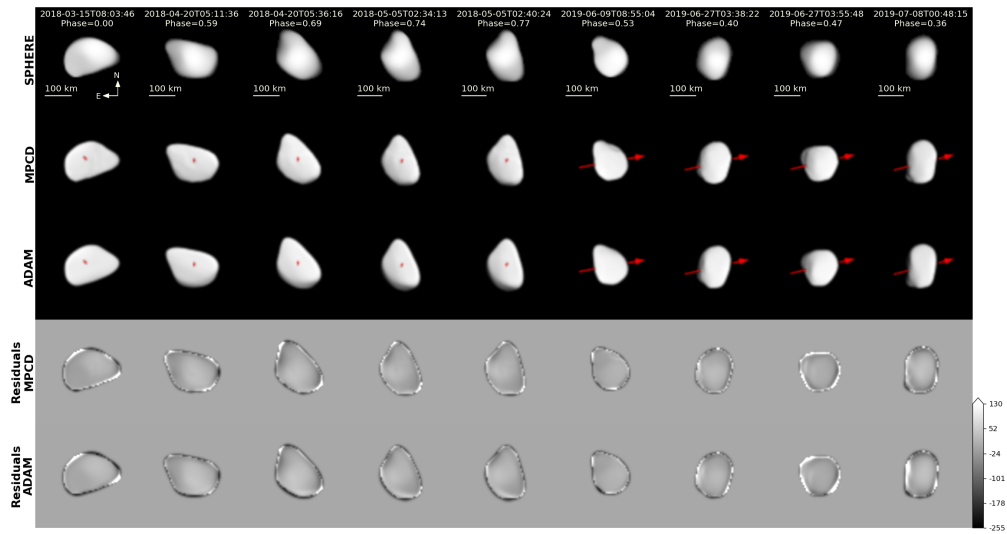


Fig. B.18: (22) Kalliope.

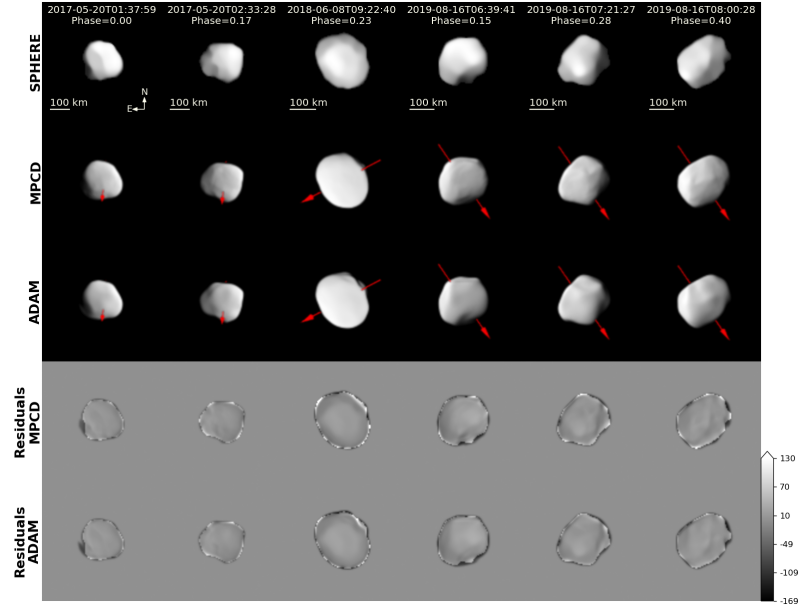


Fig. B.20: (29) Amphitrite.

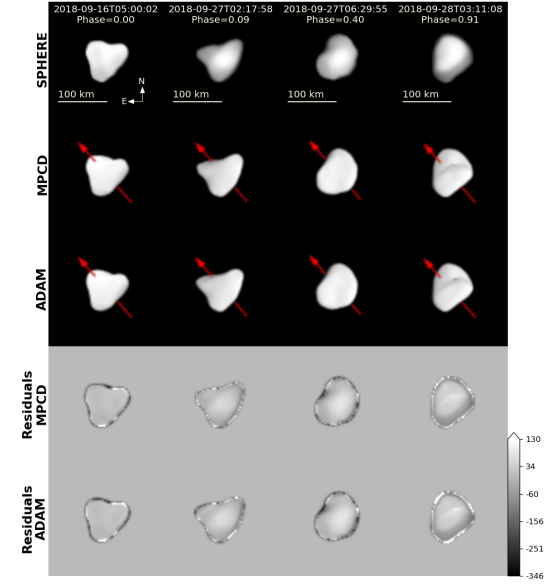


Fig. B.21: (30) Urania.

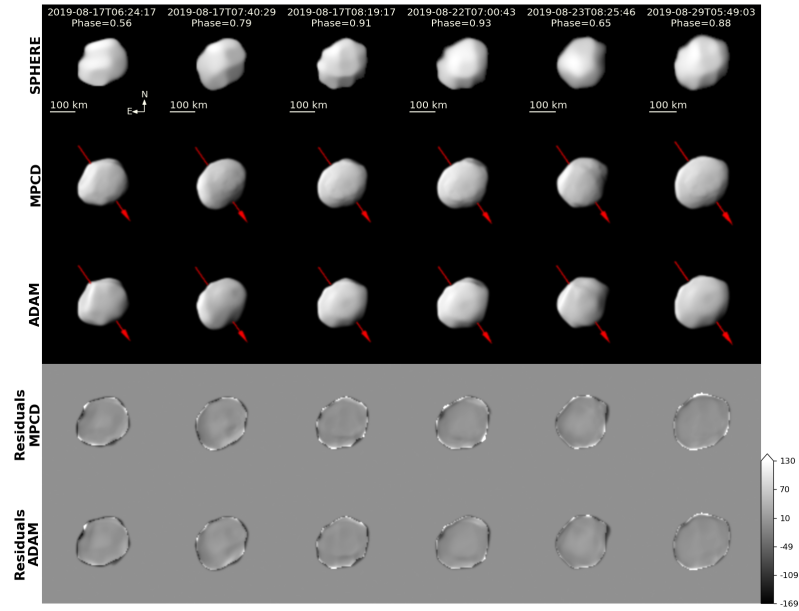


Fig. B.22: (31) Euphrosyne.

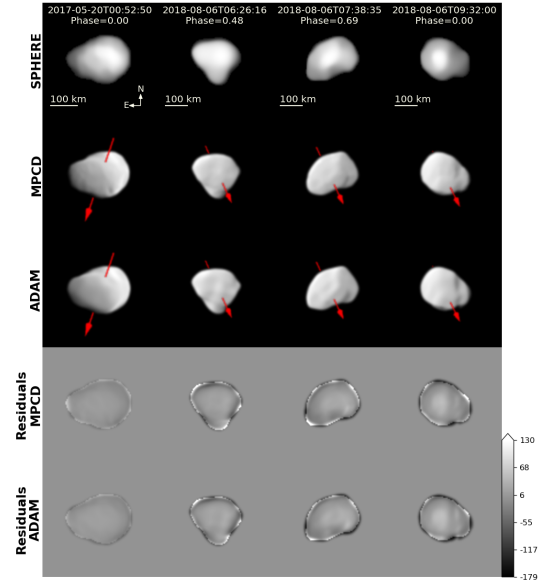


Fig. B.23: (41) Daphne.

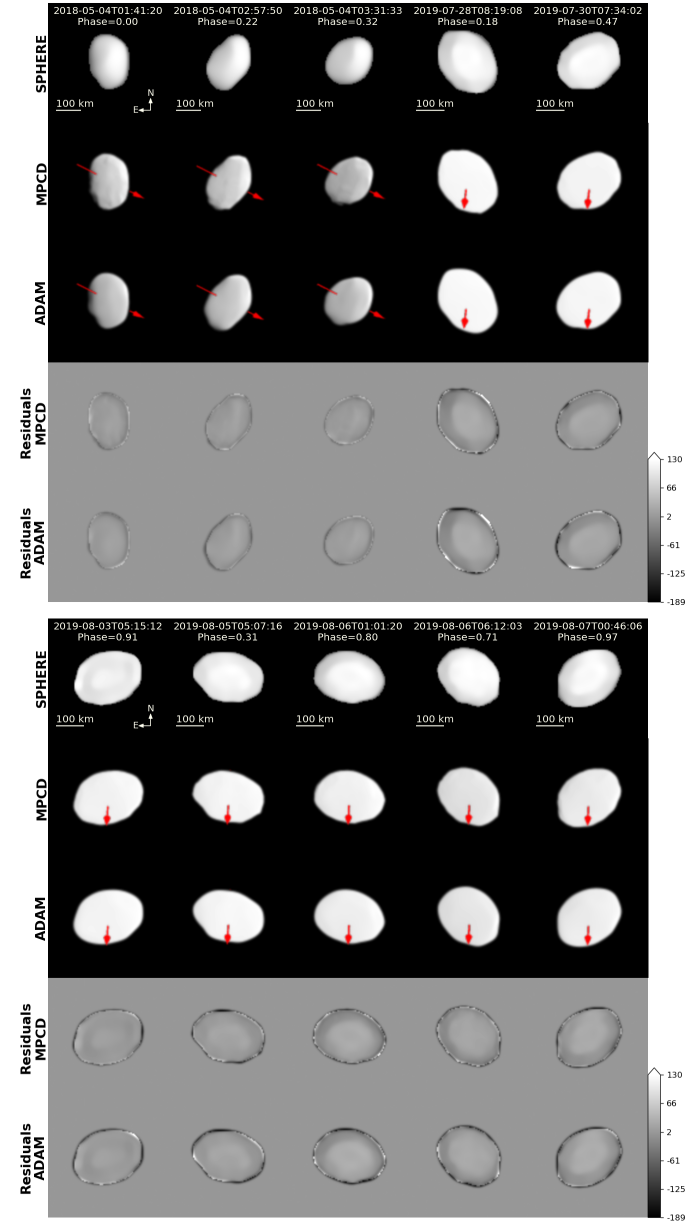


Fig. B.24: (45) Eugenia.

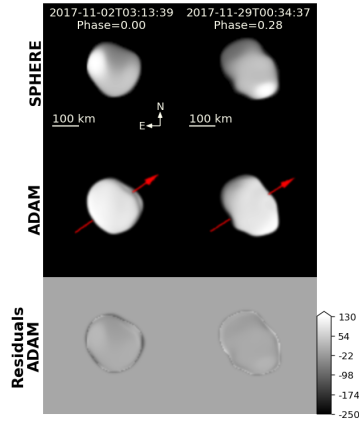


Fig. B.25: (48) Doris.

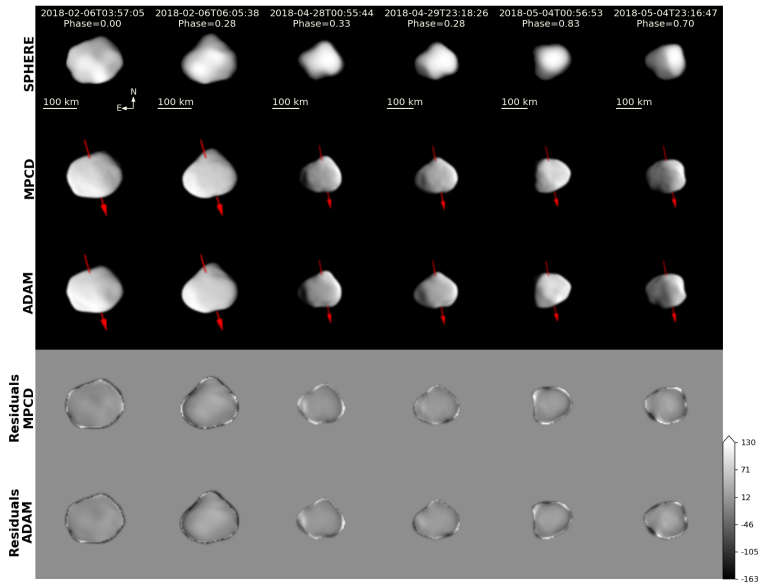


Fig. B.26: (51) Nemausa.

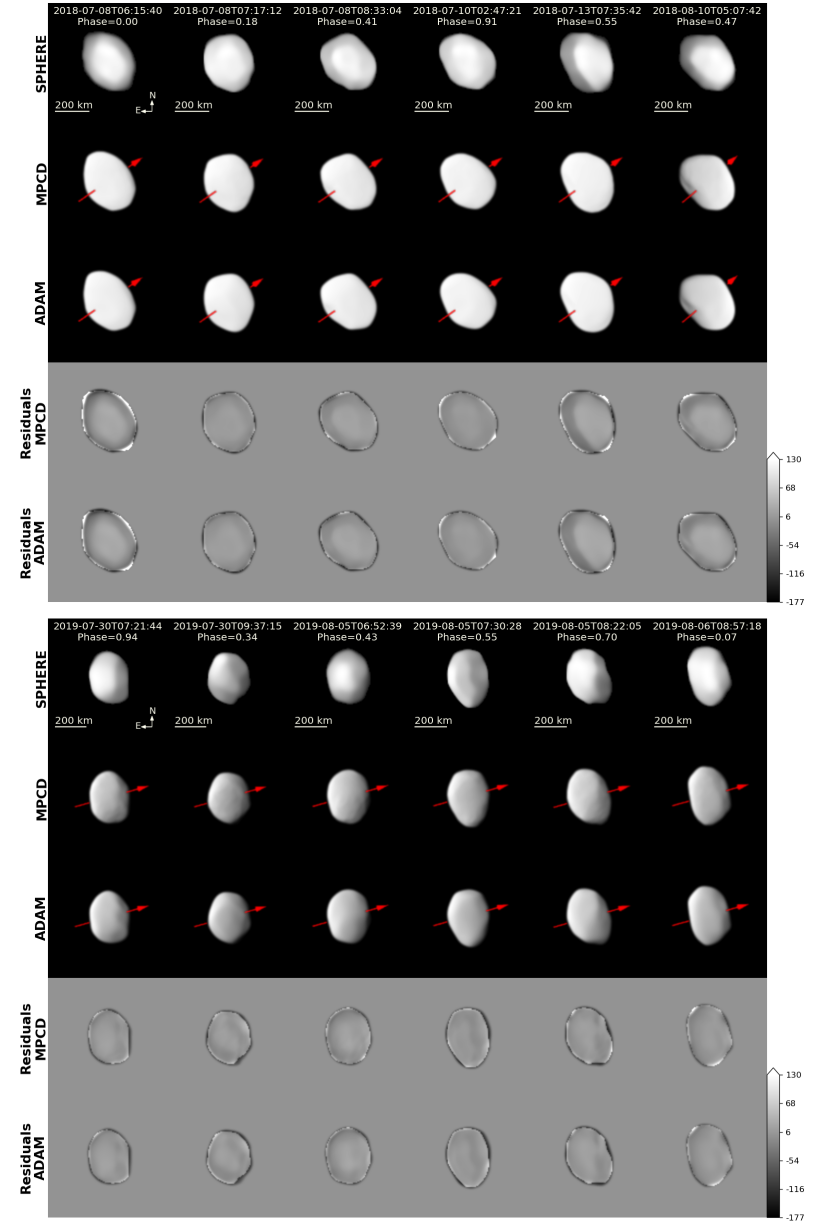


Fig. B.27: (52) Europa.

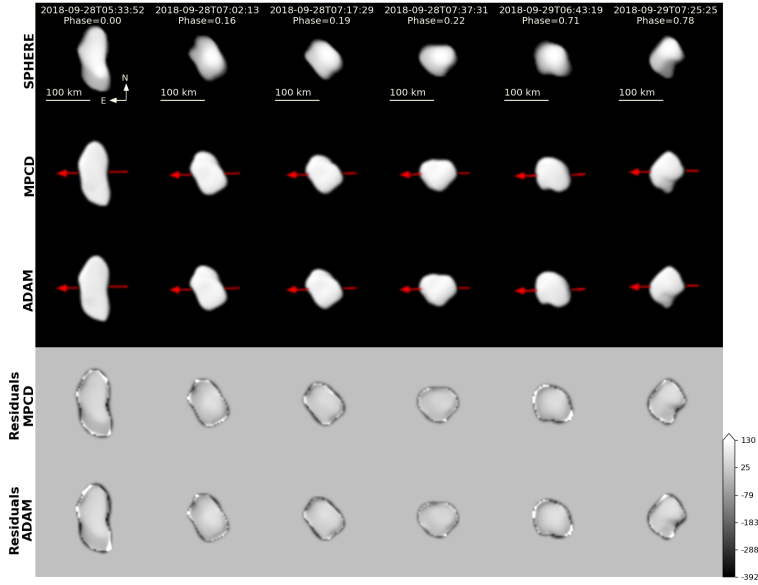


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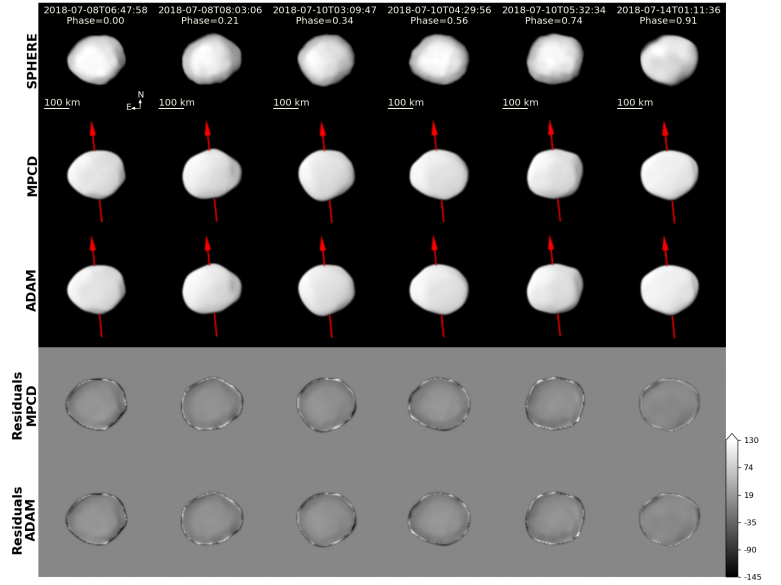


Fig. B.30: (88) Thisbe.

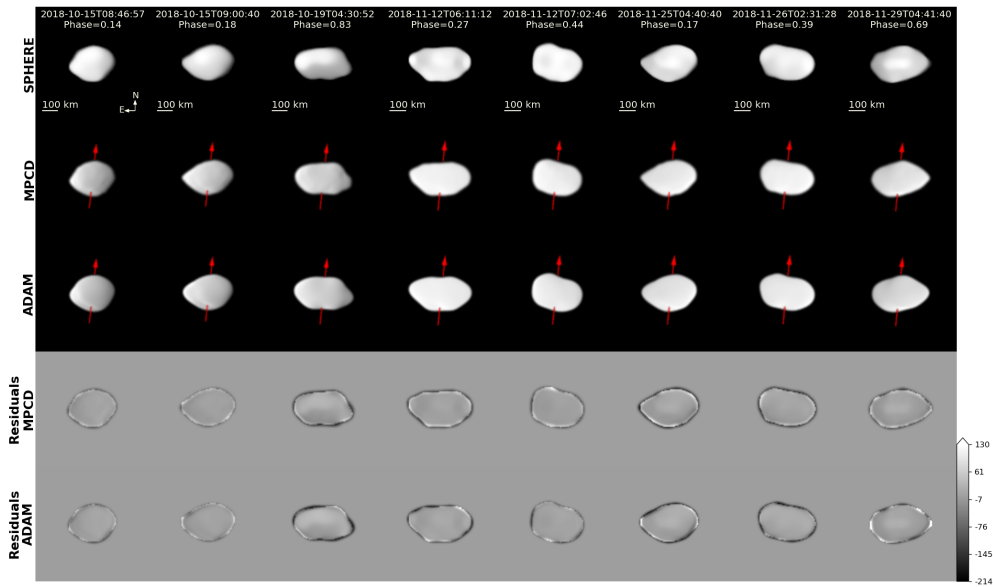


Fig. B.29: (87) Sylvia.

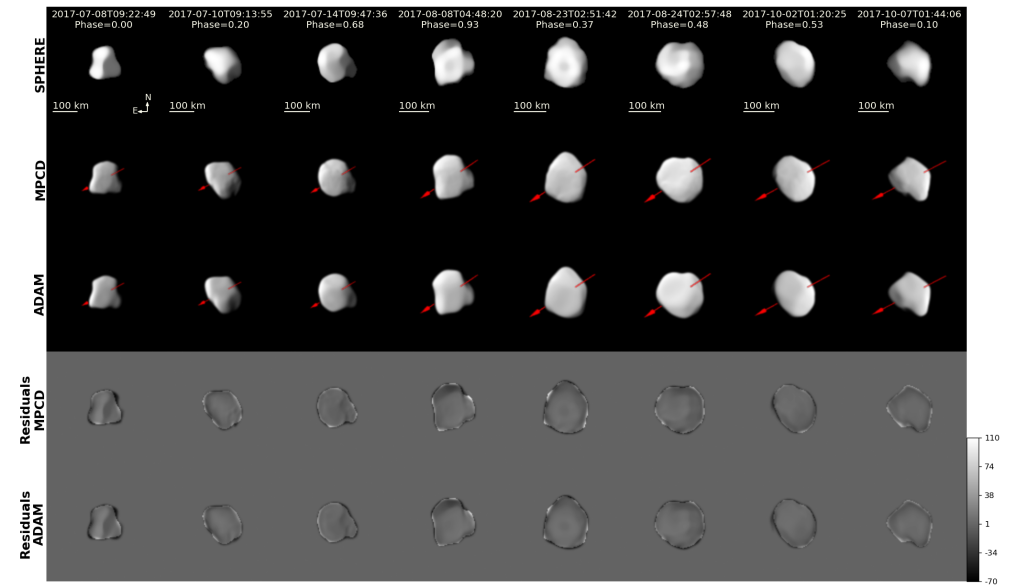


Fig. B.31: (89) Julia.



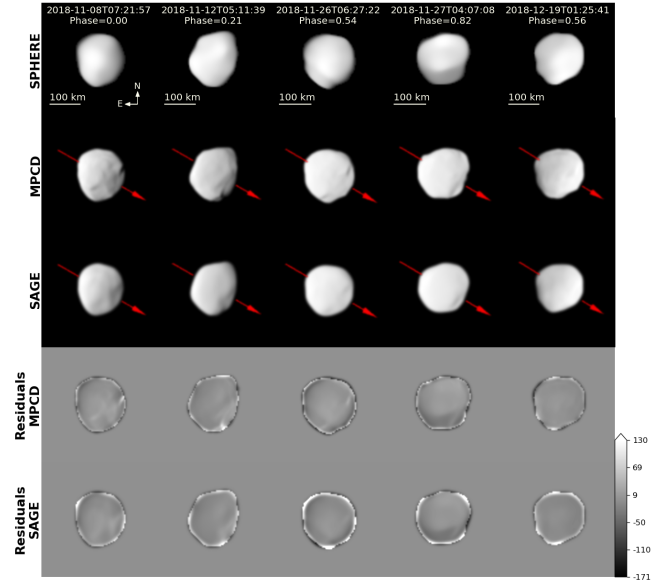


Fig. B.32: (128) Nemesis.

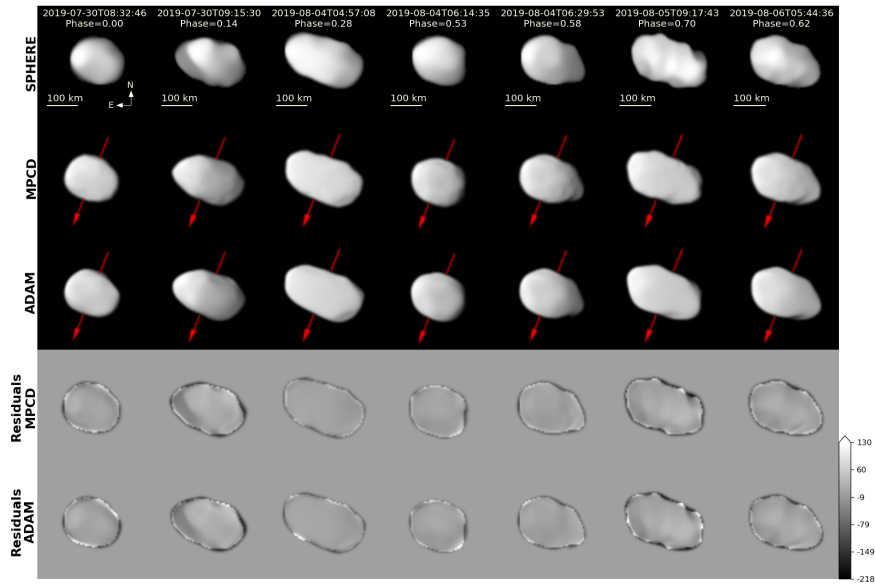


Fig. B.33: (130) Elektra.

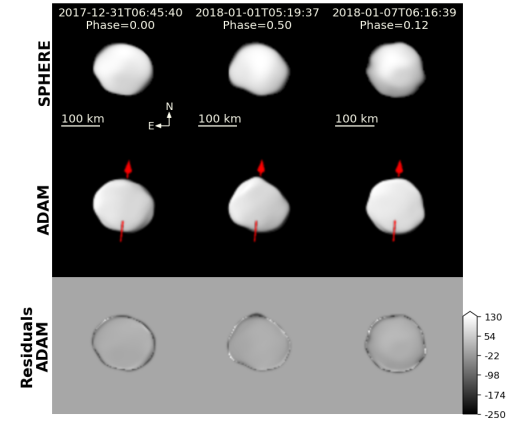


Fig. B.34: (145) Adeona.

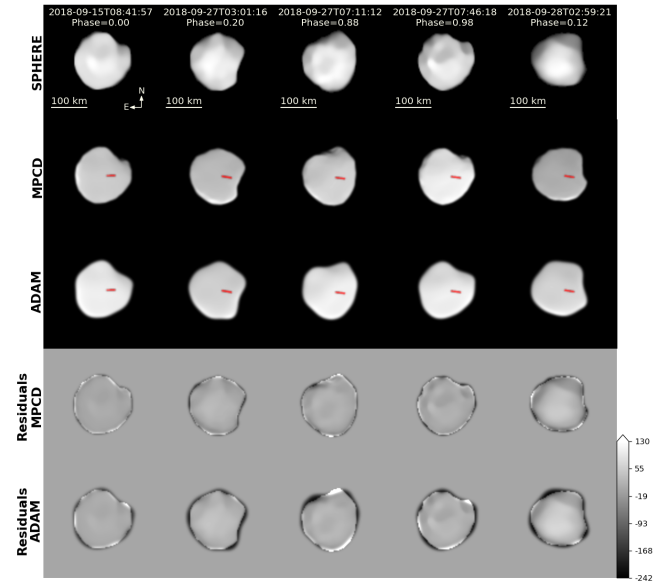


Fig. B.35: (173) Ino.

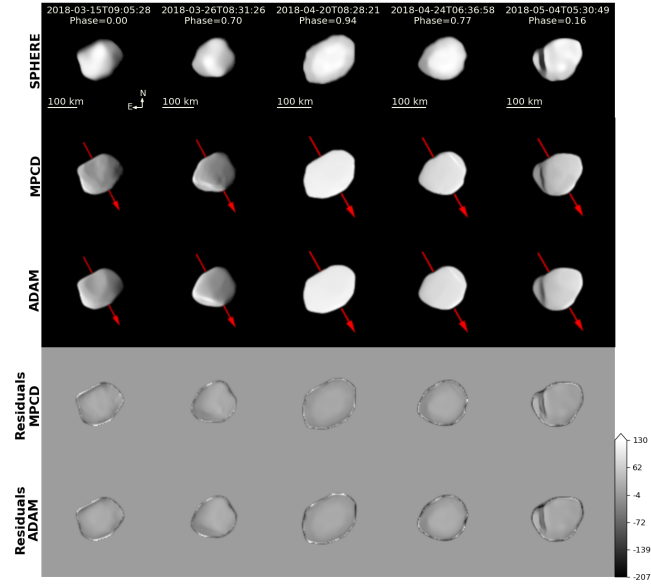


Fig. B.36: (187) Lamberta.

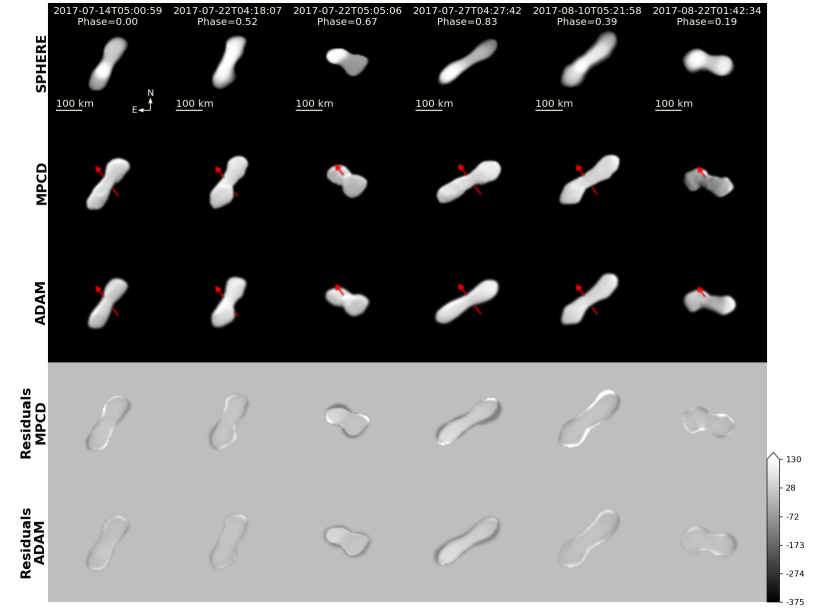


Fig. B.37: (216) Kleopatra.

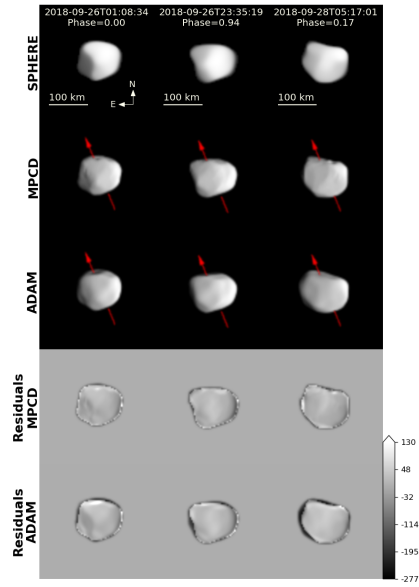


Fig. B.38: (230) Athamantis.

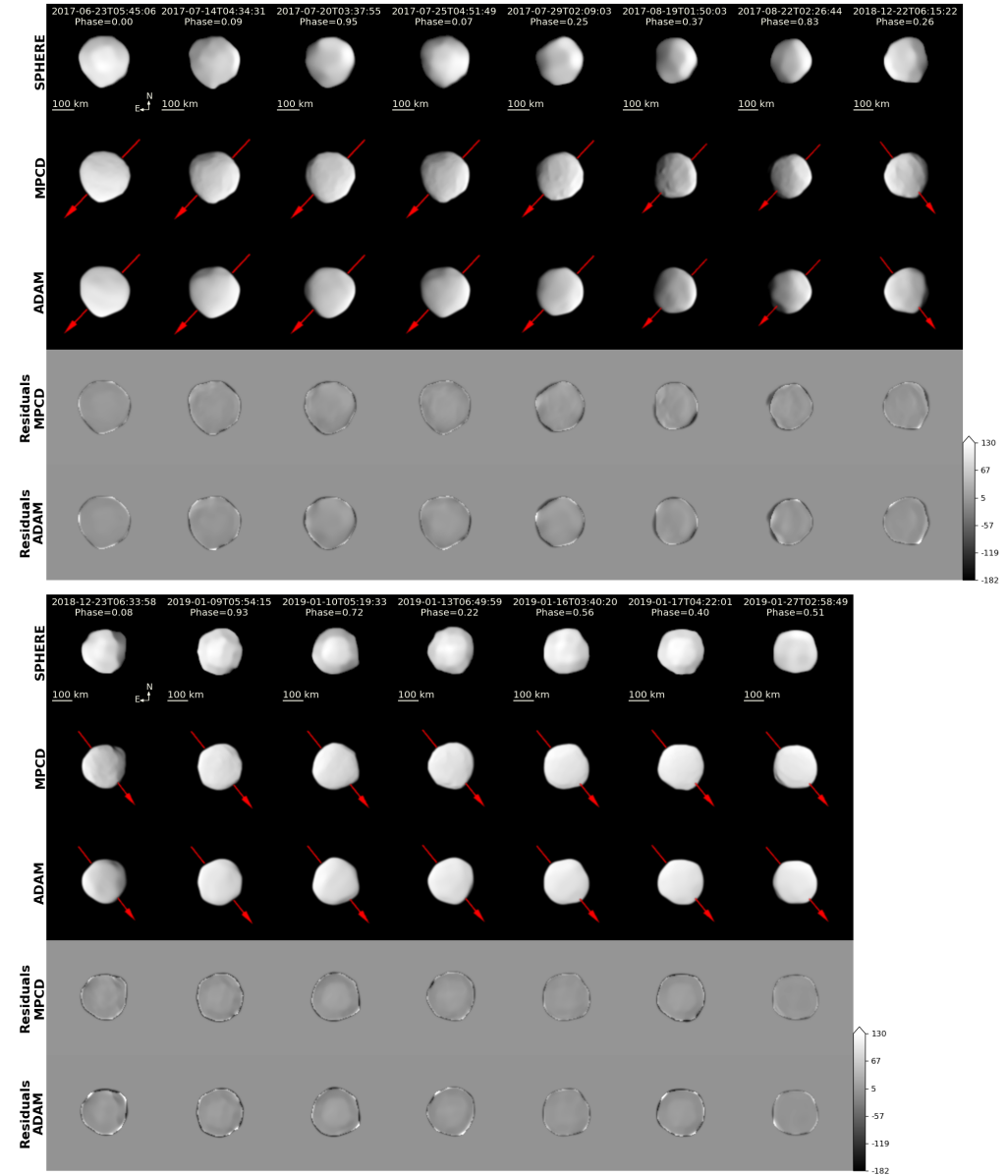


Fig. B.39: (324) Bambergia.

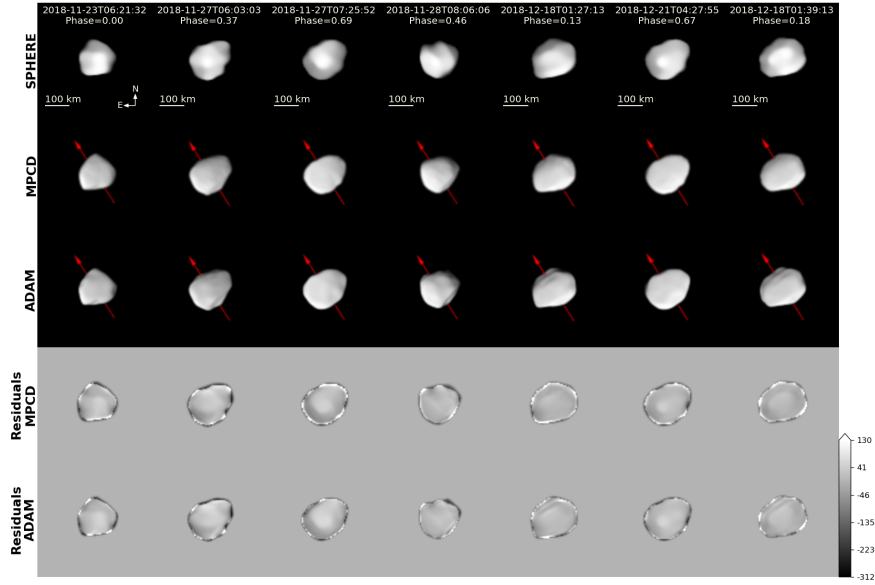


Fig. B.40: (354) Eleonora.

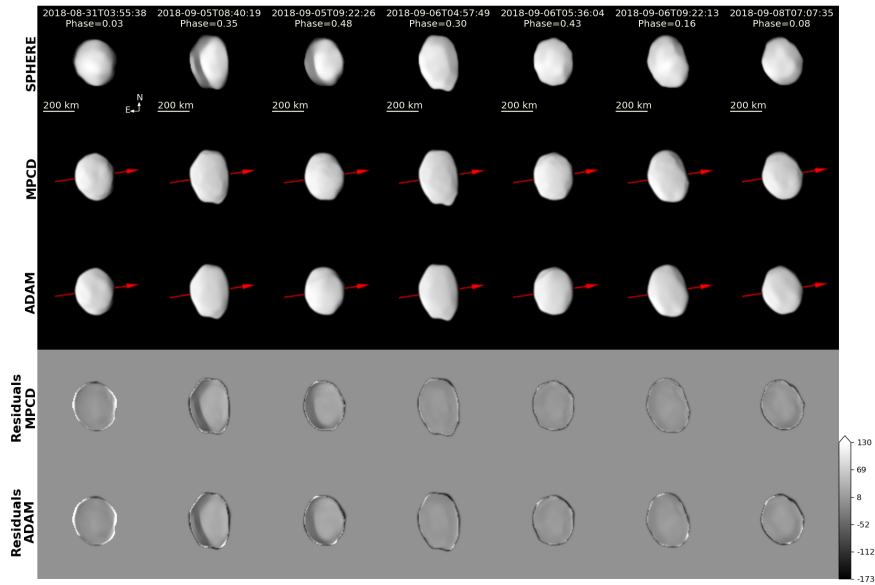


Fig. B.41: (511) Davida.

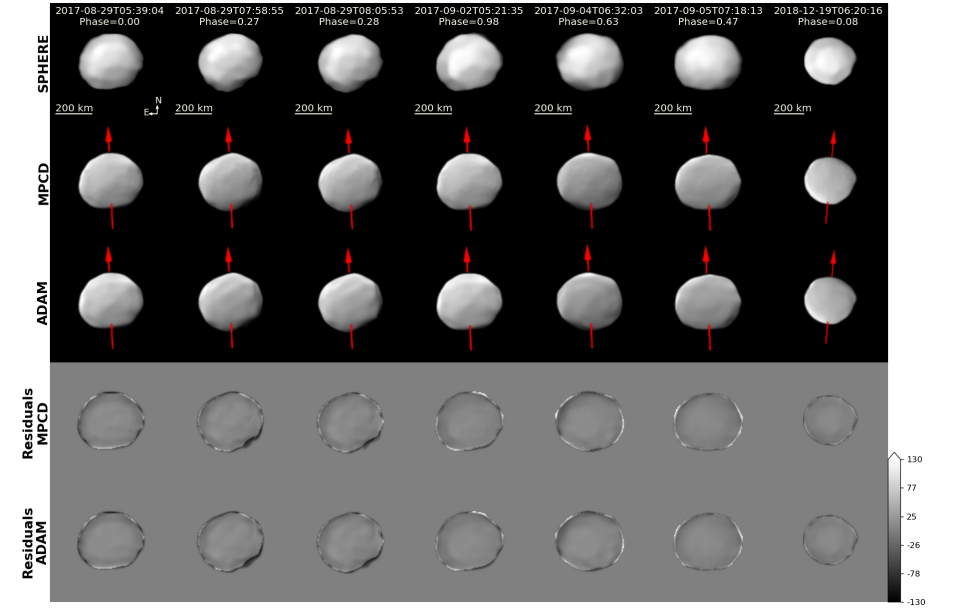


Fig. B.42: (704) Interamnia.

## 6. Conclusions and perspectives

This thesis aimed to bring new constraints on the formation and evolution of the largest main belt asteroids in the framework of an ESO large program. This imaging survey used the VLT/SPHERE/ZIMPOL instrument to obtain high-resolution observations for a significant sample of the largest ( $D \geq 100$  km) asteroids. The resolutions of these asteroid images, unprecedented from a ground-based facility, allowed for the first time to characterize the topology and shape, thus the volume, of a large number of MBAs.

First, numerous lightcurves of these objects were obtained using the two TRAPPIST telescopes. These photometric data were then used by the multi-data modeling algorithms ADAM and SAGE where they helped to constrain the spin parameters as well as the global shape, when combined to the SPHERE images. For some asteroids, the produced lightcurves also allowed to determine their correct rotation periods (Hygiea and Nemesis) or helped to find their previously unknown spin axis coordinates (Intermania and Bambergia) via extensive observations of these challenging targets.

Then, we applied the MPCD 3D reconstruction method to 40 out of the 42 targets of the large program. MPCD was first adapted for the usage of the AO deconvolved images obtained with SPHERE. We then used the shape models previously generated by other methods as input meshes for MPCD in order to attempt to further refine them. In almost all cases, the obtained MPCD models showed a better fit to the observed images. The diameters provided by the ADAM and MPCD models were combined with previous mass estimates to derive new estimations of the bulk density of our targets.

The densities in our sample show a large difference between the least dense objects ( $1.3 \text{ g}\cdot\text{cm}^{-3}$ ; Sylvia and Lamberta) and the densest one ( $4.4 \text{ g}\cdot\text{cm}^{-3}$ ; Kalliope), indicating large variation of interior compositions across the sample. Such variety of compositions hints at migration processes at work after the formation of these bodies. Hence, different composition classes must have originated from distinct regions in the early Solar System.

In parallel to the 3D reconstruction of all the large program targets with MPCD, we dedicated special efforts to the detailed characterizations of two particularly interesting asteroids, (16) Psyche and (22) Kalliope. Both objects are metallic rich asteroids whose densities were found to be among the highest known for small bodies. The obtained 3D shape of Psyche, which is the target of a forthcoming NASA discovery mission, was found to be close to that of an ellipsoid, except for three large depressions possibly caused by impacts. Moreover, Psyche is compatible with a primordial

## 6. Conclusions and perspectives

shape close to that of a Jacobi ellipsoid, assuming a slightly faster initial rotation. This implies that its formation must have occurred while its interior was still in a fluid state. The bulk density of Kalliope, determined from its shape model and from the dynamics of its satellite, was found to be higher than most previous estimations. Coupled with its silicate-rich surface composition, this results strongly suggests a differentiated interior with a thin silicate mantle and a large metallic core contributing to most of the mass of the body. This internal structure is similar to that of the planet Mercury and could have resulted from collisional stripping, which could also explain the formation of its satellite Linus and of a recently discovered family linked to Kalliope.

Finally, a shape analysis was performed on each target of our sample. We computed the departure to an ellipsoid and the asphericity of each asteroid. Both quantities showed strong anti-correlations with the size, thus the mass. Moreover, a bimodal distribution appeared in the asphericity distribution, allowing to define two groups composed of more spherical bodies on the one hand, and of more elongated bodies in the other hand. Furthermore, the origin of the different type of shape appears to be driven mainly by the rotation period after the mass. The computation of the normalized angular velocity and the specific angular momentum showed that all of our targets, except for the particular case of Kleopatra, fall along the Maclaurin sequence. We then also compute the specific angular momentum and normalized angular velocity of our targets based on their derived 3D shapes, rotation periods and bulk densities, and compared them with the theoretical values for the Maclaurin, Jacobi, and dumb-bell sequences. All of our targets fall along the Maclaurin sequence, except for Kleopatra who is on the dumb-bell sequence. Psyche is found near the intersection between the Maclaurin and Jacobi sequence. This also allowed to differentiate the volatile-rich bodies from the volatile-poor due stronger relaxation of their interiors.

The imaging survey of large MBAs proved to be a great success with many important results and marked the beginning of ground-based asteroid geology. They are a few topics that could still be investigated using the large program data. One of them concerns the study of the craters visible at the surfaces of several objects, and notably of their size-frequency distributions. These asteroids are: Pallas, Juno, Hebe, Iris, Egeria, Eunomia, Melpomene, Ino and Lamberta. Refined modeling of these asteroids with the MPCD method could be possible by using masks on the limbs in order to better capture the visible craters on the 3D shape while avoiding the apparitions of artifacts coming from the signal of the limbs.

On another topic, Kalliope's satellite, Linus, is resolved by SPHERE thanks to its angular diameter of  $\sim 25$  mas. We thus started to investigate on the determination of its shape but this work is still in progress. Ongoing works on the deconvolution of the SPHERE images should be highly beneficial to this task.

In the future, it will also be interesting to continue to observe new asteroids by taking advantages of close oppositions, as in the case of Cybele and Hermione. A dedicated survey aiming to find and characterize binary asteroids would also be of importance.

## 6. Conclusions and perspectives

While S, Ch/Cgh and C/Cb asteroid classes have been well sampled by the SPHERE survey, only four M-type asteroids have been observed so far (Psyche, Kalliope, Lutetia, and Kleopatra). However, these objects are of particular importance notably because they might hold the keys to the mystery of the origin of metal-rich iron meteorites for which we don't have any direct association with possible parent bodies at the moment. In total, 11 M-type MBAs can be resolved by SPHERE which would more than double our current sample of M-type MBAs with accurate bulk densities. A dedicated survey of this enigmatic population with SPHERE would therefore be promising.

Finally, the techniques employed in this thesis, notably the application of the MPCD method, will highly benefit from the future next-generation telescopes such as the Extremely Large Telescope (ELT), TMT, or GMT. For instance, the ELT is expected to provide resolutions  $\sim 3$  times better than SPHERE at first ( $\sim 5$  mas, in the NIR) and  $\sim 5$  times better with second-generation AO instrument in the visible ( $\sim 3$  mas). This will allow to observe a much larger number of smaller MBAs with diameters between 35–80 km. It will even be possible to reach objects outside of the main belt. At a distance of 5 AU, the largest 40 Jupiter Trojans have an apparent angular diameter between  $\sim 20$  mas and  $\sim 80$  mas and thus will be resolvable with ELT. Even the largest TNOs will be observable as, for instance, a 700 km object at 45 AU has an apparent angular diameter of 21 mas.



# A. Lightcurves of the ESO large program targets

I show here the lightcurves of asteroids observed for the ESO large program with TRAPPIST, but not discussed in the main text (Sect. 2.6). They were also presented in three Minor Planet Bulletin reports ([Ferrais et al., 2019](#), [2021](#), [2022](#)).

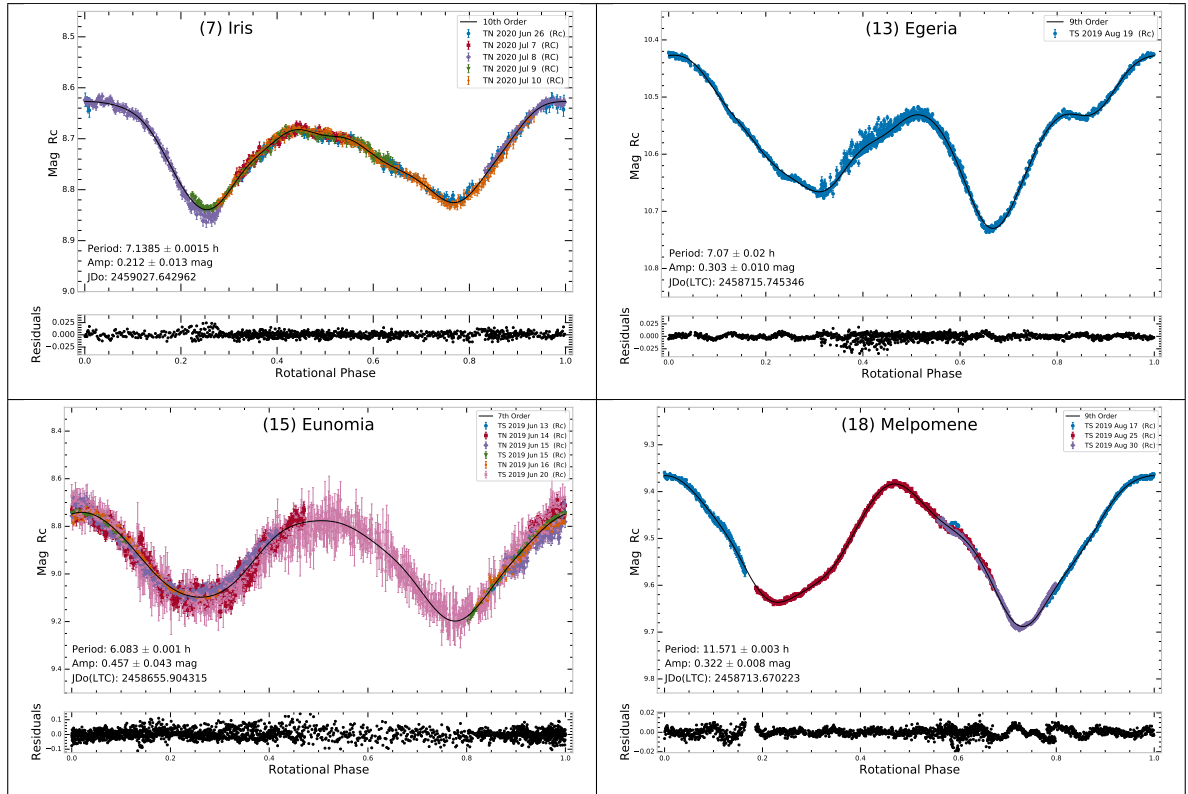


Figure A.1.: Lightcurves of large MBAs observed with TRAPPIST in support of the ESO large program between 2017 and 2021.

## A. Lightcurves of the ESO large program targets

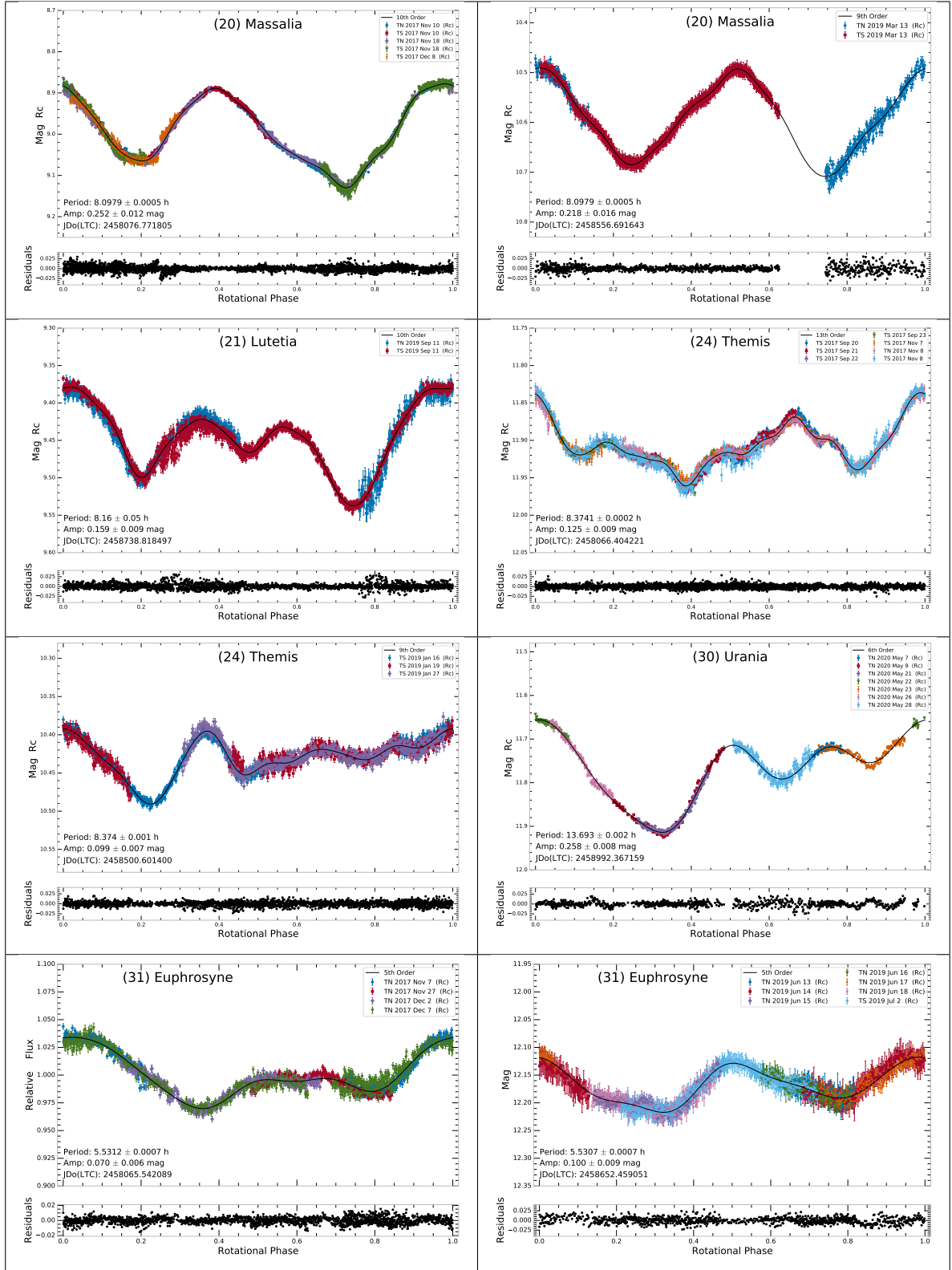


Figure A.1.: Lightcurves of large MBAs observed with TRAPPIST in support of the ESO large program between 2017 and 2021 (continued).

## A. Lightcurves of the ESO large program targets

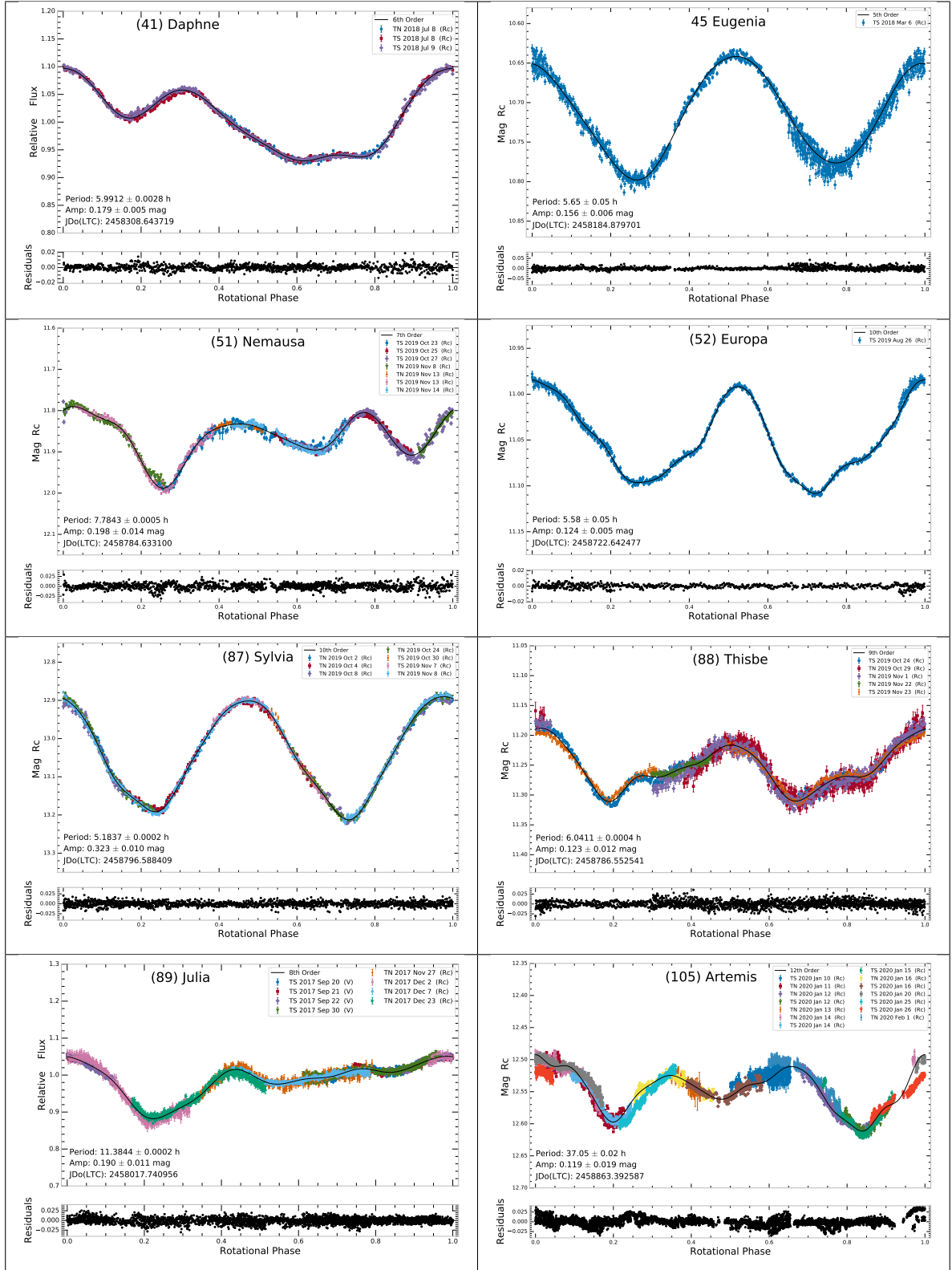


Figure A.1.: Lightcurves of large MBAs observed with TRAPPIST in support of the ESO large program between 2017 and 2021 (continued).

## A. Lightcurves of the ESO large program targets

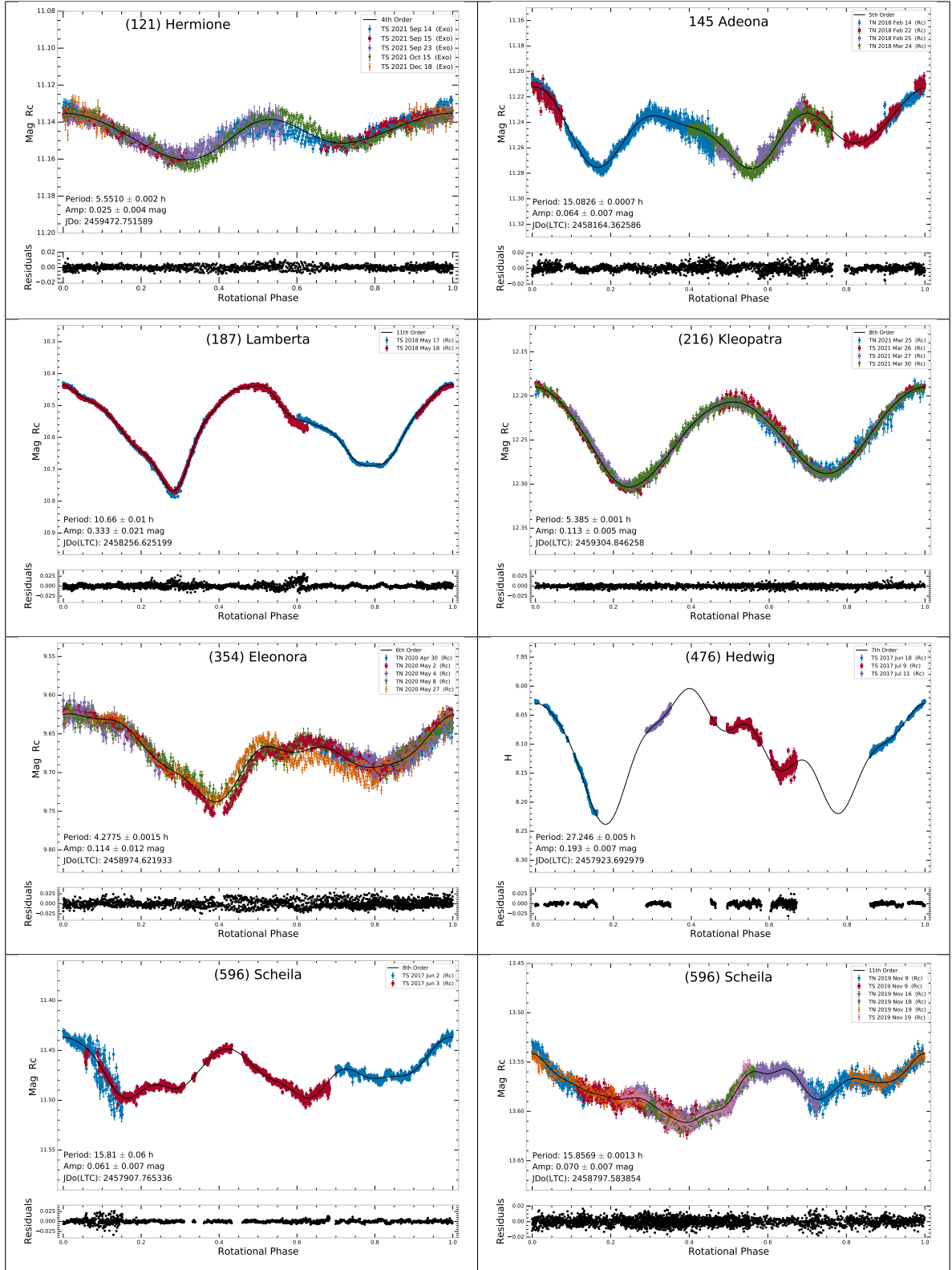


Figure A.1.: Lightcurves of large MBAs observed with TRAPPIST in support of the ESO large program between 2017 and 2021 (continued).

## B. Additional TRAPPIST asteroid observations

This section presents brief descriptions of the studies of some important asteroids carried out with the TRAPPIST telescopes, in collaboration of various projects. They concern both MBAs and NEAs such as active asteroids, targets of space missions, or binary systems. At the end, summary tables of all asteroids observed with TRAPPIST between 2018 and 2022 are provided (Table B.6.1 for the MBAs, and Table B.6.2 for the NEAs).

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### B.1. (3200) Phaethon and 2005 UD

The asteroid (3200) Phaethon is an Apollo NEA of  $\sim 5$  km in diameter with a highly elliptical orbit ( $e = 0.89$ ) that brings it closer to the Sun than any other known asteroid ( $q = 0.14$  AU). It is classified as a B-type asteroid, like the large MBA (2) Pallas with which it also shares dynamical connections. Phaethon is considered as the parent body at the origin of the Geminid meteor shower that peaks in December. Indeed, during its perihelion passage of 2009 and 2012, a brightening by a factor two associated to a comet-like tail was detected (Jewitt and Li, 2010; Jewitt et al., 2013). Because the surface temperature of Phaethon near perihelion ( $\sim 1000$  K) is too large for water to survive, it was proposed that thermal fracturing would be the cause of the ejection of dust particles.

The unique characteristics of Phaethon makes it a privileged target for a space mission. The DESTINY+ mission (Demonstration and Experiment of Space Technology

for Interplanetary voyage Phaethon flyby and dUst Science) is a joint mission between JAXA and the DLR. The spacecraft is planned to be launched in 2024 and should fly by Phaethon in 2028 to analyze dust samples originating from Phaethon and investigate the mechanisms of ejection.

Before the arrival of DESTINY+ to Phaethon, a great observation opportunity occurred in December 2017 when it made a close approach to the Earth with a minimum distance of 27 lunar distances. The flyby as well visible from the northern hemisphere, we thus planned to extensively observe it with TN to gather rotational lightcurve at a large range of solar phase angles (angle between the Sun and the Earth as seen from the asteroid). Such data are valuable to derive a convex shape using lightcurve inversion, or to be combined with other type of data such as the radar observations by the Arecibo planetary radar system and the Goldstone Solar System Radar.

We also obtained multi-color photometric observations to investigate the presence of surface color heterogeneity, notably motivated by the report by [Kinoshita et al. \(2017\)](#) of the detection of longitudinal inhomogeneity from their rotationally time-resolved spectroscopic data. During the first two nights of observations (December 9 and 10), we used alternatively the B, V, Rc and Ic Johnson-Cousins filters to sample the lightcurve in different colors. We observed during 11.5 h the first night and 8.2 h during the second, covering over 3 and 2 complete rotations respectively. The multi-filter lightcurves are showed in Fig. B.1.

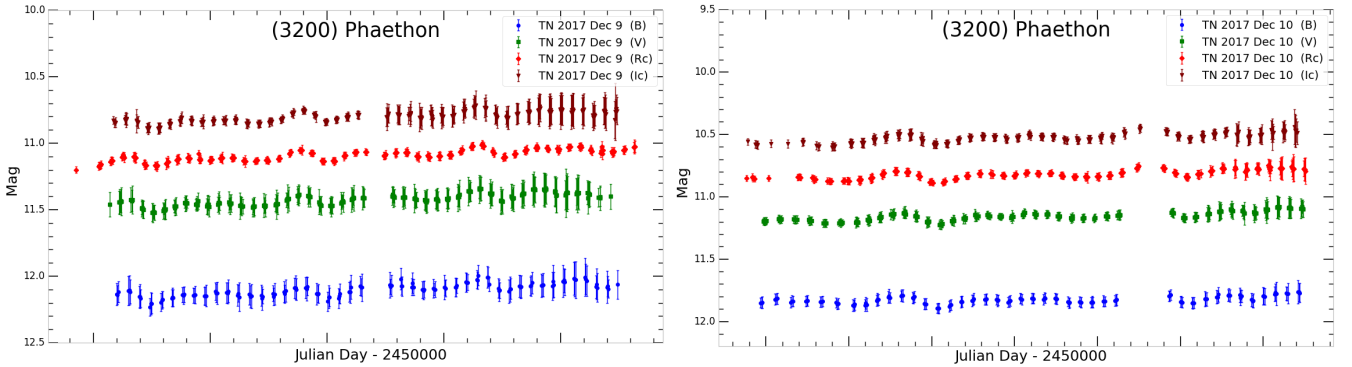


Figure B.1.: Observations of Phaethon in the B, V, Rc and Ic bands obtained with TN a few days before Phaethon's close flyby of Earth. The left figure shows the magnitudes as a function of time covering multiple rotations obtained on December 9 and the right figure is for December 10.

The multi-color lightcurves were separated in groups, each containing the four different filters, to compute color indexes at different rotational phases. The color indexes, phased with the spin period  $P = 3.6034$  h, do not show any significant rotational variations (Fig. B.2). This results is consistent with other color measurements by [Borisov et al. \(2018\)](#), which found, however, a clear rotational variation of the degree of linear polarization. This indicates the presence of heterogeneity of the surface albedo, of the regolith properties, or of the mineralogy but the latter is not supported by the

color data.

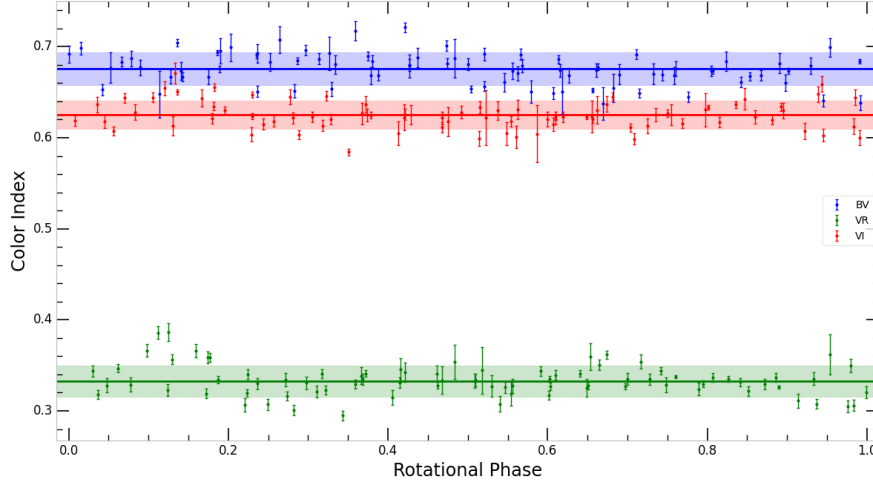


Figure B.2.:  $B - V$ ,  $V - R_c$  and  $V - I_c$  color indexes of Phaethon as a function of the rotational phase from observations obtained in December 9 and 10, 2017. The shaded regions correspond to the uncertainties on the mean values:  $BV = 0.67 \pm 0.02$ ,  $VR = 0.33 \pm 0.02$ ,  $VI = 0.63 \pm 0.02$ .

The following nights were mostly carried out using the  $R_c$  filter. The phase angle varied considerably, from  $19^\circ$  on December 9 up to  $110^\circ$  on December 20. The lightcurves showed large variations in shape and an increase by more than one magnitude of the amplitude: from 0.13 mag to 1.37 mag. We continued to observe Phaethon during the following apparitions of 2020 and 2021 to gather data at different viewing geometries and support ongoing modeling works. The observing circumstances are provided in Table B.6.2, along with the information for all the other NEAs observed with TRAPPIST.

(155140) 2005 UD is also an Apollo-type NEA with similar color and dynamical properties to Phaethon, suggests a possible common origin. 2005 UD could also be the target of a mission extension of DESTINY+. This triggered an observational campaign focused on 2005 UD aimed at investigating the possibility of a link with Phaethon and to prepare the mission. We participate by observing 2005 UD during five nights in October 2018 and three more in November 2019. Our data cover multiple rotations, assuming a period  $P \sim 5.23$  h, which produces a symmetrical double-peaked lightcurve. They were used to study the shape of 2005 UD and its rotation properties by [Devogèle et al. \(2020\)](#) and Kueny et al. (in prep.).

## B.2. (99942) Apophis

(99942) Apophis is an Aten-type NEA with a size of  $\sim 340$  m. It caused a stir after its discovery in 2004 because of early predictions on the possibility of an impact with Earth in 2029 with a probability of more than 2% ([Chesley, 2006](#)). Apophis reached



Level 4 (out of 10) on the Torino impact hazard scale that is used to categorize the asteroid and comet impact predictions (Binzel, 2000)

Follow-up observations allowed to reduce the probability of impact. Radar measurements at the Arecibo Observatory in 2005, 2006 and 2017, and at the Goldstone Solar System Radar and the Green Bank Telescope in March 2021 were used to precisely estimate the orbit of Apophis. These predictions allowed to make disappear the impact threats. Instead, they indicated that Apophis will perform an exceptionally close flyby of Earth in April 2029, at a geocentric distance of 32 000 km, which is within the geosynchronous orbit.

Such a close approach is expected to induce variations of its physical properties because of the gravitational perturbation of the Earth. The orbit but also the spin state and surface arrangement are expected to be affected. The close Earth encounter of 2029 is thus a great opportunity to study the evolutionary processes that take place under tidal forces. A good characterization of the pre-encounter physical properties of Apophis is required to be compared to the post-encounter values. It was recently announced that the OSIRIS-REx spacecraft, on its way to Earth to return samples of the NEA Bennu in 2023, would continue its mission to a rendezvous with Apophis in 2029. The spacecraft should reach Apophis only a few days after its closest approach of Earth, allowing a post-event characterization.

The last close approach of Apophis in March 2021 provided an excellent opportunity to obtain important data for more detailed studies of its physical properties. We observed it in photometry with both TN and TS during the visibility period which extended from January to April 2021. We gathered more than 6300 individual data points spread on 56 nights. The phase angle varied from 59° in January to 21° at the end of February, before increasing again up to 74° at the end of the observations in April.

Apophis is known to be in non-principal axis rotation state with a rotation periods of 27.38 h and a precession period of 263 h (Pravec et al., 2014). Our data are in agreement with a period of 30.59 h producing the strongest lightcurve amplitude in single axis mode (Fig. B.3).

Our data are currently used by different teams and analyzed together with data reported by other groups of the campaign to derive a shape model, study the rotational properties of Apophis (spin poles and tumbling state), and constrain the YORP affecting it.

### **B.3. The active asteroid (6478) Gault**

(6478) Gault is a ~ 4 km MBA which was discovered to display cometary-like activity in December 2018 (Smith et al., 2019). This activity, along with its orbital properties, classifies Gault as a new member of the active asteroid population (Jewitt et al., 2015). To decipher the nature of the displayed activity, the rotation period is one of the key parameter to be determined. Indeed, a very fast rotation would point to a rotational

B. Additional TRAPPIST asteroid observations – B.3. The active asteroid (6478) Gault

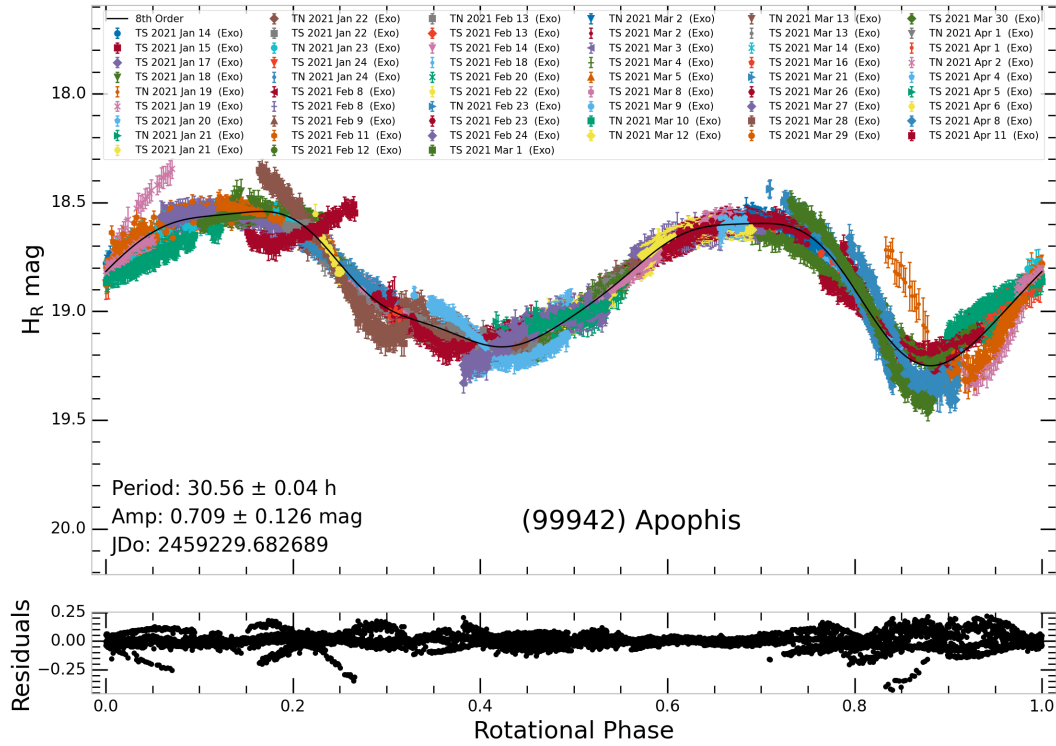


Figure B.3.: Phased lightcurve of Apophis using our data obtained with TN and TS from January to April 2021 and a single axis mode period of 30.59 h. The epochs have been light-time corrected and the  $H_R$  magnitudes have been reduced to one AU from the Earth and the Sun and corrected to a consistent phase angle.

disruption as the most probable cause of the dust ejection.

### 2019 apparition

Long photometric series were obtained with TS and TN on 2019 January 13, 14, and 15. Five lightcurves of about 5 h each were acquired with the Rc filter. We also observed it with both telescopes on the same night on January 14 and 15, providing 7.3 h long lightcurves with some overlap between the telescopes. The resulting lightcurves were essentially flat except for a weak slope at the beginning of the observation of January 13, but which did not repeat in following observations (Fig. B.4). We were therefore unable to determine the period at that time. The most likely cause was that the presence of dust around the nucleus was hiding its surface. By comparing the magnitude before and after the activity period, it can be estimated that approximately half of the total brightness was produced by the dust. Moreover, fast rotators often present a so-called spinning top shape which is close to a spheroid and thus produce small rotational amplitudes.

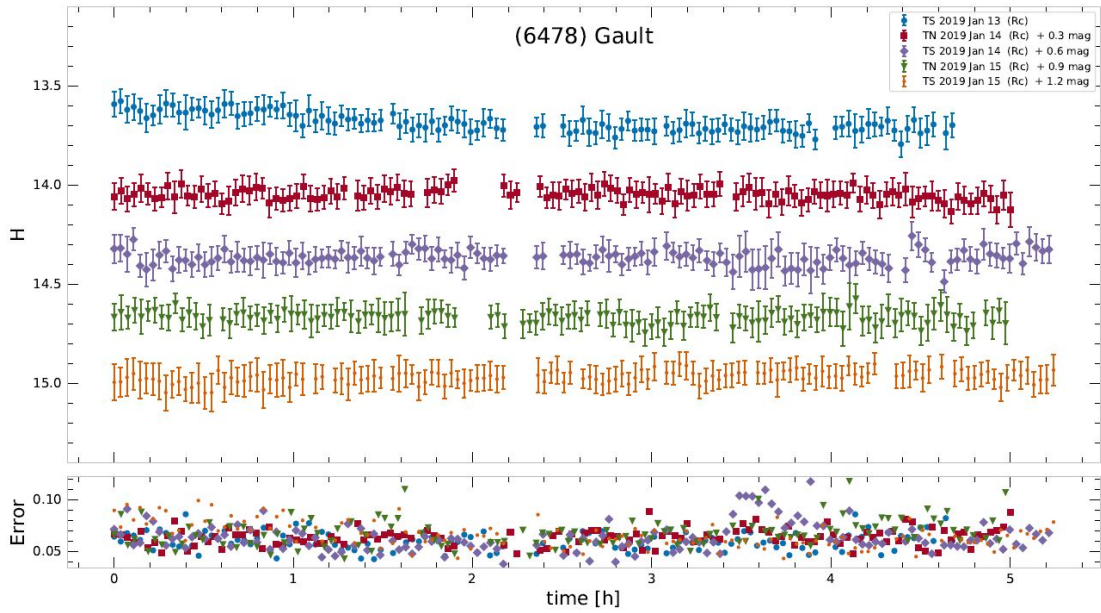


Figure B.4.: Lightcurves of Gault obtained with TN and TS on January 13, 14, and 15 in 2019, and shifted for clarity. The  $H$  magnitude was computed assuming  $V - Rc = 0.049$  and a slope parameter  $G = 0.227$ . Data published in [Moreno et al. \(2019\)](#).

### 2020 apparition

During the next apparition of Gault, the dust had dispersed and no more signs of activity could be detected. A new tentative of the determination of the rotation period was carried out. We observed Gault with TN from August 22 through September 26, 2020

and once with the 1-m telescope Artemis on September 19, for a total of 9 lightcurves. More details on Artemis are given in Sect. B.5. The observing circumstances of Gault are provided in Table B.6.1, along with those of other MBAs observed with TRAPPIST.

Devogèle et al. (2021) combined our data with observations from multiple larger facilities. The TRAPPIST data allowed to extend the arc of observation and thus to improve the period determination. The analysis of Devogèle et al. (2021) found a rotation period of  $P = 2.4929 \pm 0.0003$  h. The TRAPPIST data phased using this period show a small but clear periodic signal with an amplitude of  $0.05 \pm 0.02$  mag (Fig. B.5). This short period is compatible with an activity event driven by rotational instability, probably caused by the YORP spin-up effect (Bottke et al., 2006).

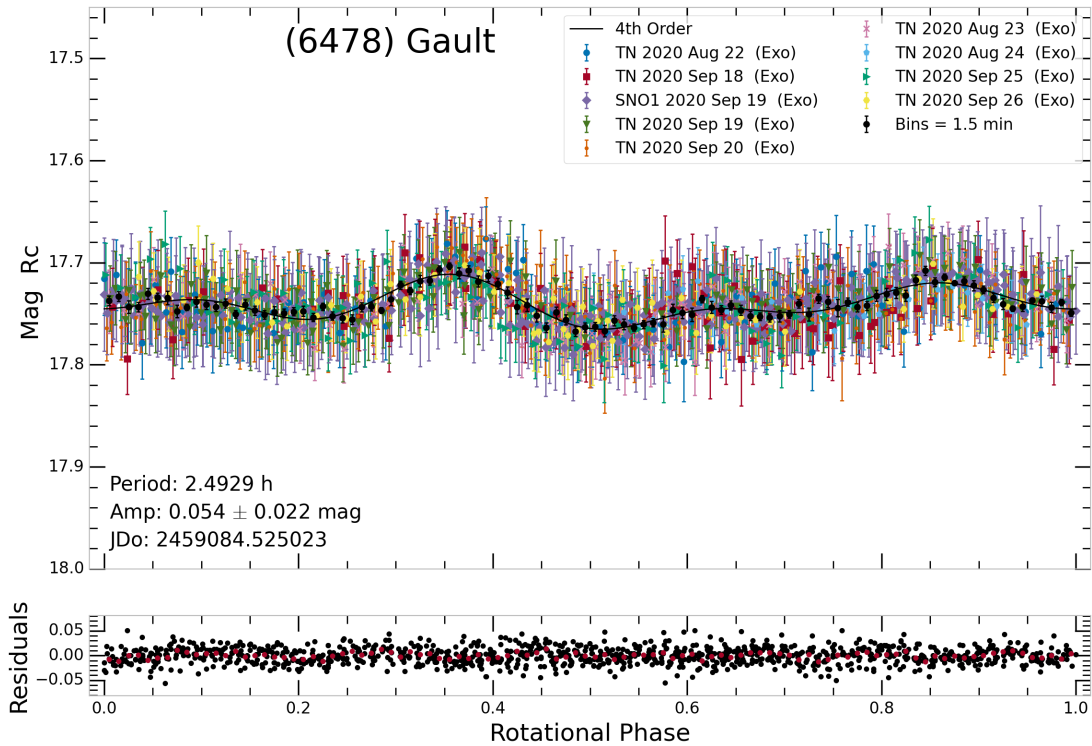


Figure B.5.: Phased lightcurve of Gault from TRAPPIST and Artemis observations during the 2020 apparition while Gault’s nucleus was no longer obscured by dust.

### Color and phase curve

In addition to the long series destined to the determination of the period, we also regularly obtained short series to determine color values and to monitor the variation of Gault’s magnitude as a function of the solar phase angle.

For the colors, we acquired images using the B, V, Rc, and Ic filters with both TN and TS over the two apparitions. The resulting colors show no rotational variations as well as no significant differences between the two apparitions (Fig. B.6). The mean

values found are  $BV = 0.79 \pm 0.12$ ,  $VR = 0.44 \pm 0.09$ , and  $VI = 0.78 \pm 0.11$ . They are consistent with other measurements in (Devogèle et al., 2021).

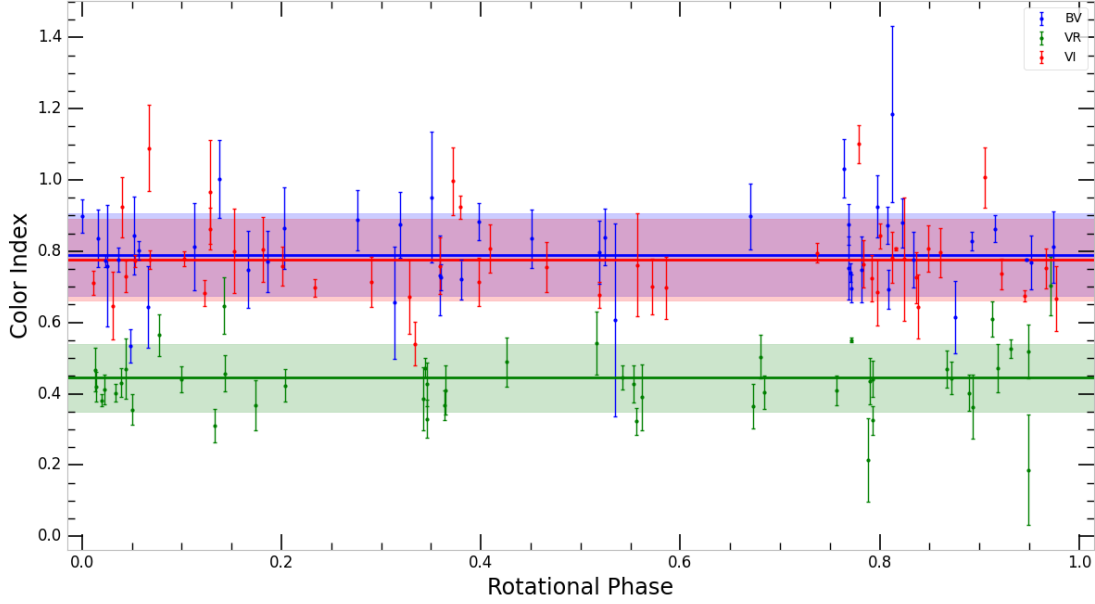


Figure B.6.:  $B - V$ ,  $V - Rc$  and  $V - Ic$  color indexes of Gault as a function of the rotational phase from observations obtained in 2019 and 2020. The shaded regions correspond to the uncertainties on the mean values.

The phase curve was constructed by calibrating the  $B$ ,  $V$ ,  $Rc$ , and  $Ic$  magnitudes in the  $R$  band using the Pan-STARRS photometric catalog. When Gault got fainter, we continued the observations with the Exo filter to extend the range of phase angles to larger values. In 2020, we covered phase angles from  $0.4^\circ$  to  $23.6^\circ$ . The magnitudes were converted to reduced  $R$  magnitudes by correcting from the distance of Gault to the Earth and the Sun (Fig. B.7). These measurements were used by (Devogèle et al., 2021) which fitted them using the  $H$ ,  $G1$ ,  $G2$  system (Muinonen et al., 2010). The result can then be used to constrain the taxonomical type, the albedo and the grain sizes of Gault's surface.

## B.4. The Lucy target (52246) Donaldjohanson

(52246) Donaldjohanson is a MBA and a target of opportunity of the NASA Discovery mission Lucy that will fly by it in 2025 while on its way to the Jupiter Trojans (Marchi et al., 2020). This is a  $\sim 4$  km Cg-type asteroid (Souza-Feliciano et al., 2020) that belongs to the Erigone family, one of the most recent collisional family (Nesvorný et al., 2015). It was named in honor of the American paleoanthropologist Donald Carl Johanson, known as the discoverer of the Lucy fossil. This small asteroid is still poorly characterized, most importantly its rotation period and shape.

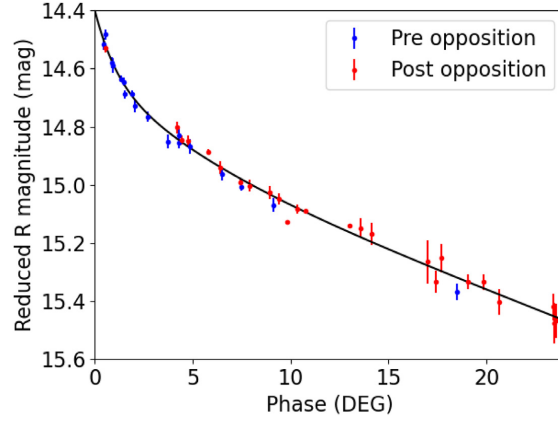


Figure B.7.: Phase curve of Gault for the 2020 apparition. The individual points correspond to the mean magnitude of a given night. Figure from (Devogèle et al., 2021).

We started observing Donaldjohanson in November 2020 to try to determine its previously unknown rotation period. It quickly appeared from the lightcurves of the first few nights that Donaldjohanson was a slow rotator. We thus modified our observations to one or two short series ( $< 1$  h) at the start and/or the end of the night on both telescopes, every night when possible. We stopped in February 2021 because it was getting too faint ( $V > 19$ ). In total we gathered 91 individual lightcurves spread on 68 different nights under good weather conditions (Fig. B.8).

The analysis of the data yields a unique period solution for a bimodal lightcurve at  $P = 251.9 \pm 0.5$  h. The lightcurve features a high amplitude, suggesting a very elongated shape, possibly bilobed, or a binary nature. The phased lightcurve displays a rather important scattering of the data, larger than the photometric uncertainties. This can be caused by a complex shape or a tumbling state of the rotation. However, systematic errors in the calibration are still possible due to the large observation time span and the use of short time series.

Additionally, we regularly acquired BVRI sequences to try to detect color variations with the rotational phase. No variations higher than the dispersion of the data is detected which suggests a relatively homogeneous surface. The obtained mean colors are  $BV = 0.74 \pm 0.04$ ,  $VR = 0.36 \pm 0.03$ ,  $RI = 0.37 \pm 0.05$ , which are compatible with the C and G taxonomic types (Dandy et al., 2003).

## B.5. Rotation period of Haumea’s moon Hi’iaka

Hi’iaka is the largest ( $D \sim 300$  km) of the two satellites of the dwarf planet Haumea located in the Kuiper belt. Its rotation period was estimated from HST photometry, resulting in a period of  $\sim 9.8$  h (Hastings et al., 2016). Hi’iaka’s rotation period is short compared to its orbital period of 49 days, contrasting with other know satellites of



*B. Additional TRAPPIST asteroid observations – B.5. Rotation period of Haumea's moon Hi'iaka*

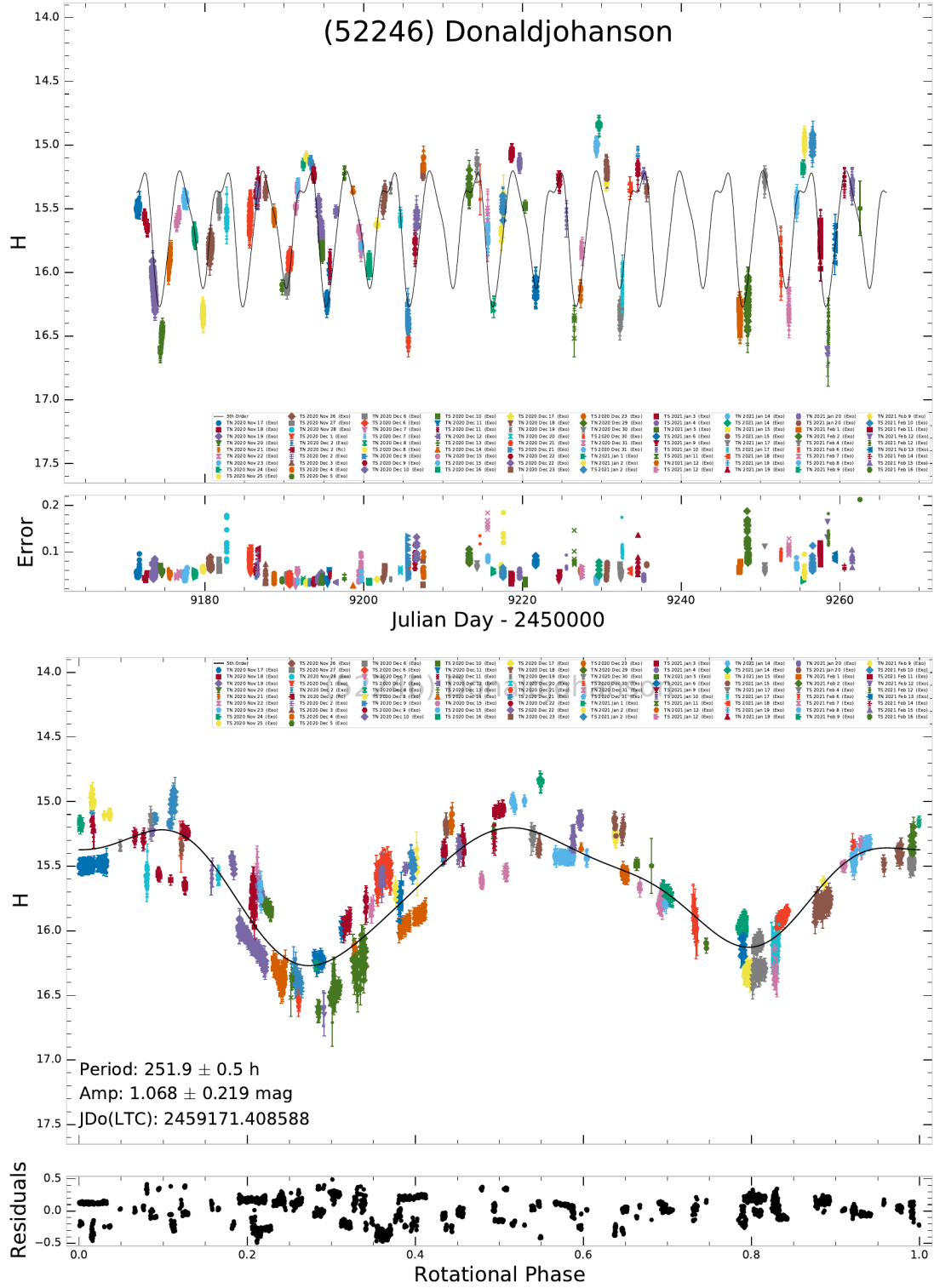


Figure B.8.: *Top*: Lightcurve of DonaldJohanson showing the H magnitudes as a function of time. *Bottom*: The same lightcurve phased with  $P = 251.9$  h.



TNOs which are thought to be in synchronous rotation.

Following the observation of two stellar occultations of Hi'iaka in 2021, we have been proposed to participate to an observational campaign aiming at determining the rotational phase of Hi'iaka at the same time as the occultations (Fernández-Valenzuela et al., in prep.). Because of the photometric quality requirements ( $\text{SNR} > 100$  at  $V \sim 17.4$ ), we asked observation time with the 1-m Artemis telescope (for a description of Artemis, see Sect. 4.2.9).

We observed Haumea with Artemis during four nights in May 2021 and again during four nights in March and May 2022 (Fig. B.9). Each observation were scheduled to cover at least one complete cycle of the fortunately rapid rotation of Haumea ( $P = 3.9153$  h). The observing circumstances of Haumea have been included to the table for the MBAs (Table B.6.1).

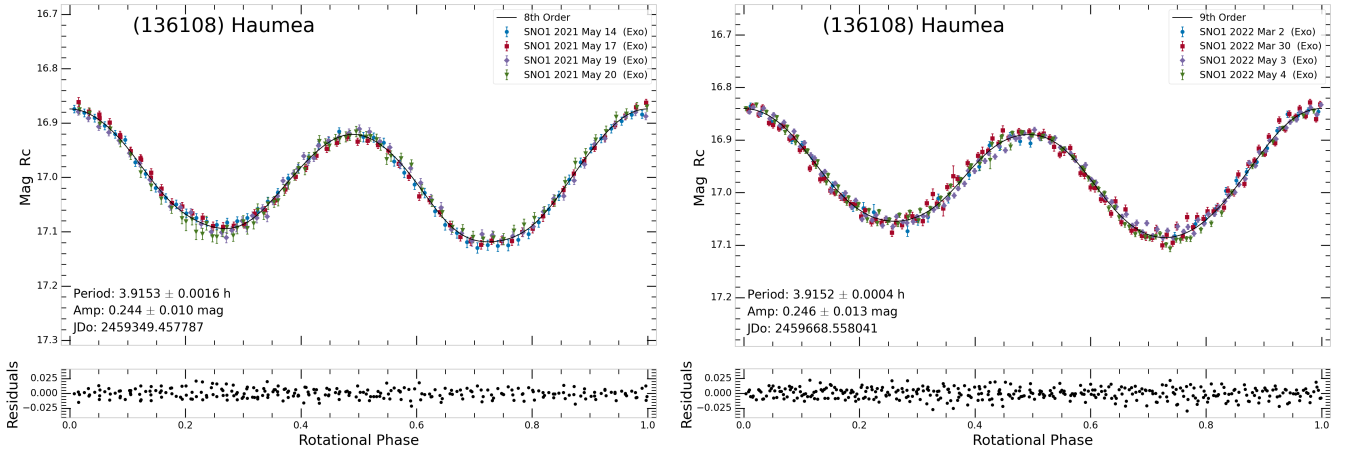


Figure B.9.: Rotational lightcurve of the dwarf planet Haumea obtained with Artemis in 2021 (left) and 2022 (right).

It is then possible to isolate the contribution of Hi'iaka rotation to the lightcurve by fitting and subtracting a fourth-order Fourier function. We then searched for periodicities in the residuals to determine Hi'iaka rotation period. From our data alone, it was possible to recover a period of  $P = 9.84$  h and to produce a bimodal lightcurve with an amplitude of 0.018 mag, in agreement with [Hastings et al. \(2016\)](#) values (Fig. B.10). However, it is not possible to find a unique period solution from our data alone, but the goal here was to obtain good quality lightcurves to be used by Fernández-Valenzuela et al. (in prep.) along with more data from other observatories.

## B.6. Summary tables

The two following tables present a summary of the asteroid observations carried out with the TRAPPIST telescopes between 2018 and 2022. The observing circumstances

## B. Additional TRAPPIST asteroid observations – B.6. Summary tables

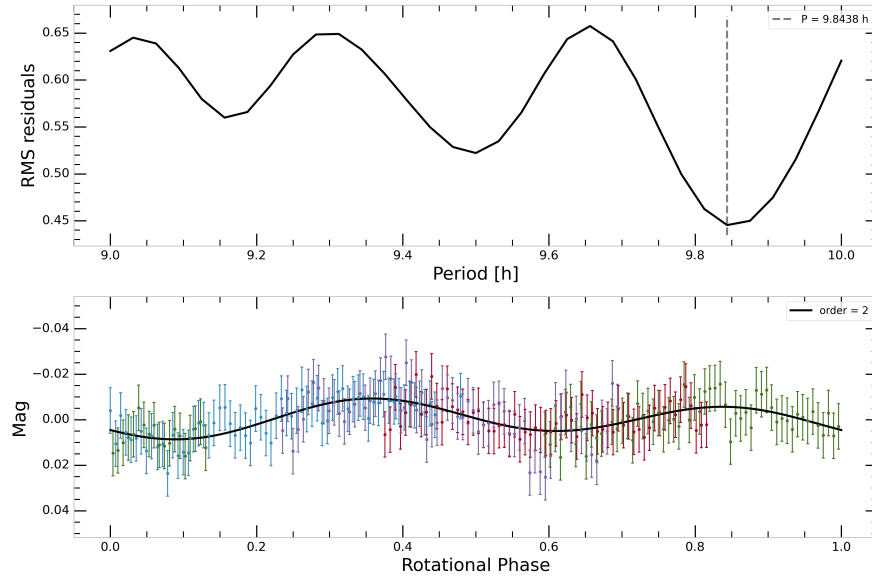


Figure B.10.: *Top*: Periodogram of the residuals of the 2021 observations. *Bottom*: Rotational lightcurve of Hi'iaka with the period  $P = 9.8438$  h

are provided along the obtained period and amplitude when possible. Multiple rows for the same asteroid indicate observations during multiple apparitions.

### B.6.1. Main belt asteroids

Table B.1.: Observing circumstances and results of the main belt asteroids observed with TRAPPIST for various projects.

| Number | Name      | yyyy mm/dd         | Pts    | Phase      | $L_{PAB}$ | $B_{PAB}$ | Period (h) | P.E.   | Amp  | A.E. |
|--------|-----------|--------------------|--------|------------|-----------|-----------|------------|--------|------|------|
| 27     | Euterpe   | 2020 01/23 - 02/01 | 2589.0 | 23.4,20.7  | 170.0     | 1.0       | 10.4       | 0.01   | 0.18 | 0.01 |
| 68     | Leto      | 2019 05/11 - 05/12 | 4239.0 | 1.6,0.9    | 234.0     | -2.0      | 14.8543    | 0.0015 | 0.28 | 0.02 |
| 101    | Helena    | 2021 04/09 - 10/04 | 1584.0 | *19.7,24.2 | 253.0     | -13.0     |            |        |      |      |
| 114    | Kassandra | 2019 06/28 - 07/16 | 1671.0 | 15.8,19.5  | 241.0     | 6.0       | 10.7432    | 0.0003 | 0.33 | 0.02 |
| 165    | Loreley   | 2019 06/23 - 07/10 | 1088.0 | 15.4,18.4  | 230.0     | -12.0     | 7.2252     | 0.0007 | 0.14 | 0.01 |
| 200    | Dynamene  | 2022 05/13 - 06/09 | 395.0  | 20.1,19.9  | 165.0     | -4.0      |            |        |      |      |
| 208    | Lacrimosa | 2020 03/07 - 03/19 | 1879.0 | 19.6,18.7  | 238.0     | -1.0      | 14.088     | 0.0007 | 0.28 | 0.01 |
| 208    | Lacrimosa | 2020 06/01 - 06/17 | 1566.0 | 4.0,9.8    | 242.0     | -2.0      | 14.088     | 0.0007 | 0.25 | 0.01 |
| 218    | Bianca    | 2019 05/10 - 05/22 | 1204.0 | 24.0,22.9  | 297.0     | 16.0      | 6.3418     | 0.0016 | 0.05 | 0.01 |
| 221    | Eos       | 2019 01/05         | 570.0  | 14.5       | 219.0     | 12.0      |            |        |      |      |
| 223    | Rosa      | 2019 07/19         | 519.0  | 12.7       | 226.0     | -1.0      |            |        |      |      |
| 223    | Rosa      | 2020 07/20 - 10/19 | 2129.0 | 7.2,16.5   | 260.0     | -1.0      | 20.27      | 0.02   | 0.07 | 0.02 |
| 241    | Germania  | 2019 01/06         | 942.0  | 17.4       | 83.0      | 0.0       |            |        |      |      |
| 259    | Aletheia  | 2019 02/02 - 02/04 | 365.0  | 18.8,18.6  | 197.0     | 12.0      | 8.143      | 0.002  | 0.12 | 0.03 |
| 259    | Aletheia  | 2019 06/19 - 07/20 | 1533.0 | 20.2,21.3  | 209.0     | 9.0       | 8.1463     | 0.0006 | 0.09 | 0.01 |

*Continued on next page*

*B. Additional TRAPPIST asteroid observations – B.6. Summary tables*

Table B.1 – *Continued from previous page*

| Number | Name       | yyyy mm/dd         | Pts    | Phase      | $L_{PAB}$ | $B_{PAB}$ | Period (h) | P.E.   | Amp  | A.E. |
|--------|------------|--------------------|--------|------------|-----------|-----------|------------|--------|------|------|
| 317    | Roxanne    | 2019 09/02 - 09-17 | 1873.0 | 0.3,8.9    | 340.0     | 0.0       | 8.1692     | 0.0011 | 0.61 | 0.04 |
| 336    | Lacadiera  | 2020 09/01 - 09/06 | 2531.0 | 20.6,22.1  | 303.0     | 7.0       | 13.7       | 0.02   | 0.29 | 0.01 |
| 357    | Ninina     | 2022 03/22 - 03/27 | 605.0  | 4.5,4.7    | 183.0     | 13.0      |            |        |      |      |
| 360    | Carlova    | 2019 03/11 - 03/13 | 708.0  | 16.1,16.0  | 243.0     | 12.0      | 6.188      | 0.002  | 0.46 | 0.02 |
| 373    | Melusina   | 2019 07/29 - 07/30 | 747.0  | 7.5        | 304.0     | -17.0     | 13.03      | 0.07   | 0.25 | 0.01 |
| 395    | Delia      | 2022 04/09 - 04/10 | 276.0  | 3.1,3.5    | 194.0     | -4.0      |            |        |      |      |
| 429    | Lotis      | 2021 04/11 - 05/17 | 2175.0 | 15.6,20.5  | 163.0     | -8.0      | 13.582     | 0.008  | 0.15 | 0.01 |
| 429    | Lotis      | 2022 01/04         | 113.0  | 14.3       | 245.0     | 3.0       |            |        |      |      |
| 441    | Bathilde   | 2018 07/29 - 08/05 | 632.0  | 19.8       | 232.0     | -2.0      | 10.446     | 0.007  | 0.24 | 0.01 |
| 495    | Eulalia    | 2022 05/17 - 05/20 | 208.0  | 12.6,13.6  | 205.0     | 1.0       |            |        |      |      |
| 527    | Euryanthe  | 2021 05/28 - 06/24 | 770.0  | 15.1,20.5  | 212.0     | 11.0      |            |        |      |      |
| 541    | Deborah    | 2022 05/17 - 06/16 | 308.0  | 21.9,18.6  | 311.0     | 4.0       |            |        |      |      |
| 636    | Erika      | 2018 07/30 - 08/27 | 766.0  | 13.2,20.7  | 282.0     | -10.0     | 10.604     | 0.008  | 0.35 | 0.04 |
| 664    | Judith     | 2021 02/19 - 04/14 | 2870.0 | 20.1,8.5   | 219.0     | 7.0       | 19.307     | 0.002  | 0.41 | 0.01 |
| 712    | Boliviana  | 2021 07/23 - 10/20 | 3286.0 | *16.3,22.4 | 333.0     | 16.0      |            |        | 0.28 | 0.01 |
| 755    | Quintilla  | 2022 06/30 - 07/04 | 278.0  | 11.0,9.8   | 307.0     | 3.0       | 4.552      | 0.004  | 0.07 | 0.01 |
| 782    | Montefiore | 2020 03/02 - 04/22 | 727.0  | 8.6,26.6   | 153.0     | 7.0       | 4.0724     | 0.0003 | 0.59 | 0.06 |
| 814    | Tauris     | 2021 08/28 - 10/17 | 1679.0 | 13.6,23.8  | 322.0     | -24.0     |            |        |      |      |
| 838    | Seraphina  | 2020 12/20 - 12/31 | 1960.0 | 11.8,15.1  | 61.0      | -1.0      | 11.715     | 0.011  | 0.19 | 0.01 |
| 838    | Seraphina  | 2022 01/01 - 02/06 | 730.0  | 14.4,5.5   | 146.0     | -12.0     | 11.724     | 0.006  | 0.18 | 0.02 |
| 845    | Naema      | 2021 10/21 - 10/28 | 454.0  | 19.0,20.0  | 335.0     | -12.0     | 13.39      | 0.02   | 0.12 | 0.01 |
| 859    | Bouzareah  | 2019 08/02         | 502.0  | 5.9        | 310.0     | -16.0     |            |        |      |      |
| 893    | Leopoldina | 2021 07/27 - 11/23 | 1182.0 | 22.6,11.0  | 43.0      | -19.0     | 12.597     | 0.006  | 0.34 | 0.02 |
| 907    | Rhoda      | 2020 11/10 - 11/14 | 455.0  | 18.1       | 332.0     | -18.0     |            |        |      |      |
| 908    | Buda       | 2021 03/31 - 04/01 | 428.0  | 10.4,10.1  | 205.0     | 16.0      |            |        |      |      |
| 908    | Buda       | 2022 04/17         | 46.0   | 20.7       | 292.0     | -4.0      |            |        |      |      |
| 931    | Whitemora  | 2019 07/30 - 09/03 | 1792.0 | *9.1,5.5   | 331.0     | -9.0      | 19.18      | 0.01   | 0.2  | 0.01 |
| 953    | Painleva   | 2020 09/11 - 11/24 | 4371.0 | *17.1,11.5 | 33.0      | -1.0      | 24.88      | 0.05   | 0.1  | 0.01 |
| 1056   | Azalea     | 2021 02/08 - 02/22 | 1133.0 | 19.9,16.6  | 189.0     | 6.0       | 15.026     | 0.008  | 0.6  | 0.02 |
| 1062   | Ljuba      | 2022 04/07 - 05/24 | 1586.0 | *11.9,5.1  | 232.0     | -6.0      | 33.8       | 0.03   | 0.18 | 0.01 |
| 1089   | Tama       | 2019 08/31 - 09/01 | 1062.0 | 13.1,12.8  | 359.0     | -5.0      | 16.45      | 0.03   | 0.1  | 0.01 |
| 1090   | Sumida     | 2021 12/21 - 12/23 | 355.0  | 17.7,17.5  | 95.0      | -26.0     | 2.718      | 0.004  | 0.2  | 0.01 |
| 1129   | Neujmina   | 2022 06/06 - 06/12 | 163.0  | 13.4,14.6  | 215.0     | -7.0      | 5.085      | 0.005  | 0.25 | 0.02 |
| 1145   | Robelmonte | 2021 07/25 - 08/21 | 318.0  | 23.0,16.1  | 1.0       | 1.0       | 7.583      | 0.002  | 0.18 | 0.01 |
| 1157   | Arabia     | 2020 10/16 - 11/18 | 1033.0 | *19.2,20.1 | 327.0     | 0.0       | 11.546     | 0.002  | 0.59 | 0.03 |
| 1165   | Imprinetta | 2020 08/15 - 08/28 | 558.0  | 20.1,18.1  | 28.0      | 1.0       | 10.8072    | 0.0009 | 0.25 | 0.01 |
| 1184   | Gaea       | 2021 09/02 - 09/05 | 111.0  | 23.7       | 261.0     | -12.0     | 2.87       | 0.02   | 0.18 | 0.03 |
| 1295   | Deflotte   | 2020 10/17 - 12/16 | 1495.0 | *7.5,13.2  | 45.0      | -2.0      | 26.45      | 0.01   | 0.3  | 0.01 |
| 1295   | Deflotte   | 2022 03/18 - 05/15 | 832.0  | *14.2,18.7 | 139.0     | -1.0      | 26.43      | 0.02   | 0.38 | 0.02 |
| 1318   | Nerina     | 2022 03/20 - 03/24 | 148.0  | 29.9,30.0  | 263.0     | -25.0     | 2.528      | 0.003  | 0.25 | 0.04 |
| 1322   | Copernicus | 2018 12/28 - 12/29 | 240.0  | 11.1       | 68.0      | 0.0       | 4.354      | 0.004  | 0.65 | 0.02 |
| 1540   | Kevola     | 2020 10/26 - 12/30 | 1938.0 | *15.9,9.4  | 78.0      | 6.0       | 20.082     | 0.002  | 0.25 | 0.02 |
| 1582   | Martir     | 2020 11/22 - 12/18 | 1031.0 | 10.1,2.0   | 93.0      | -1.0      | 12.385     | 0.005  | 0.4  | 0.02 |

*Continued on next page*

## B. Additional TRAPPIST asteroid observations – B.6. Summary tables

Table B.1 – *Continued from previous page*

| Number | Name            | yyyy mm/dd              | Pts    | Phase      | $L_{PAB}$ | $B_{PAB}$ | Period (h) | P.E.   | Amp  | A.E. |
|--------|-----------------|-------------------------|--------|------------|-----------|-----------|------------|--------|------|------|
| 1783   | Albitskij       | 2020 10/19 - 11/12      | 1312.0 | 14.5,6.9   | 60.0      | -12.0     |            |        |      |      |
| 1783   | Albitskij       | 2022 02/15 - 04/04      | 716.0  | 21.6,4.3   | 201.0     | 1.0       |            |        |      |      |
| 1786   | Raahe           | 2021 04/27 - 10/18      | 1600.0 | *20.3,20.4 | 317.0     | -11.0     | 30.18      | 0.01   | 0.26 | 0.02 |
| 1816   | Liberia         | 2022 02/25 - 03/02      | 440.0  | 14.8,12.8  | 175.0     | 12.0      | 3.0856     | 0.0009 | 0.41 | 0.01 |
| 2017   | Wesson          | 2018 11/01 - 11/03      | 967.0  | 15.9,16.3  | 13.0      | -3.0      | 3.416      | 0.004  | 0.56 | 0.03 |
| 2760   | Kacha           | 2020 08/27 - 11/17      | 1772.0 | *10.6,8.9  | 20.0      | 7.0       | 26.51      | 0.01   | 0.23 | 0.01 |
| 3331   | Kvistaberg      | 2020 06/21 - 06/30      | 286.0  | 6.7,3.1    | 284.0     | 4.0       |            |        |      |      |
| 3849   | Incidentia      | 2020 06/14 - 06/16      | 184.0  | 16.8,16.3  | 302.0     | -7.0      | 2.776      | 0.003  | 0.17 | 0.03 |
| 5312   | Schott          | 2020 07/19 - 07/23      | 1259.0 | 9.5,8.0    | 317.0     | -2.0      | 2.134      | 0.001  | 0.45 | 0.04 |
| 6478   | Gault           | 2019 01/13 - 01/15      | 637.0  | 19.9,19.5  | 158.0     | -16.0     |            |        | 0.01 | 0.03 |
| 6478   | Gault           | 2020 08/23 - 09/27      | 1068.0 | 18.5,0.4   | 4.0       | 2.0       |            |        | 0.05 | 0.02 |
| 6821   | Ranevskaya      | 2022 05/21              | 153.0  | 4.7        | 232.0     | -6.0      | 2.9        | 0.1    | 0.14 | 0.01 |
| 7427   | 1992 VD         | 2018 03/07              | 252.0  | 12.3       | 69.0      | 0.0       | 4.673      | 0.003  | 1.1  | 0.04 |
| 9117   | Aude            | 2022 03/01 - 04/15      | 216.0  | 25.2,15.9  | 235.0     | 9.0       | 2.816      | 0.001  | 0.28 | 0.04 |
| 10708  | Richardspalding | 2020 07/20 - 07/26      | 1371.0 | 8.8,6.2    | 318.0     | -2.0      | 3.099      | 0.002  | 0.13 | 0.02 |
| 17365  | 1978 VF11       | 2021 05/14 - 09/06      | 1197.0 | *4.6,10.8  | 255.0     | 1.0       | 12.6728    | 0.0018 | 0.88 | 0.08 |
| 24795  | 1994 AC17       | 2020 07/22 - 07/26      | 814.0  | 7.1,5.7    | 318.0     | -2.0      |            |        | 0.16 | 0.07 |
| 52246  | Donaldjohanson  | 2020 11/17 - 2021 02/17 | 2266.0 | *8.1,29.9  | 72.0      | 0.0       | 251.9      | 0.5    | 1.1  | 0.2  |
| 136108 | Haumea          | 2021 05/14 - 05/17      | 439.0  | 0.7        | 207.0     | 28.0      | 3.9156     | 0.0016 | 0.25 | 0.01 |
| 136108 | Haumea          | 2022 03/03 - 05/04      | 445.0  | 0.9,0.6    | 208.0     | 28.0      | 3.9152     | 0.0004 | 0.25 | 0.01 |

**Note:** Pts is the number of data points. Phase is the the solar phase angles for the first and last date. A \* indicates that it reached a minimum during the observation period.  $L_{PAB}$  and  $B_{PAB}$  are the phase angle bisector longitude and latitude at the middle of the date range. Period is the synodic period and Amp is the amplitude determined for the corresponding apparition. P.E. and A.E. are the period and amplitude uncertainties, respectively.

### B.6.2. Near-Earth asteroids

Table B.2.: Observing circumstances and results of the near-Earth asteroids observed with TRAPPIST for various projects.

| Number | Name     | yyyy mm/dd         | Pts  | Phase      | $L_{PAB}$ | $B_{PAB}$ | Period (h) | P.E.   | Amp  | A.E. |
|--------|----------|--------------------|------|------------|-----------|-----------|------------|--------|------|------|
| 1864   | 2004 QY2 | 2021 07/01 - 08/01 | 647  | 46.4,62.2  | 246       | -30       | 7.068      | 0.001  | 0.43 | 0.06 |
| 3122   | Florence | 2020 09/03         | 927  | 43.7       | 331       | 22        | 2.352      | 0.05   | 0.19 | 0.01 |
| 3200   | Phaethon | 2017 12/09 - 12/20 | 5478 | 19.1,110.3 | 63        | 14        | 3.6034     | 0.0001 | 0.8  | 0.05 |
| 3200   | Phaethon | 2020 11/02 - 11/10 | 650  | 71.8,86.2  | 125       | 0         | 3.601      | 0.002  | 0.25 | 0.03 |
| 3200   | Phaethon | 2021 12/11 - 12/11 | 113  | 16.8,17.4  | 51        | 13        |            |        | 0.17 | 0.04 |
| 4660   | Nereus   | 2021 10/27 - 11/13 | 404  | *15.5,12.2 | 47        | 5         | 15.166     | 0.012  | 0.76 | 0.03 |
| 4660   | Nereus   | 2022 04/26 - 05/09 | 327  | 7.0,16.6   | 211       | -3        | 15.15      | 0.02   | 1.03 | 0.05 |
| 4953   | 1990 MU  | 2021 06/09 - 06/14 | 328  | 31.6,29.3  | 305       | -19       | 14.22      | 0.03   | 0.93 | 0.03 |
| 5407   | 1992 AX  | 2022 02/22 - 03/08 | 456  | 11.6,21.3  | 145       | 11        | 2.549      | 0.001  | 0.11 | 0.02 |
| 5693   | 1993 EA  | 2022 05/12 - 05/24 | 750  | 37.2,67.0  | 260       | 14        | 2.494      | 0.001  | 0.09 | 0.03 |
| 7335   | 1989 JA  | 2022 04/20 - 05/26 | 1040 | 27.1,45.2  | 224       | 17        | 2.589      | 0.001  | 0.17 | 0.01 |
| 7482   | 1994 PC1 | 2021 12/11 - 01/18 | 1216 | 54.9,78.3  | 108       | -41       | 2.6008     | 0.0004 | 0.07 | 0.04 |

*Continued on next page*

B. Additional TRAPPIST asteroid observations – B.6. Summary tables

Table B.2 – *Continued from previous page*

| Number | Name       | yyyy mm/dd              | Pts  | Phase      | $L_{PAB}$ | $B_{PAB}$ | Period (h) | P.E.   | Amp  | A.E. |
|--------|------------|-------------------------|------|------------|-----------|-----------|------------|--------|------|------|
| 7889   | 2015 DP155 | 2021 06/28 - 06/30      | 65   | 69.6,67.5  | 238       | -2        |            |        | 1.78 | 0.18 |
| 10302  | 1989 ML    | 2022 05/25 - 07/04      | 689  | 21.9,32.0  | 252       | 9         |            |        | 1.07 | 0.09 |
| 18736  | 1998 NU    | 2019 02/09 - 02/29      | 241  | 20.8,32.2  | 129       | -3        | 2.475      | 0.003  | 0.13 | 0.01 |
| 22771  | 1999 CU3   | 2019 03/09 - 04/13      | 1970 | 30.8,76.6  | 204       | -19       | 3.7796     | 0.0002 | 0.87 | 0.27 |
| 52768  | 1998 OR2   | 2020 03/07 - 03/16      | 641  | 49.0,58.2  | 137       | 14        | 4.109      | 0.002  | 0.27 | 0.01 |
| 65690  | 1991 DG    | 2020 03/01 - 03/02      | 227  | 18.6,18.7  | 157       | -12       |            |        |      |      |
| 66391  | 1999 KW4   | 2019 05/28 - 06/08      | 1895 | 78.1,69.4  | 211       | 8         |            |        |      |      |
| 68063  | 2000 YJ66  | 2021 10/02 - 10/13      | 532  | 26.6,29.7  | 355       | 12        | 3.1647     | 0.001  | 0.14 | 0.01 |
| 99942  | Apophis    | 2021 01/15 - 04/11      | 6406 | *59,0,74.1 | 157       | -12       | 30.59      | 0.04   | 0.73 | 0.15 |
| 137805 | 1999 YK5   | 2018 12/14 - 2019 02/13 | 607  | 47.5,63.8  | 131       | 31        | 3.4696     | 0.0005 | 0.13 | 0.03 |
| 138971 | 2001 CB21  | 2022 02/22 - 02/27      | 275  | 47.8,63.5  | 176       | 22        | 3.304      | 0.003  | 0.29 | 0.03 |
| 153591 | 2001 SN263 | 2022 01/08 - 04/28      | 1837 | 48.3,29.6  | 135       | -9        | 3.4246     | 0.0006 | 0.13 | 0.04 |
| 155140 | 2005 UD    | 2018 10/06 - 10/19      | 945  | 19.5,12.2  | 19        | 0         | 5.237      | 0.0005 | 0.37 | 0.04 |
| 155140 | 2005 UD    | 2019 11/24 - 11/26      | 328  | 50.7,52.7  | 91        | 45        | 5.235      | 0.005  | 0.48 | 0.16 |
| 159402 | 1999 AP10  | 2020 08/12 - 10/08      | 1417 | *16.4,35.3 | 343       | -4        | 7.916      | 0.002  | 0.27 | 0.05 |
| 159857 | 2004 LJ1   | 2021 11/18 - 2022 01/27 | 787  | 62.5,28.9  | 96        | -31       | 2.7256     | 0.0004 | 0.15 | 0.03 |
| 161989 | Cacus      | 2022 01/28 - 02/17      | 292  | 39.0,42.9  | 120       | -31       | 3.7544     | 0.0009 | 0.92 | 0.12 |
| 231937 | 2001 FO32  | 2021 03/13 - 03/18      | 2132 | 37.7,43.0  | 194       | -13       | 39.85      | 0.08   |      |      |
| 242450 | 1994 LX    | 2021 07/08 - 07/19      | 323  | 25.0,21.3  | 313       | -15       | 2.74       | 0.002  | 0.26 | 0.03 |
| 285571 | 2000 PQ9   | 2021 06/29 - 08/02      | 2388 | *38.8,38.9 | 290       | -7        | 3.7433     | 0.0007 | 0.12 | 0.04 |
| 326732 | 2003 HB6   | 2021 09/03 - 09/10      | 578  | 7.3,4.1    | 347       | -1        | 3.461      | 0.005  | 0.11 | 0.05 |
| 350751 | Daedalus   | 2022 02/09 - 04/30      | 609  | *15.7,27.3 | 164       | 9         | 8.572      | 0.001  | 0.9  | 0.1  |
| 350751 | 2002 AW    | 2022 03/10 - 03/14      | 272  | 5.1,13.1   | 165       | 0         | 4.64       | 0.01   | 0.11 | 0.02 |
| 418929 | 2009 DM1   | 2018 10/16 - 2019 01/10 | 3690 | *40.4,45.1 | 41        | -40       | 22.58      | 0.02   | 0.23 | 0.04 |
| 441987 | 2010 NY65  | 2020 06/27 - 06/30      | 380  | 69.6,55.6  | 254       | 24        | 4.96       | 0.02   | 0.28 | 0.06 |
| 612098 | 1999 RM45  | 2021 02/27 - 03/01      | 1958 | 28.8,48.5  | 144       | -12       |            |        |      |      |
|        | 2006 QQ23  | 2019 08/06 - 08/15      | 3755 | 69.4,76.1  | 306       | -37       | 16.77      | 0.02   | 1.1  | 0.16 |
|        | 2017 VR12  | 2018 01/03              | 272  | 49         | 191       | -10       | 1.3712     | 0.0032 | 0.82 | 0.02 |
|        | 2018 RC    | 2018 09/07 - 09/09      | 2191 | 22.1,105.7 | 340       | -6        | 0.1656     | 0.0002 | 0.54 | 0.26 |
|        | 2021 NY1   | 2021 09/26 - 09/29      | 185  | 77.9,68.3  | 32        | -26       | 0.2224     | 0.0001 | 1.42 | 0.11 |

**Note:** Pts is the number of data points. Phase is the the solar phase angles for the first and last date. A \* indicates that it reached a minimum during the observation period.  $L_{PAB}$  and  $B_{PAB}$  are the phase angle bisector longitude and latitude at the middle of the date range. Period is the synodic period and Amp is the amplitude determined for the corresponding apparition. P.E. and A.E. are the period and amplitude uncertainties, respectively.

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### C.1. List of publications in peer reviewed journals

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2. Viikinkoski, M., Vernazza, P., Hanuš, J., et al. (2018), (16) Psyche: A mesosiderite-like asteroid?, A&A, 619, L3
3. Fétick, R. J., Jorda, L., Vernazza, P., et al. (2019), Closing the gap between Earth-based and interplanetary mission observations: Vesta seen by VLT/SPHERE, A&A, 623, A6
4. Carry, B., Vachier, F., Berthier, J., et al. (2019), Homogeneous internal structure of CM-like asteroid (41) Daphne, A&A, 623, A132
5. Hanuš, J., Marsset, M., Vernazza, P., et al. (2019), The shape of (7) Iris as evidence of an ancient large impact?, A&A, 624, A121
6. Moreno, F., Jehin, E., Licandro, J., et al. (2019), Dust properties of double-tailed active asteroid (6478) Gault, A&A, 624, L14
7. Hanuš, J., Vernazza, P., Viikinkoski, M., et al. (2020), (704) Interamnia: a transitional object between a dwarf planet and a typical irregular-shaped minor body, A&A, 633, A65
8. Podlowska-Gaca, E., Marciniak, A., Alí-Lagoa, V., et al. (2020), Physical parameters of selected Gaia mass asteroids, A&A, 638, A11
9. Vernazza, P., Jorda, L., Ševeček, P., et al. (2020), A basin-free spherical shape as an outcome of a giant impact on asteroid Hygiea, Nature Astronomy, 4, 136
10. Marsset, M., Brož, M., Vernazza, P., et al. (2020), The violent collisional history of aqueously evolved (2) Pallas, Nature Astronomy, 4, 569
11. **Ferrais, M.**, Vernazza, P., Jorda, L., et al. (2020), (16) Psyche's primordial shape: a Jacobi ellipsoid?, A&A, 638, L15
12. Devogèle, M., MacLennan, E., Gustafsson, A., et al. (2020), New Evidence for a Physical Link between Asteroids (155140) 2005 UD and (3200) Phaethon, PSJ, 1, 15

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13. Yang, B., Hanuš, J., Carry, B., et al. (2020), Binary asteroid (31) Euphrosyne: ice-rich and nearly spherical, A&A, 641, A80
14. Dudziński, G., Podlowska-Gaca, E., Bartczak, P., et al. (2020), Volume uncertainty of (7) Iris shape models from disc-resolved images, MNRAS, 499, 4545
15. Devogèle, M., **Ferrais, M.**, Jehin, E., et al. (2021), (6478) Gault: physical characterization of an active main-belt asteroid, MNRAS, 505, 245
16. Vokrouhlický, D., Ďurech, J., Hanuš, J., et al. (2021), (208) Lacrimosa: A case that missed the Slivan state?, A&A, 649, A45
17. Carry, B., Vernazza, P., Vachier, F., et al. (2021), Evidence for differentiation of the most primitive small bodies, A&A, 650, A129
18. Brož, M., Marchis, F., Jorda, L., et al. (2021), An advanced N-body model for (216) Kleopatra triple system, A&A, 653, A56
19. Marchis, F., Jorda, L., Vernazza, P., et al. (2021), (216) Kleopatra, a low density critically rotating M-type asteroid, A&A, 653, A57
20. Vernazza, P., **Ferrais, M.**, Jorda, L., et al. (2021), VLT/SPHERE imaging survey of the largest main belt asteroids: Final results and synthesis, A&A, 654, A56
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1. Jehin, E., Moreno, F., **Ferrais, M.**, et al. 2019, in EPSC-DPS Joint Meeting 2019, Vol. 2019, EPSC–DPS2019–1826
2. Devogèle, M., Virkki, A., Marshall, S. E., et al. 2020, in AAS/Division for Planetary Sciences Meeting, Vol. 52, DPS2020-415.04
3. **Ferrais, M.**, Vernazza, P., Jorda, L., et al. 2020, in AAS/Division for Planetary Sciences Meeting, Vol. 52, DPS2020-202.04
4. **Ferrais, M.**, Vernazza, P., Jorda, L., et al. 2020, in European Planetary Science Congress, EPSC2020–289



*C. Publications – C.3. Publications in the Minor Planet Bulletin*

5. Kueny, J. K., Chandler, C. O., Devogèle, M., et al. 2020, in AAS/Division for Planetary Sciences Meeting, Vol. 52, DPS2020-415.02
6. **Ferrais, M.**, Vernazza, P., Jorda, L., et al. 2021, in European Planetary Science Congress, EPSC2021–696
7. Devogele, M., **Ferrais, M.**, Jehin, E., et al. 2021, in AAS/Division for Planetary Sciences Meeting, Vol. 53, DPS2021-309.04
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2. **Ferrais, M.**, Jehin, E., Moulane, Y., et al. 2020, Minor Planet Bulletin, 47, 21
3. **Ferrais, M.**, Jehin, E., Vernazza, P., et al. 2021, Minor Planet Bulletin, 48, 166
4. **Ferrais, M.**, Vernazza, P., Jorda, L., et al. 2022, Minor Planet Bulletin, accepted

# List of acronyms

## **2D**

Two-Dimensional. 33

## **3D**

Three-Dimensional. 33

## **ADAM**

All-Data Asteroid Modeling. 41, 52, 70

## **ALCDEF**

Asteroid Lightcurve Data Exchange Format. 62, 108

## **AO**

Adaptive optics. 36, 53, 71, 84, 111, 185

## **AU**

Astronomical Unit. 21

## **CCD**

Charge Coupled Device. 59

## **CONICA**

Near-Infrared Imager and Spectro-graph. 38

## **DAMIT**

Database of Asteroid Models from Inversion Techniques. 32, 108, 133

## **DN**

Digital Numbers. 75

## **DTM**

Digital Terrain Model. 73

## **ELT**

Extremely Large Telescope. 185

**ESA**

European Space Agency. 33

**ESO**

European Southern Observatory. 38, 45, 53

**FWHM**

Full-Width at Half-Maximum. 62, 83, 89

**IRDIS**

Infra-Red Dual Imaging and Spectrograph. 39, 111

**ISAM**

Interactive Service for Asteroid Models. 133

**KOALA**

Knitted Occultation, Adaptive optics and Light-curve Approach. 41, 42

**LP**

Large Program. 45, 49

**mas**

MilliArcSecond. 39, 46, 184

**MBA**

Main-Belt Asteroid. 21, 32, 54, 70, 96, 139, 183

**MISTRAL**

Myopic Iterative STep preserving Restoration ALgorithm. 40, 46

**MPCD**

Multiresolution PhotoClinometry by Deformation. 50, 70, 71, 183

**NACO**

NAOS-CONICA. 38

**NAOS**

Nasmyth Adaptive Optics System. 38

**NEA**

Near-Earth Asteroid. 21, 32, 54

**NIR**

Near-InfraRed. 23, 38, 185

**NIRC2**

Near InfraRed Camera 2. 38

**NIRI**

Near Infra-Red Imager and Spectrometer. 38

**OASIS**

Optimized Astrophysical Simulator for Imaging Systems. 47, 74

**PDF**

Probability Distribution Function. 139, 140

**PSF**

Point Spread Function. 39, 46, 62, 89

**RMS**

root mean square. 31

**SAGE**

Shaping Asteroid models using Genetic Evolution. 41, 52, 70, 108

**SMASS**

Small Main-belt Asteroid Spectroscopic Survey. 23

**SNR**

Signal to Noise Ratio. 62, 200

**SPC**

StereoPhotoClinometry. 73

**SPECULOOS**

Search for habitable Planets ECliPSing ULtra-cOOl Stars. 53, 135

**SPG**

StereoPhotoGrammetry. 73

**SPHERE**

Spectro-Polarimetric High-contrast Exoplanet REsearch. 38, 46, 71

**TN**

TRAPPIST-North. 53, 55, 108

**TNO**

Trans-Neptunian Object. 21, 22, 32, 54, 185, 200

**TRAPPIST**

TRAnsiting Planets and PlanetesImals Small Telescope. 53

**TS**

TRAPPIST-South. 53, 55

**VLT**

Very Large Telescope. 6

**YORP**

Yarkovsky-O'Keefe-Radzievskii-Paddack. 29, 31, 54, 193, 196

**ZIMPOL**

Zurich IMaging POLarimeter. 39, 46

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