Physical and dynamical characterization of the Euphrosyne asteroid family

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Aims. The Euphrosyne asteroid family occupies a unique zone in orbital element space around 3.15 au and may be an important source of the low-albedo near-Earth objects. The parent body of this family may have been one of the planetesimals that delivered water and organic materials onto the growing terrestrial planets. We aim to characterize the compositional properties as well as the dynamical properties of the family.

Methods. We performed a systematic study to characterize the physical properties of the Euphrosyne family members via low-resolution spectroscopy using the NASA Infrared Telescope Facility. In addition, we performed smoothed-particle hydrodynamics (SPH) simulations and N-body simulations to investigate the collisional origin, determine a realistic velocity field, study the orbital evolution, and constrain the age of the Euphrosyne family.

Results. Our spectroscopy survey shows that the family members exhibit a tight taxonomic distribution, suggesting a homogeneous composition of the parent body. Our SPH simulations are consistent with the Euphrosyne family having formed via a reaccumulation process instead of a cratering event. Finally, our N-body simulations indicate that the age of the family is $280^{+300}_{-180}$ Myr, which is younger than previous estimates.

Key words. minor planets, asteroids: general – minor planets, asteroids: individual: (31) Euphrosyne – methods: observational – methods: numerical

1. Introduction

The asteroid belt is a living relic leftover from the planet-formation epoch of our Solar System. However, traces of primordial conditions have been gradually obscured by ongoing collisional and dynamical evolution processes (Bottke et al. 2015). Physical observations and dynamical models of the main asteroid belt allow us to constrain the planet-formation scenarios and gain understanding of how the main belt reached its current state (Bottke et al. 2015). Asteroid families, products of collisional events, serve as a powerful tool to investigate the collisional and dynamical evolution of the asteroid belt (Milani et al. 2014).

Among a few large low-albedo families, the Euphrosyne asteroid family uniquely occupies a highly inclined region in the outer main belt, bisected by the $v_6$ secular resonance (Carruba et al. 2014). Asteroids in circulating orbits and aligned librating states of the $v_6$ resonance are unstable on short timescales because of close encounters with planets. In contrast, asteroids in anti-aligned librating states of the $v_6$ resonance, such as the Euphrosyne family members, may be stable on timescales up to hundreds of millions of years (Machuca & Carruba 2012; Carruba et al. 2014). The Euphrosyne family is one of the largest families, with more than 2600 associated members and may be an important contributor to the low-albedo subpopulations of the near-Earth objects (Mainzer et al. 2011; Masiero et al. 2015).

Given the low number density in the phase space for proper inclination $i_p > 0.3$, the remarkably large number of members in the Euphrosyne family may be due to the relatively high collisional velocities (Milani et al. 2014) in the Euphrosyne region. Dynamical analysis suggests that the cratering event that formed the Euphrosyne family most likely occurred between 560 and 1160 Myr ago (Carruba et al. 2014).

Using the method introduced by DeMeo & Carry (2013), Carruba et al. (2014) analyzed the photometric data from the Sloan Digital Sky Survey (SDSS) Moving Object Catalog to investigate the taxonomical distribution in the Euphrosyne region. Similar to other regions in the outer belt, the Euphrosyne region is overwhelmingly dominated by primitive materials, with ~68% C-type, 20% X-type, and 7% B-type asteroids. The family shows an average albedo of $p_V = 0.056 \pm 0.016$, with only 1.5% of members having an albedo $>0.1$ (Masiero et al. 2013).

In this paper, we present the physical and dynamical characterization of the properties of the Euphrosyne family. We obtain low-resolution spectra of 19 suggested family members with NASA Infrared Telescope Facility (IRTF)/SpeX (Sect. 3). We identify members associated with this family using the hierarchical clustering method and construct the size–frequency distribution of this family (Sect. 4). We further constrain the family-forming event by smoothed-particle hydrodynamics (SPH) simulations (Sect. 5), study the orbital evolution of the family, and constrain its age using N-body simulations.
Fig. 1. Relative reflectance spectra of the Euphrosyne family members. All the spectra are normalized at 1.1 $\mu$m and are offset vertically for clarification.

(6, Sect. 6). An additional discussion related to the observed shape of (31) Euphrosyne using disk-resolved images obtained with the Very Large Telescope (VLT) can be found in Yang et al. (2020).

2. Observations and data reduction

The near infrared (NIR) spectra of the Euphrosyne family members were obtained using the IRTF 3-m telescope atop Mauna Kea, Hawaii. The observed family members ($n = 19$), including (31) Euphrosyne, are selected based on the dynamical study of Novaković et al. (2011), targeting the best observables in terms of their brightness and on-sky placement. An upgraded medium-resolution 0.7–5.3 $\mu$m spectrograph (SpeX) was used, equipped with a Raytheon $1024 \times 1024$ InSb array that has a spatial scale of 0.$^\prime$10 pixel$^{-1}$ (Rayner et al. 2003). The low-resolution prism mode was used to cover an overall wavelength range from 0.7 to 2.5 $\mu$m for all of our observations. We used a 0.8$^\prime\prime \times 15$ $^\prime\prime$ slit that provided an average spectral resolving power of $\sim$130. To correct for strong telluric absorption features from atmospheric oxygen and water vapor, we used G2V-type stars that are close to the scientific target both in time and sky position as telluric calibration standard stars as well as solar analogs for computing relative reflectance spectra of scientific targets. During our observations, the slit was always oriented along the parallactic angle to minimize effects from differential atmospheric refraction. The SpeX data were reduced using the SpeXtool reduction pipeline (Cushing et al. 2004). A journal of observations is provided in Table 1.

3. Spectroscopy survey of the Euphrosyne family

The reflectance spectra of the Euphrosyne family members are shown in Fig. 1. The physical properties of these asteroids are listed in Table 2. Our observations show that the family members exhibit neutral to slightly red spectral slopes in the NIR. We classified 17 family members for the first time using their NIR reflectance spectra from 0.80 to 2.45 $\mu$m based on the Bus-DeMeo (BD) taxonomic system (DeMeo et al. 2009). To classify these objects, we resampled and normalized all the spectra at 1.5 $\mu$m, which is free of intrinsic absorption features as well as atmospheric absorptions, and calculated $\chi^2$ difference between the asteroid spectrum and the mean spectrum of each taxonomy class taken from DeMeo et al. (2009). We compared

| Object | UT date   | $V$ (mag) | $r_h$ (au) | $\Delta$ (au) | $\alpha$ (°) | Airmass | Standard |
|---------|-----------|-----------|------------|--------------|-------------|---------|----------|
| 31      | 2017-Dec.-29 | 10.54     | 2.46       | 1.61         | 14.37       | 1.49    | HD 237451|
| 895     | 2018-Mar.-06 | 14.04     | 2.77       | 3.17         | 17.62       | 1.81    | HD 30854 |
| 16708   | 2018-Nov.-27 | 17.44     | 2.55       | 1.92         | 19.85       | 1.04    | HD 73708 |
| 16712   | 2018-Nov.-27 | 17.42     | 2.61       | 2.10         | 20.75       | 1.02    | HD 73708 |
| 24440   | 2018-Mar.-06 | 17.78     | 3.57       | 2.60         | 3.62        | 1.08    | HD 98562 |
| 24478   | 2018-Mar.-06 | 16.67     | 2.76       | 1.82         | 7.99        | 1.16    | HD 98562 |
| 28959   | 2018-Jun.-15 | 16.44     | 2.55       | 1.64         | 12.52       | 1.30    | HD 164595|
| 34119   | 2018-Nov.-27 | 17.07     | 2.70       | 2.00         | 17.23       | 1.00    | HD 73708 |
| 35534   | 2017-Sep.-24 | 18.64     | 3.69       | 2.80         | 8.12        | 1.06    | SAO73377 |
| 42318   | 2018-Nov.-27 | 17.55     | 2.70       | 1.85         | 12.97       | 1.21    | HD 34828 |
| 54240   | 2018-Aug.-17 | 17.49     | 2.78       | 1.88         | 11.43       | 1.03    | HD 190605|
| 54808   | 2018-Nov.-27 | 16.72     | 2.45       | 1.98         | 22.75       | 1.06    | HD 206828|
| 55940   | 2018-Nov.-27 | 16.97     | 2.78       | 1.80         | 4.03        | 1.03    | HD 283691|
| 66360   | 2018-Nov.-27 | 17.98     | 3.02       | 2.13         | 9.76        | 1.07    | HD 11532 |
| 68085   | 2018-Mar.-06 | 16.48     | 2.56       | 1.62         | 8.66        | 1.62    | HD 106172|
| 79478   | 2018-Aug.-17 | 17.84     | 2.76       | 1.76         | 4.74        | 1.12    | HD 207079|
| 87926   | 2017-Sep.-24 | 18.54     | 2.68       | 2.44         | 21.99       | 1.12    | HD 250641|
| 114190  | 2018-Aug.-17 | 17.11     | 2.33       | 1.45         | 15.87       | 1.87    | HD 5331 |
| 127211  | 2018-Mar.-06 | 17.42     | 2.56       | 1.63         | 9.39        | 1.01    | HD 98590 |

Notes. $r_h$ and $\Delta$ are the heliocentric and geocentric distances, respectively. $\alpha$ is the phase angle.
Table 2. Physical properties of studied Euphrosyne family members.

| Object | Diameter (km) | $D_e$ (km) | $p_V$ | $p_W$ | Slope ($\%/10^3$ Å) | $S_L$ ($\%/10^3$ Å) | Taxonomy |
|--------|---------------|------------|-------|-------|----------------------|----------------------|----------|
| 31     | 281.98        | 10.16      | 0.045 | 0.008 | 1.91                 | 0.01                 | Ci       |
| 895    | 110.67        | 2.21       | 0.074 | 0.017 | 2.17                 | 0.02                 | B        |
| 16708  | 14.66         | 0.15       | 0.057 | 0.004 | 1.13                 | 0.06                 | Ch, Ch   |
| 16712  | 16.85         | 0.45       | 0.047 | 0.003 | 0.94                 | 0.05                 | Ch, C    |
| 24440  | 25.00         | 3.72       | 0.063 | 0.019 | 2.17                 | 0.11                 | Ci       |
| 24478  | –             | –          | –     | –     | 1.60                 | 0.06                 | Ci       |
| 28959  | 18.45         | 0.17       | 0.052 | 0.010 | 1.22                 | 0.05                 | Ci, Cg   |
| 3419   | –             | –          | –     | –     | 1.78                 | 0.05                 | Ci       |
| 35534  | 16.84         | 0.10       | 0.028 | 0.007 | 2.21                 | 0.05                 | Ci       |
| 42318  | –             | –          | –     | –     | 2.37                 | 0.10                 | Ci, C    |
| 54240  | 13.38         | 0.22       | 0.062 | 0.012 | 2.36                 | 0.16                 | Ci, C    |
| 54808  | 22.63         | 0.31       | 0.038 | 0.004 | 1.53                 | 0.04                 | Ci, C    |
| 55940  | 13.26         | 1.23       | 0.063 | 0.020 | 1.80                 | 0.04                 | X        |
| 66360  | 8.62          | 0.23       | 0.125 | 0.014 | 2.89                 | 0.06                 | D        |
| 68085  | 15.02         | 0.37       | 0.065 | 0.009 | 1.36                 | 0.10                 | Ci, Cg   |
| 79478  | 8.74          | 0.45       | 0.058 | 0.014 | 3.72                 | 0.18                 | D        |
| 89726  | 13.08         | 1.37       | 0.059 | 0.017 | 1.79                 | 0.10                 | Ci, C    |
| 11490  | 10.24         | 0.27       | 0.073 | 0.027 | 2.32                 | 0.14                 | X        |
| 127211 | –             | –          | –     | –     | 1.75                 | 0.09                 | Ci, Cg   |

Notes. The diameter and albedo values are taken from Masiero et al. (2013). The taxonomy classification is based on the BD taxonomic system.

Fig. 2. Relative taxonomic distributions of the Euphrosyne family based on the BD taxonomic system: (a) with all the objects (n = 19); (b) with the interlopers (895, 66360, and 79478) removed (n = 16).

Our classification results with the results based on the principal component analysis performed with the Bus-DeMeo Taxonomy Classification Web tool1 and found that the two methods are consistent for most cases. Using the NIR-only spectra, the BD classification system returned unique classification for less than 10% of the family members. For members with non-unique taxonomic classifications, we list the two types with the lowest $\chi^2$ values in Table 2. The majority of the family members belong to the C-types, as shown in Fig. 2, indicating a homogeneous composition of the parent body for the Euphrosyne family. Our finding is consistent with the previous study using the SDSS data (Carruba et al. 2014).

3.1. Detection of 1-μm absorption feature

The largest member, asteroid 31, shows a broad but shallow absorption feature, centered near 1.0-μm; see Fig. 3. Such a rounded absorption feature near 1.0-μm has also been observed on other large C-type asteroids, e.g. (1) Ceres and (10) Hygiea (Takir & Emery 2012). Compared to the two larger asteroids, the absorption features of Euphrosyne, in both the 1-μm region and the 3-μm region, appear weaker in terms of the band depth.

We detected the broad 1-μm feature in 8 of the 19 objects. Among these eight asteroids, seven are C-types with one exception, which is 79478, a D-type based on its very red spectral slope. The band centers of these absorption features vary from 0.84 to 1.05 μm. It is well known that some silicates and hydrated minerals show a diagnostic absorption band around 1.0-μm, such as pyroxene, olivine, and magnetite. Magnetite is a product of aqueous alteration and has been detected on some B-type asteroids (Yang & Jewitt 2010) and on the dwarf planet Ceres (de Sanctis et al. 2015). To further explore the compositional origin of this absorption feature, we searched for spectral analogs for the Euphrosyne family members among meteorites and silicate minerals. We present the results in Sect. 3.2.

3.2. Spectral analogs

We selected four asteroids that have high-quality spectra and are representative of the spectral diversity of the family for further analysis. We excluded 79478 from the spectral modeling because its spectrum is rather noisy beyond 1.5 μm. We combined the IRTF data with the available optical data to cover a wider range of wavelengths. We searched for spectral analogs for the Euphrosyne family among the collections of the RELAB spectral library (Hiroi et al. 2001) and the USGS spectral library (Survey et al. 2017).

As shown in Fig. 4, the shape of the absorption band of asteroid 31 is different from that of magnetite (shown in green), where the magnetite band has a narrower profile and the band center is at a longer wavelength. Instead, the round feature on 31 is similar to the B-type asteroids (Yang & Jewitt 2010) and on the dwarf planet Ceres.

When combining with the optical spectrum, the difference between asteroid 31 and asteroid 895 in terms of the 1.0-μm feature appears more prominent. Compared to the feature of 31,
the latter is broader with a band center at shorter wavelength and it cannot be fit with either carbonaceous meteorites or with olivine. Except for the wavelengths below 0.6-μm, the spectrum of hedenbergite fits the overall spectral profile of 895 adequately well including the 1.0-μm feature.

The spectrum of 16712 shows a marginal absorption feature between 0.7 and 1.5 μm, which can be fit with the heated Murchison or with the heated olivine spectrum. However, the optical colors of 16712 obtained by the SDSS (Ivezić et al. 2001) show a downturn below 0.7 μm, which is not observed in the olivine spectrum. A mixture of heated Murchison with a small amount of heated Ivuna fits the spectrum of 16712 better, especially when taking into account the optical part.

Among all the observed family members, asteroid 66360 is one of the reddest objects in the NIR and has the steepest spectral slope in the optical. The spectrum of 66360 is very different from those of C-type asteroids; instead it is more similar to D-type asteroids or Trojan asteroids. As suggested in Yang et al. (2013), the red Trojan asteroid spectra can be fitted with a mixture of fine-grained silicates and iron. The spectrum of metallic iron can fit the 66360 spectrum well but discrepancies were observed at wavelengths longwards of 1.5 μm. The similarity between the D-type asteroids and the Tagish Lake meteorite was previously noted by Hiroi et al. (2001). Consistently, we found the best spectral analog for 66360 is the Tagish Lake meteorite.

### 3.3. Possible interlopers

The second largest body in the Euphrosyne region, (895) Helio, is identified as a family member by Masiero et al. (2013) but is considered a dynamical interloper by Carruba et al. (2014). Our IRTF observation combined with the optical data reveal notable differences between Euphrosyne and Helio, especially at wavelengths shortwards of 1.0–1.5 μm. Also, spectral modeling shows that the best spectral analog for Helio is hedenbergite instead of carbonaceous meteorites, which are the best match for Euphrosyne as well as other Cb-type members. Therefore, 895 is likely an interloper. In addition, 66360 and 79478 have much redder spectral slopes than others, indicating that these objects have substantially different compositions, in contrast to other family members. Therefore, 66360 and 79478 are also likely interlopers.
or reaccumulation event. For the density \( \rho = 1665 \pm 242 \, \text{kg m}^{-3} \)
taken from Yang et al. (2020), this means the escape speed \( v_{\text{esc}} = 135 \, \text{m s}^{-1} \)
which is an important parameter for further modeling. The asteroid (895) Helio appears as an intermediate-
size outlier. If we include 895 in the SFD, the parent body related parameters changes slightly to \( D_{\text{PB}} = 289 \, \text{km}, M_{\text{LR}}/M_{\text{PB}} = 0.876; \)
we discuss its membership further in Sect. 5.

5. Collisional formation of the family

We coupled the observational data of the Euphrosyne family with hydrodynamical simulations to study the family-formation event. The simulations were used to constrain the impact parameters, such as the impact angle and the diameter of the impactor. We further estimated the initial speed distribution of the fragments. The simulations were performed using code OpenSPH (Seveček 2019) with varying impact parameters. In these simulations, the impactor diameters ranged from \( d_{\text{imp}} = 50 \) to 100 km and the impact angles from \( \phi_{\text{imp}} = 15^\circ \) to \( 60^\circ \). The impact speed was \( v_{\text{imp}} = 5 \, \text{km s}^{-1} \) in all simulations, which roughly corresponds to the mean relative velocity in the main belt. We assumed a monolithic carbonaceous material with initial density \( \rho_0 = 1600 \, \text{kg m}^{-3} \) for both the target and the impactor (consistent with the measurement presented in Yang et al. 2020). The numerical model is described in detail in Ševeček et al. (2019). We modeled the family formation using a hybrid SPH/N-body approach. The impact, fragmentation, and initial reaccumulation were carried out using an SPH solver, which ran up to \( t_{\text{esc}} = 24 \, \text{h} \). We then passed the results to a simple N-body solver with collision handling instead of hydrodynamics. The N-body reaccumulation phase ran for another \( t_{\text{esc}} = 10 \, \text{days} \), at which point the resulting SFD was almost stationary.

During the fragmentation phase, we solved the continuity equation, the equation of motion, the energy equation, and the Hooke’s equation for the evolution of the stress tensor. For the equation of state, we used the Tillotson equation with the material parameters of basalt. To account for plasticity and fragmentation of the material, the von Mises rheology together with the Grady–Kipp fragmentation model were used. This implies that completely fractured material is frictionless and essentially behaves like a fluid. To assess the plausibility of such a model for the studied impact, we also performed several simulations with the Drucker–Prager rheology, which – unlike the von Mises rheology – also includes cohesion and dry friction, meaning that even completely fractured material has non-negligible strength, determined by the coefficient \( \mu_d \) of dry friction. The equations were integrated using a predictor–corrector scheme and the time-step was limited by the Courant–Friedrichs–Lewy (CFL) criterion with the Courant number \( C = 0.2 \). Figure 7 shows several snapshots of one of the performed SPH simulations.

At the end of the SPH phase, each SPH particle was converted into a sphere of equal volume and these spheres were used as inputs for an N-body solver. The N-body approach allowed us to use significantly larger time-steps, thus obtaining the final SFD much faster. We further merged collided fragments into larger spheres, provided their relative speed was lower than the escape speed \( v_{\text{esc}} \) and the spin rate of the formed merger was lower than the critical spin rate \( \omega_{\text{crit}} \).

From the set of performed SPH/N-body simulations, we selected a few that are the most consistent with the SFD of the observed family. The synthetic SFDs as well as the observed SFD for reference are plotted in Fig. 8. Generally, impacts at low impact angles (\( \phi \approx 15^\circ \)) tend to produce an intermediate-sized body originating from the antipode of the target. More oblique impacts (\( \phi \geq 30^\circ \)) create no such fragments. This effect was previously recognized by Vernazza et al. (2020). However, even the largest intermediate body obtained in our simulations (\( D = 66 \, \text{km} \)) is still considerably smaller than asteroid (895) Helio with a diameter \( D \approx 148 \, \text{km} \) (Carry 2012). Since no single fragment with similar size was created in the simulations, we conclude that (895) Helio is indeed an interloper, consistent with the spectroscopic arguments laid out above.

The lack of intermediate-sized bodies in the observed family suggests that the impact angle was likely in the mid-range values; a head-on impact would produce a large body which is not observed and a highly oblique impact would not have enough energy to eject the observed fragment mass. The probable size of the impactor is \( d_{\text{imp}} = 70–80 \, \text{km} \). Naturally, a higher impact angle also implies a larger impactor to deliver the same kinetic energy into the target. Regardless of the impact angle, the SFDs of synthetic families have slightly steeper slopes compared to the observed SFD, suggesting the family has been modified by orbital evolution since its origin.

In addition to the SFDs, we plot the speed distribution of fragments in Fig. 9, since they were subsequently used as an input for the evolution simulations (Sect. 6). The distributions are similar in all performed simulations. The maximum value is approximately located at the escape speed \( v_{\text{esc}} \approx 109.7 \, \text{m s}^{-1} \) of the largest remnant. The impacts at larger impact angles generally produce flatter tails of the distribution, that is, faster fragments compared to head-on impacts.

6. Evolution and age of the family

Using the results of Sect. 5, we revisit here the question of the family age. For this purpose, we performed an N-body integration of a synthetic family. The integration was carried out with the symplectic Regularized Mixed Variable Symplectic 3 (RMVS3) scheme of the SWIFT package (Levison & Duncan 1994; Laskar & Robutel 2001). Our dynamical model contained (i) the gravitational influence of the Sun, six planets (from Earth to Neptune), and (31) Euphrosyne (\( M_{31} = 1.7 \times 10^{12} \, \text{kg} \), Yang et al. 2020); (ii) the Yarkovsky diurnal and seasonal effects (Vokrouhlický 1998; Vokrouhlický & Farinella 1999); and (iii) the YORP effect (Čapek & Vokrouhlický 2004) with collisional reorientations (Farinella et al. 1998) and random period changes for critically rotating asteroids, as described in Brož et al. (2011).
Fig. 7. Snapshots of the SPH simulation with the impactor diameter $d_{\text{imp}} = 70 \text{ km}$ and the impact angle $\phi_{\text{imp}} = 30^\circ$. The images were captured at times $t = 0, 4, 8, 12, 16, 20, 24 \text{ h}$ after the impact. The color palette is given by the specific internal energy of the particles.

Fig. 8. Size–frequency distribution of three selected SPH simulations compared with the distribution of the observed Euphrosyne family. The diameter of a probable interloper (895) Helio is plotted as a black circle.

Fig. 9. Differential histogram of fragment speeds at the end of the reaccumulation phase. The velocities were evaluated in the reference frame of the largest remnant.

The synthetic family was initially comprised of $n_T = 5712$ test particles (i.e. twice as many as the observed family). Their initial orbits and parameters are described in detail in Appendix A. The family was integrated over 1 Gyr with a time-step of $\Delta t = 1/20 \text{ yr}$. We performed an on-line computation of proper orbital elements using the method discussed in Appendix A.

Figure 10 shows several snapshots of the evolving synthetic family in the $(a_p, e_p)$ plane. At $t = 50 \text{ Myr}$, the family is clearly insufficiently dispersed in $e_p$. The asymmetry of the mean eccentricity between the inner and outer part of the family (Milani et al. 2019) is inherited from the mapping of the initial conditions (depending on the orbital configuration at the time of impact) to the proper element space (see Fig. A.2). Similarly, the considered ejection velocities were high enough to populate the region between 9:4 and 11:5 mean-motion resonances with Jupiter.

After the next $\approx 200 \text{ Myr}$ of evolution, the family dynamically spreads due to combined effects of the Yarkovsky drift and resonant perturbations. Strong diffusion is observed close to the family center where the mean-motion resonances overlap with the $\nu_6$ secular resonance$^2$ and the family members are located in the anti-aligned states (Machuca & Carruba 2012; Carruba et al. 2014; Huaman et al. 2018; Milani et al. 2019). For objects that are temporarily captured in the $\nu_6$ resonance, their $e_p$ can be pumped up significantly and subsequently be implanted into Jupiter-crossing, Mars-crossing, and even near-Earth orbits (Masiero et al. 2015). Therefore, including Mars and Earth together with other massive bodies in our simulations is essential to properly model the dynamical decay of the population. Comparing the synthetic and observed family, the distributions appear to be qualitatively the same except for the region at $a_p > 3.2 \text{ au}$, $e_p < 0.17$ (which is underpopulated by

$^2$ Besides $\nu_6$, the family is also affected by $\nu_4$ and $\nu_{16}$ secular resonances (Machuca & Carruba 2012; Carruba et al. 2014).
synthetic asteroids), and the family halo (which is truncated from the observed population by the HCM).

At \( t = 600 \) Myr, the synthetic family seems to be strongly dispersed, especially towards low eccentricities. This suggests that the Euphrosyne family might be considerably younger than previous estimates (between 560 and 1160 Myr, Carruba et al. 2014).

To determine the age of the family, we analyzed our \( N \)-body simulation using the “black-box” method which was extensively described and tested in Brož & Morbidelli (2019). We split the intervals \( a_p \in (3.03; 3.258) \text{ au}, e_p \in (0; 0.45), \sin i_p \in (0.43; 0.453) \) into a grid of \( 10 \times 9 \times 3 \) boxes. In order to extend our statistical test to the family halo as well, we combined the observed family with all C-type asteroids in the given range of the orbital element space. The observed asteroids in the individual boxes were counted to obtain \( N_{\text{obs},i} \) and we also determined the respective SFD.

For a given \( t \), we randomly selected a subset of test particles from our synthetic family. The selection was always performed in given size bins to match the synthetic SFD with the observed SFD. The total number of test particles was exactly the same as the number of observed asteroids. Regarding the background population, we simply assumed that it is negligible because Euphrosyne is located in a highly inclined part of the main belt. The test particles were counted to obtain \( N_{\text{syn},i} \). We constructed a statistical metric (Press et al. 1992):

\[
\chi^2 = \sum_{i=1}^{N_{\text{box}}} \left( \frac{N_{\text{syn},i} - N_{\text{obs},i}}{\sigma^2_{\text{syn},i} + \sigma^2_{\text{obs},i}} \right)^2,
\]

where \( N_{\text{box}} \) is the number of boxes with nonzero \( N_{\text{syn}} \); with Poisson uncertainties \( \sigma = \sqrt{N} \). This way we compare the distributions in the orbital element space.

Figure 11 shows the results of our \( \chi^2 \) test as a function of \( t \). The global minimum at \( t = 281 \) Myr can be characterized by the ratio \( \chi^2/N_{\text{box}} = 2.4 \) which we consider low enough for the observed distributions to be equivalent. By calculating the 3-\( \sigma \) confidence levels of our test, we determined the age of the Euphrosyne family \( \tau = 281 \pm 280 \) Myr.

Figure 11 also shows the result of the \( \chi^2 \) test at \( t = 281 \) Myr in individual boxes (for a single selected section in inclinations). One can see that the largest difference between the observed and synthetic population surprisingly arises in the central region of the family.

7. Discussion

In the NIR, the spectra of the Euphrosyne family members resemble those of the carbonaceous chondrite meteorites, and in particular, the CI and CM chondrites. Takir et al. (2015) report that CM and CI chondrites are possible meteorite analogs for asteroids with the sharp 3-\( \mu \text{m} \) features but do not match the rounded 3-\( \mu \text{m} \) feature observed on outer belt asteroids including (52) Europa and (31) Euphrosyne. In addition, recent studies at longer wavelengths show that the spectra of heated carbonaceous chondrites failed to fit the spectra of the C-type asteroids in the mid-infrared (Vernazza et al. 2015, 2017). The emission features in the 10-\( \mu \text{m} \) region of large asteroids can be reproduced using interplanetary dust particles (IDPs, Vernazza et al. 2015, 2017) or fine grained silicates entrained in a transparent matrix (Emery et al. 2006; Yang et al. 2013). At present, there is no natural material or synthetic mixture that can simultaneously fit both the NIR and the mid-IR spectra of primitive asteroids to a satisfactorily level. In order to gain a deeper and more comprehensive understanding of the intrinsic composition of an object, it is important to obtain observations over a wide range of wavelength coverage. To date, the thermal properties of intermediate and small asteroids remain largely unknown. The James Webb Space Telescope will be launched in 2021, which will offer an unprecedented opportunity to study small asteroids (Rivkin et al. 2016), such as the Euphrosyne family members in the 3-\( \mu \text{m} \) region and beyond.

The properties of the Euphrosyne family and our SPH simulations indicate that the family formed via a reaccumulation event. This means that the original shape of the parent body as well as the impact crater were not preserved, which is in agreement with AO observations (see the related discussion in Yang et al. 2020). Moreover, our orbital evolution model indicates that the age of the Euphrosyne family is \( \tau \approx 280 \) Myr. This is substantially younger than the previous estimates (Carruba et al. 2014) which were based on the evolution of the size–frequency distribution (with the assumed initial cumulative slope of \( \sim -3.8 \)). The main goal of the previous work by Carruba et al. (2014) was to check the effect of the \( \nu_6 \) secular resonance on the size distribution of the family and on its evolution. Therefore, several simplified assumptions were used, such as the value of the initial cumulative slope and the assumption that secular dynamics dominated the evolution of the size distribution. In this paper, our model adopts a more realistic velocity field (with velocities of the order of \( v_{\text{esc}} \)) than the previous assumption. The dynamical age is then constrained by the observed distribution of proper semimajor axis and eccentricity. We consider our estimate robust because the density of (31) Euphrosyne is well constrained.
As discussed in Yang et al. (2020), a large fraction of water ice is needed to account for the low bulk density of (31) Euphrosyne. One problem that needs to be addressed is the survival of the water ice through the fragmentation and reaccumulation processes. Wakita & Genda (2019) studied the status of hydrous minerals in large planetesimals during collisional processes and pointed out that an oblique impact may enhance the effect of frictional heating because the leading side of the impact point can experience strong shear. Given the large size of the impactor and the impact velocity of 5 km s$^{-1}$, it is inevitable that at least part of the original water ice was heated up and vaporized during the impact. For the surviving icy fragments, the lifetime of the exposed water ice depends on the impurity of the ice grains. The semi-major axis of the orbit of (31) Euphrosyne is 3.15 AU. At this heliocentric distance, the lifetime of 10$^{-5}$ sized dirty icy grains is about a day (10$^7$s, Beer et al. 2006). In contrast, 10$^{-5}$-sized pure water ice grains can remain in solid form for over 1 Myr (Beer et al. 2006). Since the excavated water ice is from the interior of the parent body, it is likely to be free of impurities as observed in the ejecta of 9P/Tempel 1 by Deep Impact (Sunshine et al. 2007). If a fraction of the original water ice could survive the impact heating, then it would easily remain solid during the reaccumulation phase.

In this paper, we present the characterization of the physical and water ice contents of (31) Euphrosyne, as well as the dynamical properties of the Euphrosyne family. Our main findings are briefly summarized as follows:

1. The physical properties of (31) Euphrosyne were characterized using SPH simulations with the Meso-Nv$^2$Body code. We added radiative cooling to study if we can retain enough ice to the original water ice through the fragmentation and reaccumulation processes. We also considered alternatives for the low density of (31) Euphrosyne, such as the possibility that the majority of the disrupted fragments eventually reaccumulate into a rubble pile as suggested in Arakawa (1999) or that the parent body of the Euphrosyne family was a rubble pile to begin with Benavidez et al. (2018).

8. Conclusions

In this paper, we present the characterization of the physical as well as the dynamical properties of the Euphrosyne family. Our main findings are briefly summarized as follows:

1. The spectroscopy survey of 16 family members shows that the family has a tight distribution of the spectral slopes, suggesting a homogeneous composition of the parent body; 2. Using a more realistic initial velocity field and the observed distribution of proper elements, our $N$-body simulations find the age of the Euphrosyne family to be $\tau = 280^{+180}_{-80}$ Myr; 3. The SPH simulations show that the family formed via a recent violent impact, in which the parent body was fragmented and subsequently reaccumulated into a spherical body.

This work is closely related to the ESO Large Program that is surveying large asteroids (ID: 199.C-0074, PI: Vernazza). We emphasize the need for a re-interpretation of asteroid-family models in the context of new adaptive-optics observations.
Appendix A: Technical details of the $N$-body simulation

For the sake of completeness, we provide some details regarding our dynamical model which is used in Sect. 6 to derive the family age.

A.1. Computation of proper elements

In order to compute the proper orbital eccentricity $e_p$ and inclination $i_p$, we usually apply the frequency-modified Fourier transform of Šidlichovský & Nesvorný (1996). However, we realized in our preparatory integrations that the method fails for some asteroids in the vicinity of overlapping resonances. These asteroids exhibited a splitting of the maximum of the power spectrum in $q$ and $s$ frequencies and then it became difficult to find a unique and time-stable solution for such cases.

Therefore, we replaced our routines for computation of proper elements with the approach of Knežević & Milani (2000). We proceeded as follows:

(i) we filtered the time series of osculating orbital elements by a sequence of digital low-pass filters (Quinn et al. 1991) to suppress fast oscillations with periods shorter than 1500 kyr;

(ii) we removed secular planetary forced terms from filtered equinoctial elements $k = e \cos \sigma$, $h = e \sin \sigma$ and $q = \sin i/2 \cos \Omega$, $p = \sin i/2 \sin \Omega$;

(iii) we translated the oscillating phase angles $\sigma$ and $\Omega$ into linearized time series by adding multiples of $2\pi$; and

(iv) we resampled the equinoctial elements into unequally spaced datasets $(k(\sigma), h(\sigma))$ and $(q(\Omega), p(\Omega))$ in which we searched for the amplitude of the Fourier mode with period $2\pi$ (see Ferraz-Mello 1981), thus obtaining the proper elements $e_p$ and $\sin i_p/2$, respectively. For the purposes of an off-line analysis, all proper elements (including $a_p$) were further smoothed out by a running average with a window range of 1 Myr.

A.2. Initial conditions and parameters

Initial orbital data of planets were taken from the JPL DE405 ephemeris and the osculating elements of (31) Euphrosyne were adapted from the AstOrb database (version October 2019), choosing JD = 2,458,700.5 as the initial time $t_0$. We applied a barycentric correction and a conversion to the Laplace plane. To generate synthetic family members, we created a colli- sional swarm of $n_p = 5712$ test particles (i.e. twice the number of the observed family members, excluding (31) Euphrosyne). We placed a synthetic parent body on an osculating orbit $a = 3.155$ au, $e = 0.145$, $i = 27.5^\circ$, $\omega + f = 160^\circ$, $f = 30^\circ$ and we assigned ejection velocities $v_{ej}$ to individual test particles. We chose $v_{ej}$ pseudo-randomly from a merged ejection field of one of our SPH simulations (Sect. 5), as shown in Fig. A.1, but we randomly oriented the velocities of velocity vectors, thus obtaining an isotropic collisional cluster.

The diameters of synthetic asteroids were taken from the observed SFD: each $D$ (except for (31) Euphrosyne) was randomly assigned to two test particles. Initial spins were chosen uniformly from the interval of periods $P \in (2; 10)$ h. The thermal parameters were chosen as follows:

(i) the bulk and surface densities were set to the value derived for (31) Euphrosyne $\rho_{\text{bulk}} = \rho_{\text{surf}} = \rho_{\text{31}} = 1665$ kg m$^{-3}$ (Yang et al. 2020);

(ii) the Bond albedo $A = 0.015$ and IR emissivity $\epsilon = 0.9$ were both chosen based on in situ observations of primitive C-type asteroids (101955) Bennu (DellaGiustina et al. 2019) and (162173) Ryugu (Grott et al. 2019);

(iii) the thermal capacity $C = 460$ J kg$^{-1}$ K$^{-1}$ was calculated following Wada et al. (2018) and assuming the approximate sub-solar temperature of (31) Euphrosyne $T_s \approx 160$ K; and

(iv) the conductivity was set to $K = 0.01$ W m$^{-1}$ K$^{-1}$. These parameters lead to the thermal inertia $\Gamma = \sqrt{\rho_{\text{surf}} K C} \approx 88$, which is comparable, for example, to the mean value observed for ~10$^3$ km-sized main-belt asteroids (Hanuš et al. 2018).

Figure A.2 shows the first record of the proper orbital elements which is closest to the initial state of the synthetic family. The early occurrence of the inner/outer asymmetry of the proper eccentricity $e_p$ is simply a result of the chosen impact geometry.