Binary asteroid (31) Euphrosyne: Ice-rich and nearly spherical \*\*, \**

B. Yang\(^1\), J. Hanuš\(^2\), B. Carry\(^1\), P. Vernazza\(^3\), M. Brož\(^2\), F. Vachier\(^1\), N. Rambaux\(^3\), M. Marsset\(^1\), O. Chrenko\(^2\), P. Ševeček\(^2\), M. Viikinkoski\(^2\), E. Jehin\(^3\), M. Ferrais\(^4\), E. Podlewski-Gaca\(^9\), A. Drouard\(^3\), F. Marchis\(^10\), M. Birlan\(^5\), Z. Benkhaldoun\(^11\), J. Berthier\(^5\), P. Bartczak\(^5\), C. Dumas\(^12\), G. Dudziński\(^9\), J. Duchê\(^2\), J. Castillo-Rogez\(^3\), F. Cipriani\(^14\), F. Colas\(^5\), R. Fetick\(^6\), T. Fusco\(^15\), J. Grice\(^16\), L. Jordà\(^1\), M. Kaasalainen\(^1\), A. Kryszczynska\(^9\), P. Lamy\(^1\), A. Marciniak\(^7\), T. Michalowski\(^7\), P. Michel\(^7\), M. Pajuelo\(^5,18\), T. Santana-Ros\(^19,20\), P. Tanga\(^1\), A. Vigan\(^4\), and O. Witasse\(^14\)

\footnotesize{(Affiliations can be found after the references)}

Received x-x-2019 / Accepted x-x-2019

ABSTRACT

Context. Asteroid (31) Euphrosyne is one of the biggest objects in the asteroid main belt and it is also the largest member of its namesake family. The Euphrosyne family occupies a highly inclined region in the outer main belt and contains a remarkably large number of members, which is interpreted as an outcome of a disruptive cratering event.

Aims. The goals of this adaptive-optics imaging study were threefold: to characterize the shape of Euphrosyne, to constrain its density, and to search for the large craters that may be associated with the family formation event.

Methods. We obtained disk-resolved images of Euphrosyne using SPHERE/ZIMPOL at ESO’s 8.2-m VLT as part of our large program (ID: 199.C-0074, PI: Vernazza). We reconstructed its 3D-shape using the ADAM shape modeling algorithm based on the SPHERE images and the available lightcurves of this asteroid. We analyzed the dynamics of the satellite with the Genoïd meta-heuristic algorithm. Finally, we studied the shape of Euphrosyne using hydrostatic equilibrium models.

Results. Our SPHERE observations show that Euphrosyne has a nearly spherical shape with the sphericity index of 0.9888 and its surface lacks large impact craters. Euphrosyne’s diameter is 268±6 km, making it one of the top 10 largest main belt asteroids. We detected a satellite of Euphrosyne – S/2019 (31) 1– that is about 4 km across, on an circular orbit. The mass determined from the orbit of the satellite together with the volume computed from the shape model imply a density of 1665±242 kg m\(^{-3}\), suggesting that Euphrosyne probably contain a large fraction of water ice in its interior. We find that the spherical shape of Euphrosyne is a result of the reaccumulation process following the impact, as in the case of (10) Hygiea. However, our shape analysis reveals that, contrary to Hygiea, the axis ratios of Euphrosyne significantly differ from the ones suggested by fluid hydrostatic equilibrium following reaccumulation.

Conclusions.

Key words. Minor planets, asteroids: general – Minor planets, asteroids: individual: (31) Euphrosyne – Methods: observational – Techniques: high angular resolution – Surface modeling

1. Introduction

The main asteroid belt is a dynamically living relic, with the shapes, sizes, and surfaces of most asteroids being altered by ongoing collisional fragmentation and cratering events (Bottke et al. 2015). Space probes and ground-based observations have revealed a fascinating variety among asteroid shapes, where large asteroids are nearly spherical (Park et al. 2019; Vernazza et al. 2020) and small asteroids are irregularly shaped (Duchê et al. 2010; Shepard et al. 2017; Fujiwara et al. 2006; Thomas et al. 2012). Most asteroids with diameters greater than \(\sim 100\) km have likely kept their internal structure intact since their time of formation because the dynamical lifetime of those asteroids is estimated to be comparable to the age of the Solar system (Bottke et al. 2005). There are a few exceptions covering essentially the largest remnants of giant families (e.g., (10) Hygiea, Vernazza et al. 2020), whose shapes have been largely altered by the impact. In contrast, the shapes of smaller asteroids have been determined mainly through collisions, where their final shapes depend on collision conditions such as impact energies and spin rates (Leinhardt et al. 2000; Sugiuura et al. 2018).

The arrival of second generation extreme adaptive-optics (AO) instruments, such as the Spectro-Polarimetric High-contrast Exoplanet Research instrument (SPHERE) at VLT (Beuzit et al. 2008) and the Gemini Planet Imager (GPI) at GEMINI-South (Macintosh et al. 2014), offers a great opportunity to study detailed shape, precise size and topographic feature of large main belt asteroids with diameter \(D \geq 100\) km via direct imaging. AO-aided observations with high spatial resolution also enable detection of asteroidal satellites that are much smaller and closer to their primaries, which, thus far, could have remained undetected in prior searches (Margot et al. 2015). Consequently, physical properties that are not well constrained, such as the bulk density, the internal porosity and the surface tensile strength, can be investigated using AO corrected measurements. These are the key parameters that determine crater formation, family formation and/or satellite creation (Michel et al. 2001).

Asteroid (31) Euphrosyne (hereafter, Euphrosyne) is the largest member of its namesake family. Previous studies have noted that the Euphrosyne family exhibits a very steep size frequency distribution (SFD), significantly depleted in large and medium sized asteroids (Carruba et al. 2014). Such a steep SFD is interpreted as a glancing impact between two large bodies...
resulting in a disruptive cratering event (Masiero et al. 2015). Euphrosyne is a Cb-type asteroid (Bus & Binzel 2002) with an optical albedo of \( p_v = 0.045 \pm 0.008 \) (Masiero et al. 2013). Euphrosyne’s diameter has been reported as \( D = 276 \pm 3 \) km (Usui et al. 2011) or \( D = 282 \pm 10 \) km (Masiero et al. 2013) while its mass has been estimated by various studies leading to an average value of \( M_{31} = 1.27 \pm 0.65 \times 10^{19} \) kg, with about 50% uncertainty (Carry 2012). These size and mass estimates imply a density estimate of \( \rho = 1180 \pm 610 \) kg \( \cdot \) m\(^{-3}\). As detailed hereafter and was first reported in (CBET 4627, 2019), we discovered a satellite in this study, implying that it is one of the few large asteroids for which the density can be constrained with high precision (Scheeres et al. 2015).

In this paper, we present the high-angular resolution observations of Euphrosyne with VLT/SPHERE/ZIMPOL, which were obtained as part of our ESO large program (Sect. 2.1). We use these observations together with a compilation of available and newly obtained optical lightcurves (Sect. 2.2) to constrain the 3D shape of Euphrosyne as well as its spin state and surface topography (Sect. 3). We then describe the discovery of its small moonlet S/2019 (31) 1 (Sect. 4) and constrain its mass by fitting the orbit of the satellite. Both the 3D shape (hence volume) and the mass estimate allow us to constrain the density of Euphrosyne with high precision (Sect. 5). We also use the AO images and the 3D shape model to search for large craters, which may be associated with the family-forming event.

2. Observations & Data Reduction

2.1. Disk-resolved data with SPHERE

Euphrosyne was observed, between March and April 2019, using the Zurich Imaging Polarimeter (ZIMPOL) of SPHERE (Thalmann et al. 2008) in the direct imaging mode with the narrow band filter (N_R filter; filter central wavelength = 645.9 nm, width = 56.7 nm). The angular diameter of Euphrosyne was in the range of 0.16–0.17′′ and the asteroid was close to an equator-on geometry at the time of the observations. Therefore, the SPHERE images of Euphrosyne obtained from seven epochs allow us to reconstruct a reliable 3D shape model with well-defined dimensions. The reduced images were further deconvolved with the Mistral algorithm (Fusco et al. 2003), using a parametric point-spread function ( Féi cik et al. 2019). Table A.1 contains full information about the images. We display all obtained images in Fig. A.1.

2.2. Disk-integrated optical photometry

A set of 29 individual lightcurves of Euphrosyne was previously used by Hanuš et al. (2016b) in order to derive a convex shape model of this large body. These lightcurves were obtained by Schober et al. (1980); Barucci et al. (1985); McChesney et al. (1985); Krysyczynska et al. (1996); Pilcher & Jardine (2009); Pilcher (2012). We complemented these data with five additional lightcurves from the recent apparition in 2017: four lightcurves were obtained by the TRAPPIST North telescope (Fig. 1) and the fifth one was obtained via the Gaia-GO S1. Our final photometric dataset utilized for the shape modeling of Euphrosyne consists of 34 individual lightcurves. Detailed information about these lightcurves is provided in Table A.2.

3. Determination of the 3D shape

The spin state solution from Hanuš et al. (2016b) served as an initial input for the shape modeling with the All-data Asteroid Modeling algorithm (ADAM, Viikinkoski et al. 2015a) that fits simultaneously the optical data and the disk-resolved images. We followed the same shape modeling approach applied in our previous studies based on disk-resolved data from the SPHERE large program (for instance, Vernazza et al. 2018; Viikinkoski et al. 2018; Hanuš et al. 2019). First, we constructed a low-resolution shape model based on all available data, then we used this shape model as a starting point for further modeling with decreased weight of the lightcurves and increased shape model resolution. We performed this approach iteratively until we were satisfied with the fit to the lightcurve and disk-resolved data. We also tested two different shape parametrizations – octantoids and subduction (Viikinkoski et al. 2015a). We show the comparison between the VLT/SPHERE/ZIMPOL deconvolved images of Euphrosyne and the corresponding projections of the shape model in Fig. 2.
Fig. 2. Comparison between the VLT/SPHERE/ZIMPOL deconvolved images of Euphrosyne (bottom) and the corresponding projections of our ADAM shape model (top). The red line indicates the position of the rotation axis. We use a non-realistic illumination to highlight the local topography of the model.

Fig. 3. The calculated \((a - c)\) for \((31)\) Euphrosyne as function of mean density for homogeneous case, given Euphrosyne’s rotation period of 5.53h, are shown as black dots. The green star represents the value derived in Sect. 5 with its 1-\(\sigma\) uncertainty (uncertainties of \(a\) and \(c\) are added quadratically).

Owing to the nearly equator-on geometry of the asteroid, our images taken at seven different rotation phases have a nearly complete coverage of the entire surface of Euphrosyne. The SPHERE data enable an accurate determination of Euphrosyne’s dimensions, including the ones along the rotation axis. The physical properties of Euphrosyne derived are listed in Table 1. The uncertainties reflect the dispersion of values obtained with various shape models based on different data weighting, shape resolution and parametrization. These values correspond to about 1 pixel, which is equivalent to \(\sim 5.93\) km. Our volume equivalent diameter \(D_v = 268\pm6\) km is consistent within 1\(\sigma\) with the radiometric estimates of Usui et al. \((D = 276\pm3\) km, 2011) and Masiero et al. \((D = 282\pm10\) km, 2013). The shape of Euphrosyne is fairly spherical with almost equal equatorial dimensions \((a/b=1.05\pm0.03)\) and only a small flattening \((b/c=1.13\pm0.04)\) along the spin axis. Euphrosyne’s sphericity index (see Vernazza et al. 2020 for more details) is equal to 0.9888, which is somewhat higher than that of \((4)\) Vesta, \((2)\) Pallas and \((704)\) Interamnia (Vernazza et al. 2020; Hanuš et al. 2020) making it so far the 3rd most spherical main belt asteroid after Ceres and Hygiea.

Given the rather spherical shape of Euphrosyne and the fact that its \(a\) and \(b\) axes have similar lengths (within errors), we investigated whether the shape of Euphrosyne is close to hydrostatic equilibrium, using the same approach as described in (Hanuš et al. 2020). It appears that Euphrosyne’s shape is significantly different from the Maclaurin spheroid, which would be much flatter along the c axis (see Fig. 3). Our SPHERE observations show that Euphrosyne is not actually in hydrostatic equilibrium for its current rotation, which will be further discussed in Sect. 6.

Table 2. Orbital elements of the satellite of Euphrosyne, expressed in EQJ2000, obtained with Genoid: orbital period \(P\), semi-major axis \(a\), eccentricity \(e\), inclination \(i\), longitude of the ascending node \(\Omega\), argument of pericenter \(\omega\), time of pericenter \(t_p\). The number of observations and RMS between predicted and observed positions are also provided. Finally, we report the mass of Euphrosyne \(M_{\text{Euphrosyne}}\), the ecliptic J2000 coordinates of the orbital pole \((\lambda_p, \beta_p)\), the equatorial J2000 coordinates of the orbital pole \((\alpha_p, \delta_p)\), and the orbital inclination \((\Lambda)\) with respect to the equator of Euphrosyne. Uncertainties are given at 3-\(\sigma\).

| Observing data set  | S2019-31-1 |
|---------------------|------------|
| Number of observations | 5         |
| Time span (days)     | 26        |
| RMS (mas)            | 1.52      |

| Orbital elements EQJ2000 |
|--------------------------|
| \(P\) (day)          | 1.209 \(\pm 0.003\)  |
| \(a\) (km)           | 672 \(\pm 35\)        |
| \(e\)                | 0.043 \(\pm 0.123\)   |
| \(i\) (°)            | 1.4 \(\pm 1.4\)       |
| \(\Omega\) (°)       | 80.1 \(\pm 27.9\)     |
| \(\omega\) (°)       | 135.2 \(\pm 40.5\)    |
| \(t_p\) (JD)         | 2458565.33 \(\pm 0.13\) |

| Derived parameters  |
|---------------------|
| \(M_{\text{Euphrosyne}}\) \((\times10^{19} \text{ kg})\) | 1.648 \(\pm 0.264\) |
| \(\alpha_p, \beta_p\) (°) | 86, +67 \(\pm 3, 2\) |
| \(\alpha_p, \delta_p\) (°) | 350, +89 \(\pm 21, 3\) |
| \(\Lambda\) (°) | 1 \(\pm 2\) |
Fig. 4. Processed ZIMPOL images, revealing the presence of the satellite, S/2019 (31) 1, around (31) Euphrosyne in five epochs. The pixel intensities within 0.22′′ of the primary have been reduced by a factor of ∼2000 to increase the visibility of the faint satellite. The images were smoothed by convolving a Gaussian function with FWHM of ∼8 pixels. The arrow points out the location of the satellite in the image taken on UT March 20, 2019, when the satellite appeared very dim compared to the other nights.

4. Orbital properties of the satellite

Each image obtained with SPHERE/ZIMPOL was further processed to remove the bright halo surrounding Euphrosyne, following the procedure described in details in (Pajuelo et al. 2018 and Yang et al. 2016). The residual structures after the halo removal were minimized using the processing techniques introduced in (Wahhaj et al. 2013), where the background structures were removed using a running median in a ∼50 pixel box in the azimuthal direction as well as in a ∼40 pixel box in the radial direction. Adopting the method introduced in Yang et al. (2016), we inserted 100 point sources, which known intensity and FWHM, in each science image to estimate flux loss due to the halo removal processes. In five out of of seven epochs, a faint non-resolved source was clearly detected in the vicinity of Euphrosyne (Fig 4). The variation in the brightness of the satellite is mainly due to the difference in the atmospheric conditions at the time of the observations, which directly affect the AO performance.

We measured the relative positions on the plane of the sky between Euphrosyne and its satellite (fitting two 2D Gaussians, see Carry et al. 2019) and report them in Table B.1. We then used the GenoId algorithm (Vachier et al. 2012) to determine the orbital elements of the satellite. The best solution fits the observed positions with root mean square (RMS) residuals of 1.5 mas only (Table 2). The orbit of the satellite is circular, prograde, and equatorial, similar to most known satellites around large main belt asteroids (e.g., Marchis et al. 2008; Berthier et al. 2014; Margot et al. 2015; Carry et al. 2019).

From the difference in the apparent magnitude of 9.0 ± 0.3 between Euphrosyne and S/2019 (31) 1, and assuming a similar albedo for both, we estimate the diameter of the satellite to be 4.0 ± 1.0 km. The Euphrosyne binary system has the relative component separation a/Rp = 5.0 ± 0.3 and the secondary-to-primary diameter ratio Dc/Dp = 0.015 ± 0.005, where a is the semi-major axis of the system, Dc and Dp are the diameter of the satellite and the primary respectively and Rp is the radius of the primary. The comparison of the properties of the Euphrosyne binary system to other large asteroid systems are shown in Fig. 5. Compared to the other system, S/2019 (31) 1 has one of the smallest secondary-to-primary diameter ratios and is very close to the primary. Given the small size of the satellite, S/2019 (31) is expected to be tidally locked, i.e. its spin period synchronizes to its orbital period on million year timescale (Rojo & Margot 2011).

Fig. 5. a). Relative component separation and b). primary radius versus secondary to primary diameter ratio for presently known main belt binary/triple asteroids (Johnston 2018). Large asteroids with diameter greater than 100 km are shown as open circles. Asteroid (90) Antiope is excluded because of its unusually large secondary to primary diameter ratio. Our measurements of (31) Euphrosyne are shown as the red squares.

5. Bulk density and surface topography

Owing to the presence of the satellite, we derived the mass of the system (1.7 ± 0.3) × 1019 kg with a fractional precision of 15%, which is considerably better than all the previous indirect measurements. Combining our mass measurement with the newly derived volume based on our 3D-shape, we obtain a bulk density of 1.665 ± 0.242 g · cm⁻³ for Euphrosyne.

We note that the bulk density of Euphrosyne is the lowest among all the other large C-type asteroids measured to date, e.g. (1) Ceres (2.16 ± 0.003 g · cm⁻³), D=1000 km, Park et al. 2019), (10) Hygiea (1.94 ± 0.25 g · cm⁻³), D=440 km, Vernazza et al. 2020) and (704) Interamnia (1.98 ± 0.08 g · cm⁻³, D=300 km, Hanuš et al. 2020). On the other hand, such density around 1.7 g · cm⁻³ or lower is more common among intermediate sized C-type asteroids, such as (45) Eugenia (1.4 ± 0.4 g · cm⁻³, D=200 km, Marchis et al. 2012), (93) Minerva (1.75 ± 0.68 g · cm⁻³, D=160 km, Marchis et al. 2013), (130) Eletra (1.60 ± 0.13 g · cm⁻³, D=200 km, Hanuš et al. 2016a) and (762) Pulcova (0.8 ± 0.1 g · cm⁻³, D=150 km, Marchis et al. 2012).

For the C-complex asteroids mentioned above, the density seems to show a trend with size, where the smaller asteroids have lower densities. Such trend could be explained by increasing porosity in smaller asteroids. Nonetheless, as already discussed in recent works (Carry 2012; Vukinkoski et al. 2015b; Marset et al. 2017; Carry et al. 2019; Hanuš et al. 2020), the macroporosity of Euphrosyne is likely to be small (≤20%) due to its relatively high internal pressure owing to its large mass >
10^4 kg. Given the small macroporosity of Euphrosyne, its density, therefore, is diagnostic of its bulk composition. As for the other large C-type asteroids (Ceres, Hygiea, Interamnia), a large amount of water must be present in Euphrosyne. Assuming 20% porosity, a typical density of anhydrous silicates of 3.4 g/cm^3 and a density of 1.0 g/cm^3 for water ice, the presence of water ice, up to 50% by volume, is required in the interior of Euphrosyne to match its bulk density.

In terms of topographic characteristics, the surface of Euphrosyne appears smooth and nearly featureless without any apparent large basins. This is in contrast to other objects studied by our large program that show various-sized craters on their surfaces, such as (2) Pallas (B-type, Marset et al. 2020), (4) Vesta (V-type, Fétick et al. 2019) and (7) Iris (S-type, Hanuš et al. 2019). On the other hand, lacking surface features in AO images is not unprecedented among large asteroids, especially among C-type asteroids. Ground-based AO observations have identified at least three other cases that are lacking prominent topographic structures, namely (1) Ceres (Carry et al. 2008), (10) Hygiea (Vernazza et al. 2020), and (704) Interamnia (Hanuš et al. 2020). Although NASA/Dawn observations revealed a highly cratered surface of Ceres (Hiesinger et al. 2016), this dwarf planet clearly lacks large craters which suggests rapid viscous relaxation or protracted resurfacing due to the presence of large amounts of water (Marchi et al. 2016).

Similarly, as discussed already for the cases of Hygiea (Vernazza et al. 2020) and Interamnia (Hanuš et al. 2020), the absence of apparent craters in our Euphrosyne images may be due to the flat-flored shape of >240 km craters (this diameter corresponds to the minimum size of features that can be recognized on the surface of Euphrosyne), which would be coherent with a high water content for this asteroid, in agreement with our bulk density estimate.

6. Discussion

In an attempt to understand the unexpected nearly spherical shape of Euphrosyne, we adopted a similar approach as described in Vernazza et al. (2020) and used hydrodynamical simulations to study the family-formation event. The simulations were performed with a smoothed-particle hydrodynamics (SPH) code to constrain the impact parameters, such as the impact angle and the diameter of the impactor. We assumed the target and the impactor are both monolithic bodies with an initial density of the material ρ_0 = 1.665 g · cm^{-3}, corresponding to the present-day density of Euphrosyne. Our SPH simulations find that the impact event of Euphrosyne is even more energetic in comparison to that of Hygiea. As such, the parent body of Euphrosyne is completely fragmented by the impact and the final reaccumulated shape of Euphrosyne is highly spherical, which is similar to the case of Hygiea where the nearly round shape is formed following post-impact reaccumulation (Vernazza et al. 2020).

We further studied the orbital evolution of the Euphrosyne family and determined the age of the family, using the newly developed method (Brož & Morbidelli 2019). Our N-body simulations further constrained the age of the Euphrosyne family to τ ~280 Myr that is significantly younger than the previous estimates (between 560 and 1160 Myr, Carruba et al. 2014). The details of our SPH simulation as well as a full characterization of the Euphrosyne family are presented in a forthcoming article (Yang et al., in press). The young dynamical age and post-impact re-accumulation, collectively, may have contributed to the apparent absence of craters on the surface of Euphrosyne.

Our new finding about the young age of Euphrosyne makes this asteroid a unique object for us to study the impact aftermath on a very young body that is only ~0.3 Gyr old. Previously, the SPH simulations for the case of Hygiea showed that its shape relaxed to a sphere during the gravitational reaccumulation phase, accompanied by an acoustic fluidization. The relaxation process on Hygiea could have settled down on a timescale of a few hours (Vernazza et al. 2020). However, the shape relaxation, in theory, maybe a rather long-term process, which could possibly last as long as the age of the body (τ = 3 Gyr, as suggested by its family). If the physical mechanisms work the same way on both bodies, then the relaxation timescale simply cannot be short on one body (D = 268 km) and be 10 times longer on the other, larger, one (D = 434 km). To reconcile with both observations, the shape relaxation, if it is a long-term process, should occur on timescales that are comparable to or less than 0.3 Gyr.

In addition to the much younger dynamical age, the rotation period of Euphrosyne is also shorter (P=5.53 h) than those of Hygiea and Ceres. As noted in Descamps et al. (2011), the spin rate of Euphrosyne is faster than the typical rotation rates of asteroids with similar sizes. This is interpreted as a result of a violent disruption process, where the parent body is reaccumulated into high angular momentum shape and spin configuration (Walsh & Jacobson 2015). With that spin rate, we would expect Euphrosyne to have a shorter c axis compared to the a axis using MacLaurins equation (Chandrasekhar 1969) as shown in Fig. 3. However, a MacLaurin ellipsoid represents the hydrostatic equilibrium figure of a homogeneous and intact body, which is not the case for Euphrosyne since it is a reaccumulated body. This may explain why the actual shape of Euphrosyne deviates from that of a MacLaurin ellipsoid.

7. Conclusions

In this paper, we presented high angular imaging observations of asteroid (31) Euphrosyne and its moon. Our main findings are summarized as follows:

1). The disk-resolved images and the 3D-shape model of Euphrosyne show that it is the third most spherical body among the main belt asteroids with known shapes after Ceres and Hygiea. Its round shape is consistent with a re-accumulation event following the giant impact at the origin of the Euphrosyne family.

2). The orbit of Euphrosyne’s satellite, S/2019 (31) 1, is circular, prograde, and equatorial, similar to most known satellites around large main belt asteroids. The estimated diameter of this newly detected satellite is 4 ± 1 km, assuming a similar albedo for the satellite and the primary.

3). The bulk density of Euphrosyne is 1665 ± 242 kg · m^{-3}, which is the first high precision density measurement via ground-based observations for a Cb type asteroid. Such density implies that a large amount of water (at least 50% in volume) must be present in Euphrosyne.

4). The surface of Euphrosyne is nearly featureless with no large craters detected, which is consistent with its young age and icerich composition.
under grant No. 80NSSC18K0849 issued through the Planetary Astronomy Program. The work of TSR was carried out through grant APOSTD/2019/046 by Generalitat Valenciana (Spain). This work was supported by the MINECO (Spanish Ministry of Economy) through grant RTI2018-09067-B- C21 (MINECO/FEDER, UE). The research leading to these results has received funding from the ARC grant for Conducted Research Actions, financed by the Wallonia-Brussels Federation. TRAPPiST is a project funded by the Belgian Fonds (National) de la Recherche Scientifique (F.R.S.-FNRS) under grant FRFC 2.5.594.09.F. TRAPPiST-North is a project funded by the Université de Liège, and performed in collaboration with Cadi Ayyad University of Marrakesh. E. Jehin is a FNRS Senior Research Associate.

References
Barucci, M. A., Fulchignoni, M., Burchi, R., & D’Ambrosio, V. 1985, Icarus, 61, 152
Berthier, J., Vachier, F., Marchis, F., Šurech, J., & Carry, B. 2014, Icarus, 239, 118
Beuzit, J.-L., Feldt, M., Dohlen, K., et al. 2008, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7014, SPHERE: a ‘Planet Finder’ instrument for the VLT, 701414B
Bottke, W. F., Dardà, D. D., Nesvorný, D., et al. 2005, Icarus, 179, 63
Bottke, W. F., Vokrouhlický, D., Walsh, K. J., et al. 2015, Icarus, 247, 191
Brož, M. & Morbidelli, A. 2019, Icarus, 317, 434
Bus, S. J. & Binzel, R. P. 2002, Icarus, 158, 146
Carruba, V., Alibert, S., & Souami, D. 2014, ApJ, 792, 46
Carry, B. 2012, Planet. Space Sci., 73, 98
Carry, B., Dumas, C., Fulchignoni, M., et al. 2008, A&A, 478, 235
Carry, B., Vachier, F., Berthier, J., et al. 2019, A&A, 623, A132
Chandrasekhar, S. 1969, Ellipsoidal figures of equilibrium, (New Haven, London: Yale University Press)
Descamps, P., Marchis, F., Berthier, J., et al. 2011, Icarus, 211, 1022
Šurech, J., Sidorin, V., & Kaasalainen, M. 2010, A&A, 513, A46
Félix, R. J., Jordà, L., Vernazza, P., et al. 2019, A&A, 623, A6
Fujiwara, A., Kawaguchi, J., Yeomans, D. K., et al. 2006, Science, 312, 1330
Fusco, T., Magner, L. M., Conan, J.-M., et al. 2003, in Proc. SPIE, Vol. 4839, Adaptive Optical System Technologies II, ed. P. L. Wizinowich & D. Bonaccini, 1065–1075
Hanuš, J., Marsset, M., Vernazza, P., et al. 2019, A&A, 624, A121
Hanuš, J., Delbo, M., Vokrouhlický, D., et al. 2016a, in AAS/Division for Planetary Sciences Meeting Abstracts, Vol. 48, AAS/Division for Planetary Sciences Meeting Abstracts, 516.08
Hanuš, J., Šurech, J., Oszkiewicz, D. A., et al. 2016b, A&A, 586, A108
Hanuš, J., Vernazza, P., Viikinkoski, M., et al. 2020, A&A, 633, A65
Hiesinger, H., Marchi, S., Schmedemann, N., et al. 2016, Science, 353, aaf4758
Jehin, E., Gillon, M., Queloz, D., et al. 2011, The Messenger, 145, 2
Johnston, W. R. 2018, NASA Planetary Data System
Kryszcynska, A., Colas, F., Berthier, J., Michalowski, T., & Pych, W. 1996, Icarus, 124, 134
Leinhardt, Z. M., Richardson, D. C., & Quinn, T. 2000, Icarus, 146, 133
Marchi, S., Graham, J. R., Ingraham, P., et al. 2014, Proceedings of the National Academy of Science, 111, 12661
Marchi, S., Ermakov, A. I., Raymond, C. A., et al. 2016, Nature Communications, 7, 12257
Marchis, F., Descamps, P., Baek, M., et al. 2008, Icarus, 196, 97
Marchis, F., Jensen, S., Emery, J. P., et al. 2012, Icarus, 221, 1130
Marchis, F., Vachier, F., Šurech, J., et al. 2013, Icarus, 224, 178
Margot, J. L., Pravec, P., Taylor, P., Carry, B., & Jacobson, S. 2015, Asteroid Systems: Binaries, Triples, and Pairs, in Asteroids IV, ed. P. Michel, F. E. DeMeo, & W. F. Bottke, Univ. Arizona Press, 355–374
Marchis, F., Brož, M., Vernazza, P. et al. 2020, Nature Astronomy
Marchis, F., Carry, B., Dumas, C., et al. 2017, A&A, 604, A64
Masiero, J. R., Carruba, V., Mainzer, A., Bauer, J. M., & Nugent, C. 2015, ApJ, 809, 179
Masiero, J. R., Mainzer, A. K., Bauer, J. M., et al. 2013, ApJ, 770, 7
McCleary, R. S., Eaton, N., & Meadows, A. J. 1985, Icarus, 61, 443
Michel, P., Benz, W., Tanga, P., & Richardson, D. C. 2001, Science, 294, 1696
Pajuelo, M., Carry, B., Vachier, F., et al. 2018, Icarus, 309, 134
Park, R. S., Vaughan, A. T., Konepaha, A. S., et al. 2019, Icarus, 319, 812
Pilcher, F. 2012, Minor Planet Bulletin, 39, 57
Pilcher, F. & Jardine, D. 2009, Minor Planet Bulletin, 36, 52
Rojo, P. & Margot, J. L. 2011, ApJ, 727, 69
Sheehe, D. J., Britt, D., Carry, B., & Holsapple, K. A. 2015, Asteroids IV. In press
Shepherd, M. K., Richardson, J., Taylor, P. A., et al. 2017, Icarus, 281, 388
Sugiura, K., Kobayashi, H., & Inutsuka, S. 2018, A&A, 620, A167
Thalmann, C., Schmid, H. M., Boccaletti, A., et al. 2008, in Proc. SPIE, Vol. 7014, Ground-based and Airborne Instrumentation for Astronomy II, 70143F
Thomas, N., Barbieri, C., Keller, H. U., et al. 2012, Planet. Space Sci., 66, 96
Usui, F., Kuroda, D., Müller, T. G., et al. 2011, PASJ, 63, 1117
Vachier, F., Berthier, J., & Marsch, F. 2012, A&A, 543, A68
Vernazza, P., Brož, M., Drouard, A., et al. 2018, A&A, 618, A154
Vernazza, P., Jordà, L., Ševeček, P., et al. 2020, Nature Astronomy, 4, 136
Viikinkoski, M., Kaasalainen, M., & Šurech, J. 2015a, A&A, 576, A8
Viikinkoski, M., Kaasalainen, M., Šurech, J. et al. 2015b, A&A, 581, L3
Viikinkoski, M., Vernazza, P., Hanuš, J., et al. 2018, A&A, 619, L3
Wahhaj, Z., Liu, M. C., Biller, B. A., et al. 2013, ApJ, 779, 80
Walsh, K. J. & Jacobson, S. A. 2015, Formation and Evolution of Binary Asteroids, in Asteroids IV, ed. P. Michel, F. E. DeMeo, & W. F. Bottke, Univ. Arizona Press, 375–393
Yang, B., Wahhaj, Z., Beauvalet, L., et al. 2016, ApJ, 820, L35

Appendix A: Additional figures and tables
Appendix B: Astrometry of the satellite
Fig. A.1. Full set of VLT/SPHERE/ZIMPOL images of (31) Euphrosyne. We show the images deconvolved by the Mistral algorithm. Table A.1 contains full information about the data.
Table A.1. List of VLT/SPHERE disk-resolved images obtained in the I filter by the ZIMPOL camera. For each observation, the table gives the epoch, the exposure time, the airmass, the distance to the Earth $\Delta$ and the Sun $r$, the phase angle $\alpha$, and the angular diameter $D_a$.

| Date    | UT   | Exp (s) | Airmass | $\Delta$ (AU) | $r$ (AU) | $\alpha$ (°) | $D_a$ ("") |
|---------|------|---------|---------|--------------|---------|-------------|-----------|
| 2019-03-15 | 7:07:59  | 183     | 1.07    | 2.33         | 3.18    | 10.6        | 0.159     |
| 2019-03-15 | 7:11:12  | 183     | 1.07    | 2.33         | 3.18    | 10.6        | 0.159     |
| 2019-03-15 | 7:14:25  | 183     | 1.07    | 2.33         | 3.18    | 10.6        | 0.159     |
| 2019-03-15 | 7:17:37  | 183     | 1.07    | 2.33         | 3.18    | 10.6        | 0.159     |
| 2019-03-15 | 7:20:49  | 183     | 1.07    | 2.33         | 3.18    | 10.6        | 0.159     |
| 2019-03-20 | 4:16:29  | 183     | 1.35    | 2.30         | 3.19    | 9.1         | 0.161     |
| 2019-03-20 | 4:19:43  | 183     | 1.33    | 2.30         | 3.19    | 9.1         | 0.161     |
| 2019-03-20 | 4:22:56  | 183     | 1.32    | 2.30         | 3.19    | 9.1         | 0.161     |
| 2019-03-20 | 4:26:07  | 183     | 1.31    | 2.30         | 3.19    | 9.1         | 0.161     |
| 2019-03-20 | 4:29:20  | 183     | 1.29    | 2.30         | 3.19    | 9.1         | 0.161     |
| 2019-03-25 | 2:53:48  | 183     | 1.73    | 2.27         | 3.20    | 7.5         | 0.163     |
| 2019-03-25 | 2:57:01  | 183     | 1.71    | 2.27         | 3.20    | 7.5         | 0.163     |
| 2019-03-25 | 3:00:14  | 183     | 1.68    | 2.27         | 3.20    | 7.5         | 0.163     |
| 2019-03-25 | 3:03:26  | 183     | 1.65    | 2.27         | 3.20    | 7.5         | 0.163     |
| 2019-03-25 | 3:06:38  | 183     | 1.62    | 2.27         | 3.20    | 7.5         | 0.163     |
| 2019-03-27 | 8:16:28  | 183     | 1.23    | 2.26         | 3.21    | 6.8         | 0.164     |
| 2019-03-27 | 8:19:41  | 183     | 1.24    | 2.26         | 3.21    | 6.8         | 0.164     |
| 2019-03-27 | 8:22:55  | 183     | 1.25    | 2.26         | 3.21    | 6.8         | 0.164     |
| 2019-03-27 | 8:26:06  | 183     | 1.27    | 2.26         | 3.21    | 6.8         | 0.164     |
| 2019-03-27 | 8:29:18  | 183     | 1.28    | 2.26         | 3.21    | 6.8         | 0.164     |
| 2019-04-08 | 3:58:12  | 184     | 1.13    | 2.24         | 3.23    | 2.8         | 0.165     |
| 2019-04-08 | 4:01:27  | 184     | 1.13    | 2.24         | 3.23    | 2.8         | 0.165     |
| 2019-04-08 | 4:04:40  | 184     | 1.12    | 2.24         | 3.23    | 2.8         | 0.165     |
| 2019-04-08 | 4:07:52  | 184     | 1.12    | 2.24         | 3.23    | 2.8         | 0.165     |
| 2019-04-08 | 4:11:06  | 184     | 1.11    | 2.24         | 3.23    | 2.8         | 0.165     |
| 2019-04-10 | 2:30:41  | 184     | 1.36    | 2.24         | 3.24    | 2.3         | 0.165     |
| 2019-04-10 | 2:33:56  | 184     | 1.35    | 2.24         | 3.24    | 2.3         | 0.165     |
| 2019-04-10 | 2:37:09  | 184     | 1.34    | 2.24         | 3.24    | 2.3         | 0.165     |
| 2019-04-10 | 2:40:23  | 184     | 1.32    | 2.24         | 3.24    | 2.3         | 0.165     |
| 2019-04-10 | 2:43:36  | 184     | 1.31    | 2.24         | 3.24    | 2.3         | 0.165     |
| 2019-04-10 | 2:46:44  | 184     | 1.27    | 2.24         | 3.24    | 2.2         | 0.165     |
| 2019-04-10 | 2:53:57  | 184     | 1.29    | 2.24         | 3.24    | 2.2         | 0.165     |
| 2019-04-10 | 7:27:12  | 184     | 1.30    | 2.24         | 3.24    | 2.2         | 0.165     |
| 2019-04-10 | 7:30:24  | 184     | 1.31    | 2.24         | 3.24    | 2.2         | 0.165     |
| 2019-04-10 | 7:33:38  | 184     | 1.32    | 2.24         | 3.24    | 2.2         | 0.165     |
### Table A.2. List of optical disk-integrated lightcurves used for ADAM shape modeling.

For each lightcurve, the table gives the epoch, the number of individual measurements $N_p$, asteroid’s distances to the Earth $\Delta$ and the Sun $r$, phase angle $\varphi$, photometric filter and observation information.

| N  | Epoch          | $N_p$ | $\Delta$ (AU) | $r$ (AU) | $\varphi$ (°) | Filter | Reference                      |
|----|----------------|-------|---------------|----------|---------------|--------|--------------------------------|
| 1  | 1977-09-24.3   | 41    | 2.18          | 3.13     | 7.4           | V      | Schober et al. (1980)          |
| 2  | 1978-11-14.0   | 95    | 1.84          | 2.43     | 21.7          | V      | Schober et al. (1980)          |
| 3  | 1978-11-16.0   | 74    | 1.83          | 2.43     | 21.4          | V      | Schober et al. (1980)          |
| 4  | 1978-11-19.0   | 78    | 1.80          | 2.43     | 21.0          | V      | Schober et al. (1980)          |
| 5  | 1979-01-01.4   | 16    | 1.61          | 2.44     | 15.3          | V      | Schober et al. (1980)          |
| 6  | 1983-10-29.0   | 81    | 1.72          | 2.71     | 2.0           | V      | Barucci et al. (1985)          |
| 7  | 1983-11-24.9   | 25    | 1.81          | 2.65     | 13.3          | V      | McCheyne et al. (1985)         |
| 8  | 1983-11-25.9   | 15    | 1.82          | 2.65     | 13.7          | V      | McCheyne et al. (1985)         |
| 9  | 1994-10-31.9   | 100   | 1.90          | 2.81     | 9.4           | R      | Kryszczynska et al. (1996)     |
| 10 | 2008-04-06.4   | 202   | 2.43          | 3.37     | 6.8           | R      | Pilcher & Jardine (2009)       |
| 11 | 2008-04-10.3   | 246   | 2.42          | 3.38     | 5.5           | R      | Pilcher & Jardine (2009)       |
| 12 | 2008-04-15.3   | 213   | 2.40          | 3.39     | 3.8           | R      | Pilcher & Jardine (2009)       |
| 13 | 2008-04-25.3   | 224   | 2.40          | 3.41     | 1.0           | R      | Pilcher & Jardine (2009)       |
| 14 | 2009-06-05.7   | 72    | 2.95          | 3.85     | 7.9           | R      | Pilcher & Jardine (2009)       |
| 15 | 2009-06-07.6   | 85    | 2.95          | 3.85     | 7.8           | R      | Pilcher & Jardine (2009)       |
| 16 | 2009-06-09.6   | 51    | 2.94          | 3.85     | 7.6           | R      | Pilcher & Jardine (2009)       |
| 17 | 2009-06-10.7   | 110   | 2.94          | 3.85     | 7.6           | R      | Pilcher & Jardine (2009)       |
| 18 | 2009-06-11.6   | 141   | 2.94          | 3.85     | 7.5           | R      | Pilcher & Jardine (2009)       |
| 19 | 2009-06-22.5   | 12    | 2.94          | 3.86     | 7.6           | R      | Pilcher & Jardine (2009)       |
| 20 | 2011-09-28.0   | 200   | 1.87          | 2.69     | 14.7          | C      | Hanuš et al. (2016b)          |
| 21 | 2011-10-03.0   | 179   | 1.82          | 2.69     | 13.2          | C      | Hanuš et al. (2016b)          |
| 22 | 2011-10-11.3   | 285   | 1.75          | 2.67     | 10.3          | C      | Pilcher (2012)                 |
| 23 | 2011-11-01.4   | 287   | 1.64          | 2.63     | 2.8           | C      | Pilcher (2012)                 |
| 24 | 2011-11-16.3   | 282   | 1.65          | 2.61     | 6.9           | C      | Pilcher (2012)                 |
| 25 | 2011-12-10.2   | 378   | 1.78          | 2.57     | 15.9          | C      | Pilcher (2012)                 |
| 26 | 2013-01-28.4   | 278   | 2.12          | 2.77     | 17.5          | R      | Pilcher (2012)                 |
| 27 | 2013-02-20.4   | 300   | 1.97          | 2.82     | 12.3          | R      | Pilcher (2012)                 |
| 28 | 2013-02-25.4   | 396   | 1.95          | 2.83     | 11.2          | R      | Pilcher (2012)                 |
| 29 | 2013-04-17.3   | 343   | 2.13          | 2.94     | 13.6          | R      | Pilcher (2012)                 |
| 30 | 2017-11-8.1    | 359   | 1.79          | 2.47     | 19.9          | R      | E. Jehin, M. Ferrais, Trappist North |
| 31 | 2017-11-28.1   | 261   | 1.66          | 2.46     | 16.3          | R      | E. Jehin, M. Ferrais, Trappist North |
| 32 | 2017-12-3.1    | 365   | 1.65          | 2.46     | 15.5          | R      | E. Jehin, M. Ferrais, Trappist North |
| 33 | 2017-12-8.3    | 864   | 1.62          | 2.46     | 14.8          | R      | E. Jehin, M. Ferrais, Trappist North |
| 34 | 2018-2-27.9    | 244   | 2.03          | 2.49     | 22.6          | C      | Gaia-GOSA                     |

**Notes.** Gaia-GOSA (Gaia-Ground-based Observational Service for Asteroids, [www.gaiagosa.eu](http://www.gaiagosa.eu)).
Table B.1. Astrometry of Euphrosyne’s satellite S/2019 (31) 1. Date, mid-observing time (UTC), telescope, camera, filter, astrometry ($X$ is aligned with Right Ascension, and $Y$ with Declination, $o$ and $c$ indices stand for observed and computed positions, and $\sigma$ is pixel scale), and photometry (magnitude difference $\Delta M$ with uncertainty $\delta M$).

| Date       | UTC     | Tel.       | Cam.         | Filter | $X_o$ (mas) | $Y_o$ (mas) | $X_{o-c}$ (mas) | $Y_{o-c}$ (mas) | $\sigma$ (mas) | $\Delta M$ (mag) | $\delta M$ (mag) |
|------------|---------|------------|--------------|--------|-------------|-------------|----------------|----------------|----------------|----------------|----------------|
| 2019-03-15 | 07:07:59.26 | VLT       | SPHERE/ZIMPOL | R      | -398.5      | 10.5        | -0.7           | 2.1            | 3.6           | 8.9            | 0.2            |
| 2019-03-20 | 04:16:29.04 | VLT       | SPHERE/ZIMPOL | R      | -377.7      | 12.6        | -1.4           | -3.4           | 3.6           | 9.2            | 0.4            |
| 2019-03-25 | 02:53:48.81 | VLT       | SPHERE/ZIMPOL | R      | -239.7      | 30.7        | -0.6           | 0.9            | 3.6           | 9.1            | 0.3            |
| 2019-03-27 | 08:16:28.01 | VLT       | SPHERE/ZIMPOL | R      | -410.5      | 2.8         | 0.9            | 1.3            | 3.6           | 9.0            | 0.3            |
| 2019-04-10 | 07:20:44.49 | VLT       | SPHERE/ZIMPOL | R      | 383.1       | -20.2       | -0.6           | 0.8            | 3.6           | 8.8            | 0.2            |
