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Brangäne: a new family of Barbarian asteroids

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ABSTRACT

The so-called Barbarian asteroids [from the name of the prototype of this class, asteroid (234) Barbara] are extremely interesting objects because they might be the survivors of a very early generation of planetesimals. We have identified in the past the first case of an asteroid family (the Watsonia family) whose members are Barbarians, all issued from the collisional disruption of a sizeable parent body. Here we report on the identification of another family, called after the name of its biggest member, asteroid (606) Brangäne, consisting of objects displaying the polarimetric properties characterizing the Barbarian behaviour. This is the first recognized case of a swarm of small Barbarians issued from a quite recent cratering event.

Key words: polarization – minor planets, asteroids: general.

1 INTRODUCTION

The discovery of an anomalous polarimetric behaviour of (234) Barbara (Cellino et al. 2006) was the first recognition of the existence of a new class of asteroids (now commonly referred to as the Barbarians) which are very interesting in many respects. Some of these objects are known to exhibit anomalous reflectance spectra, characterized by features that were interpreted by Burbine, Gaffey & Bell (1992) and Sunshine et al. (2008) as diagnostic of a very high content of refractory compounds on their surfaces, including primarily the aluminous spinel mineral (MgAl_2O_4). This is a major component of the so-called Calcium Aluminum-rich Inclusions (CAI) found in some meteorites. With their ages around 4.567 Gyr, derived from isotopic abundances, CAIs are the oldest samples of solid matter found in the Solar system. As pointed out by Sunshine et al. (2008), CAIs are generally classified, on the basis of petrography and geochemistry, into three major groups. Among them, the so-called ‘fluffy type A’ (FTA), characterized by a porous, strongly non-compact structure, is found in all chondritic meteorites, and produces a strong absorption feature in the reflectance spectrum, interpreted as a consequence of a high concentration of FeO-rich spinel. It is also believed that, as opposite to the other types of CAIs, FTAs may never have been totally melted by any transient heating event after their formation.

The most extensive analysis of objects belonging to the Barbarian class, based on both spectroscopic and polarimetric data, has been recently published by Devogèle et al. (2018). These authors found

conclusive evidence that all Barbarians, which had been previously classified as members of different taxonomic classes based on their reflectance spectra at visible wavelengths, once the properties of both the visible and near-IR regions of the reflectance spectrum are taken into account, appear to belong to a unique taxonomic class: the L class defined by DeMeo et al. (2009).

Devogèle et al. (2018) found that the spectra of L-class objects can be successfully modelled using mixtures of the fluffy kind of spinel present in CAIs, MgO-rich olivine, and the mineral compounds found in the matrix of CV3 meteorites. They also found that the presence of CAIs is responsible for the anomalous polarimetric inversion angle characterizing the Barbarians (for an explanation of this and other polarimetric parameters, see, for instance, Cellino, Belskaya & Gil-Hutton 2015). In particular, they pointed out the presence of a variation of the inversion angle of asteroid (234) Barbara as a function of wavelength, and interpreted it as a consequence of the known wavelength-dependent variation of the refractive index of the spinel mineral.

Until a couple of years ago, it was not clear whether the properties of Barbarians were determined by anomalous surface properties, or by structural composition. In this respect, a major step forward has been the discovery by means of polarimetric measurements that the Watsonia asteroid family (Novaković, Cellino & Knežević 2011) consists of Barbarian objects (Cellino et al. 2014).

Asteroid families are groups of objects issued by the collisional disruption of single parent bodies. The fact that the members of the Watsonia family are Barbarians strongly suggests that the Barbarian properties are not purely surface effects, because the members of the same family derive from material located at different depths inside the parent body. This was

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Table 1. Total number of currently recognized members of the Brangäne family, and the lower and upper limits of the intervals covered by its members in the space of the proper orbital elements semimajor axis, eccentricity, and sine of inclination.

N. of members	Proper semimajor axis (au)	Proper eccentricity	Sine of proper inclination
325	2.571–2.597	0.178–0.183	0.165–0.168

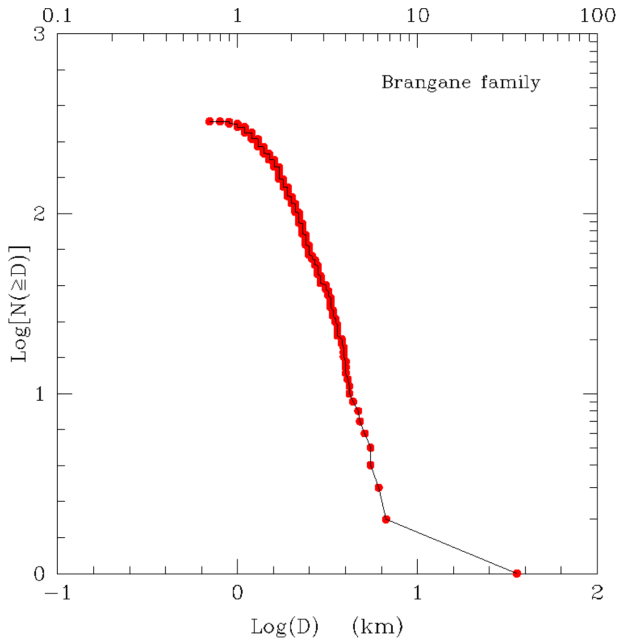


Figure 1. Cumulative size distribution of the Brangäne family. The typical trend characterized by a large difference in size between the largest member and the rest of the family members clearly shows that the family is the outcome of a cratering event. At sizes smaller than about 2 km the size distribution becomes shallower, an indication of incompleteness of the recognized smallest members.

also the first discovery of Barbarian asteroids of relatively small sizes.

The main belt asteroid (606) Brangäne, about 40 km in size (Mainzer et al. 2016), belongs to the L-class (DeMeo et al. 2009). It is the biggest member of another family (Milani et al. 2014). Table 1 summarizes the main parameters of the Brangäne family which, according to Spoto, Milani & Knežević (2015) is the result of a very recent cratering event (the age between 30 and 50 Myr being derived by the analysis of the ‘V-shaped’ diagram, see below) In this table, the data have been taken from the AstDys site,¹ where a regularly updated list of members of asteroid families is publicly available.

The cumulative size distribution of the family is shown in Fig. 1. The sizes of the family members have been taken directly from the NEOWISE catalogue (Mainzer et al. 2016), whenever available. The same albedo data have been also used to derive the average albedo of the family, 0.116 ± 0.005 , very similar to the geometric albedo of Brangäne itself (0.113 ± 0.021). The sizes of family members not

¹<http://hamilton.dm.unipi.it/astdys/index.php?pc=5>. Data base maintained at Pisa University by the colleagues of A. Milani.

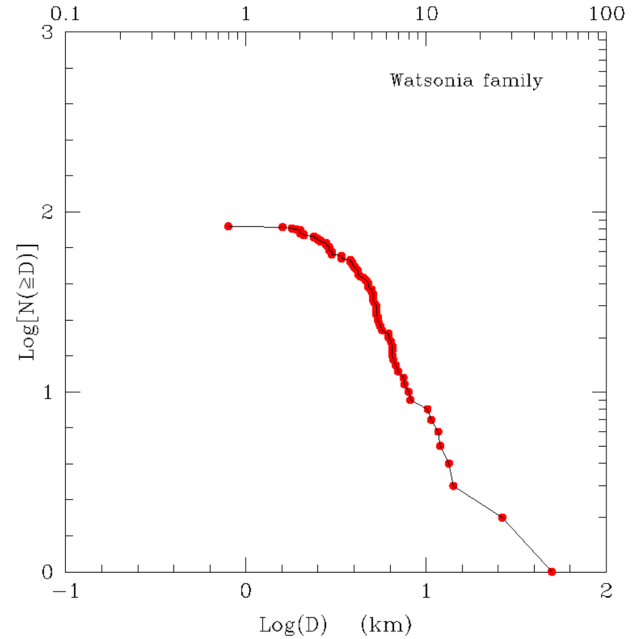


Figure 2. The same as Fig. 1, but for the family of Watsonia, the only one previously identified family of Barbarians (Cellino et al. 2014). As shown by the morphology of its cumulative size distribution, the Watsonia family may suggest a more energetic disruption event, rather than a typical cratering event as in the case of the Brangäne family.

observed by WISE were computed from the known relation linking the size to the absolute magnitude H and the geometric albedo p_V :

$$\log(D) = 3,1236 - 0.2H - 0.5 \log(p_V), \quad (1)$$

where D is the equivalent diameter in km. In the computations, the value of H was taken from the file listing the family members available in the AstDys site. For the value of the geometric albedo p_V we adopted the NEOWISE-based average value of 0.116 mentioned above.

The Brangäne family is the likely outcome of a cratering event. This is suggested by the large difference in size between its largest member, (606) Brangäne, having an absolute magnitude $H = 10.22$ and an estimated size of about 36 km (Mainzer et al. 2016), and the rest of the family members. The latter have absolute magnitudes generally fainter than 14, and sizes mostly below 5 km. In the cases of families issued from cratering events, the overall trend of the cumulative size distribution tends to exhibit at the largest sizes a characteristic concave trend (Tanga et al. 1999; Durda et al. 2007).

For a comparison, Fig. 2 shows the cumulative size distribution of the Watsonia family. The morphology of the size distribution, computed in exactly the same way as in the case of Brangäne, as explained above, is clearly different with respect to the case of Brangäne, as it is not characterized by a big difference between the size of the largest member and those of the other biggest family members. It can also be noted that in the case of Watsonia there is a stronger depletion of objects at the low end of the size distribution. This can be partly due to observational bias, due to the fact that the perihelion distances of the Brangäne family are lower than those of Watsonia members, due to a non-negligible difference in orbital eccentricity. On the other hand, the two families are located at fairly similar heliocentric distances [the orbital semimajor axis of (729) Watsonia is about 2.76 au] and, consisting of objects displaying similar spectroscopic and polarimetric properties, also

Table 2. Polarimetry and photometry of 10 asteroids in the special R filter. P_Q and P_U are the reduced Stokes parameters measured in a reference system such that P_Q is the flux perpendicular to the plane Sun–Object–Earth (the scattering plane) minus the flux parallel to that plane, divided by the sum of the two fluxes. In literature P_Q is usually designated with the symbol P_r . In the last columns, $m_R(\alpha)$ and $m(\alpha)$ are the magnitude reduced to unit distance from the observer and from the Sun, and the apparent magnitude, respectively.

Date (yyyy mm dd)	Time (UT) (hh:mm)	Exp (s)	Object	Phase angle (deg)	P_Q (per cent)	P_U (per cent)	$m_R(\alpha)$	$m(\alpha)$
2017-07-04	09:53	904	36358	30.00	0.82 ± 0.11	0.03 ± 0.11	16.07 ± 0.20	18.88 ± 0.20
2017-08-01	06:16	904		28.66	0.67 ± 0.11	0.06 ± 0.11	16.22 ± 0.21	18.71 ± 0.21
2017-08-17	09:29	496		26.02	0.02 ± 0.11	0.03 ± 0.11	16.24 ± 0.20	18.53 ± 0.20
2017-04-26	09:28	824	51187	22.04	−0.84 ± 0.17	0.13 ± 0.17	20.25 ± 0.13	22.98 ± 0.13
2017-07-28	02:01	860		17.34	−1.56 ± 0.10	0.06 ± 0.10	18.48 ± 0.52	21.31 ± 0.52
2017-06-19	01:14	992	53707	24.33	−0.35 ± 0.12	0.18 ± 0.12	16.08 ± 0.16	19.23 ± 0.16
2017-07-24	23:45	1568		26.29	0.12 ± 0.13	0.02 ± 0.13	16.01 ± 0.19	19.48 ± 0.19
2017-09-20	04:40	1568	56748	17.76	−1.36 ± 0.07	0.17 ± 0.07	16.38 ± 0.28	19.00 ± 0.28
2017-06-25	01:01	1496	75890	17.24	−1.48 ± 0.08	−0.01 ± 0.08	16.40 ± 0.12	19.14 ± 0.12
2017-07-17	02:36	2778		22.25	−0.79 ± 0.14	−0.06 ± 0.14	16.41 ± 0.11	19.49 ± 0.11
2017-06-21	04:34	1368	76378	17.54	−1.60 ± 0.08	−0.08 ± 0.08	16.31 ± 0.11	18.69 ± 0.11
2017-07-17	03:33	2856		24.18	−0.75 ± 0.11	0.20 ± 0.11	16.73 ± 0.28	19.50 ± 0.11
2017-06-23	00:30	1136	82955	24.25	−0.50 ± 0.08	0.05 ± 0.08	16.30 ± 0.11	18.86 ± 0.11
2017-08-16	01:02	2376		27.95	0.48 ± 0.14	0.48 ± 0.14	16.43 ± 0.13	19.62 ± 0.13
2017-08-28	09:26	720	87168	27.26	−0.08 ± 0.12	0.07 ± 0.12	16.78 ± 0.16	18.97 ± 0.16
2017-06-22	23:46	2072	103450	26.26	0.23 ± 0.11	0.13 ± 0.11	16.53 ± 0.19	19.74 ± 0.19
2017-09-12	03:23	2376	116799	20.55	−0.86 ± 0.15	0.06 ± 0.15	16.61 ± 0.06	19.48 ± 0.06

the albedo of the members of the two families should be similar. Our preferred interpretation is that *Watsonia* represents the outcome of a collision producing a more extensive disruption of the parent body, and the relative lack of small family members with respect to the case of the *Brangäne* family could be diagnostic of an older age, because the progressive depletion of the smallest members of a family due to the Yarkovsky effect increases with time (Rubincam 1995; Farinella et al. 1998). This interpretation is also supported by the apparently shallower slope of the cumulative size distribution of the *Watsonia* family if we compare it with that of the *Brangäne* family. A progressive decrease of slope as a function of time is expected to be a typical result of a Yarkovsky-driven erosion.

The reason why the *Brangäne* family is so interesting is that we recently discovered that (606) *Brangäne* itself is a *Barbarian* (Devogèle et al. 2018). It was therefore very tempting to carry out a campaign of polarimetric observations to check whether we could find a new example of a family consisting of *Barbarian* objects. The results of this investigation are presented in this paper.

2 NEW OBSERVATIONS

Our target list included 10 objects that are members of the *Brangäne* family according to the list of family members available at the AstDys web site. These objects are listed in Table 2.

The light that we receive at visible wavelengths from the asteroids is scattered sunlight, in a state of partial linear polarization, either parallel or perpendicular to the Sun–target–observer plane (the scattering plane). Because the direction of the polarization is identified by the view geometry, in the Solar system science literature the state of linear polarization is traditionally described by just one parameter, P_r , defined as the difference between flux perpendicular to the scattering plane and the flux parallel to the scattering plane, divided by their sum. In more general cases, linear polarization is described by the two reduced Stokes parameters $P_Q = Q/I$ and $P_U = U/I$. By adopting the direction perpendicular to the scattering plane as a reference direction for the Stokes parameters Q and U , we have $P_Q = P_r$, and for symmetry reasons we expect

P_U to be consistent with zero. In fact, P_U measurements may be used for quality check. If the light is polarized in the direction perpendicular to the scattering plane, then $P_r = P_Q > 0$, while if the light is polarized in the direction parallel to the scattering plane, then $P_r = P_Q < 0$. The latter situation is generally described with the potentially misleading term of ‘negative polarization’. Practically one finds that at small phase angles ($\ll 20^\circ$) all asteroids exhibit negative polarization, while at phase angles ($\gtrsim 20^\circ$) nearly all asteroids exhibit positive polarization. *Barbarian* asteroids represent an exception because their polarization changes sign around phase angle $\gtrsim 27 \div 30^\circ$. To identify *Barbarians*, we decided to observe our targets at phase angles in the range $17\text{--}30^\circ$, and establish whether the polarization would change sign around $18\text{--}22^\circ$ or around $27\text{--}30^\circ$.

We observed our targets using the VLT FORS2 instrument (Appenzeller et al. 1998) in imaging polarimetric mode, and obtained 15 broad-band linear polarization measurements in the R special filter from 2017 April to 2017 September. Polarimetric measurements were performed with the retarder wave-plate at all positions between 0° and 157.5° , at 22.5° steps. For each observation, the exposure time accumulated over all exposures varied from 720 (for 87168) to 2857 s (for 76378). Polarimetric data were treated as explained in Bagnulo et al. (2016); observing log and results are given in Table 2.

Each polarimetric series was preceded by the acquisition of an image to fine-tune the telescope pointing and ensure target is properly centred and not vignetted by the Wollaston masks. These acquisition images were used for photometric measurements. PSF fitting photometry of all objects in the images was performed using the procedures in the DAOPHOT package of IRAF using the following strategy. Objects where a maximum of 10 iterations were required in order to fit the PSF and no error was recorded for the resulting photometry were kept for the following steps. The objects were matched by sky coordinate to those recorded in the PanSTARRS Mean Object Catalog. For each image, a linear regression model was fit for the measured apparent magnitude m_r , to the Mean PSF magnitude, $m_r(\text{PanSTARRS})$, recorded by PanSTARRS in the r filter. An average of 100 objects per image were used to generate

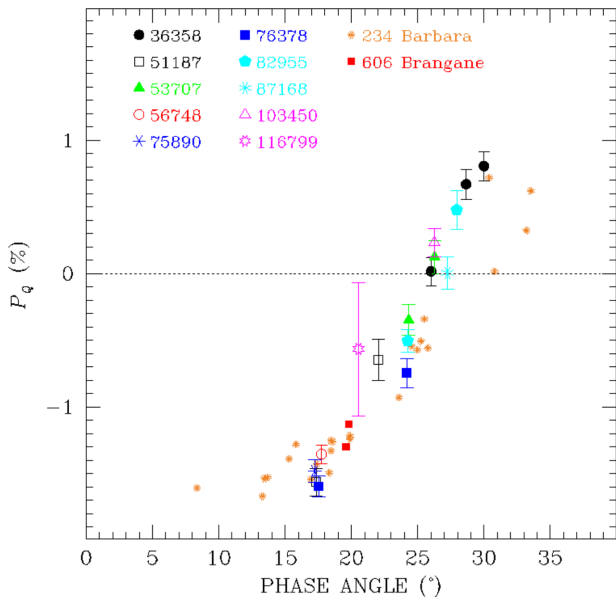


Figure 3. Polarization versus phase angle data for the targets of the present investigations, as well as a couple of measurements of (606) Brangäne, the largest member of the family, previously observed at the Calern observatory. The family data are compared with the polarization curve of the prototype of Barbarians, (234) Barbara, whose available measurements are shown, for sake of clarity, without their associated error bars (orange symbols).

the model. The model was then used to predict the magnitude of the target asteroid. Reduced magnitudes were computed using helio- and geo-centric distances taken from HORIZONS (Giorgini et al. 1996), and are given in Table 2, together with the corresponding apparent magnitudes. It is important to comment that, at least in the present case, we do not expect that individual photometric measurements can provide the same physical insight as polarimetric measurements, as the limited phase angle range covered by our observations does not even allow us to estimate the slope of the magnitude-phase angle curve. However, both photometry and polarimetry data could be useful in a future work for modelling purposes, if more data are collected.

It is important to note also that the errors on the polarimetric measurements were calculated based only on photon noise using normal error propagation of the flux errors (see e.g. Bagnulo et al. 2009). Systematics with FORS2 are of the order of a few units in 10^{-4} (e.g. Bagnulo et al. 2016). It is also useful to point out that FORS acquired polarimetric standard stars within its calibration plan, and the fact that P_U is always consistent with zero, means that the polarimetric optics were consistently well aligned.

Our polarimetric measurements are shown in Fig. 3, in which we show also two measurements of (606) Brangäne obtained in the V filter by Devogèle et al. (2018). A comparison is also made with the phase-polarization curve of (234) Barbara, the prototype of this class of objects using literature data (Cellino et al. 2016; Devogèle et al. 2018), and adding the three new measurements of Table 3 obtained in the framework of a recent spectro-polarimetric survey of asteroids (observations and data reduction were performed in the same way as Bagnulo, Cellino & Sterzik 2015).

3 DISCUSSION AND CONCLUSIONS

All asteroids of our target list exhibit the Barbarian polarimetric behaviour, characterized by a wide negative polarization branch, and

Table 3. New polarimetric measurements of (234) Barbara in the V filter. Uncertainties are somewhat arbitrarily estimated based on our knowledge of the instrument polarization. Contribution from photon-noise is $\lesssim 0.01$ per cent.

Observation date	Phase angle (deg)	P_Q (per cent)
2015-05-09	13.5	-1.54 ± 0.05
2015-05-27	18.5	-1.33 ± 0.05
2016-07-07	33.2	0.32 ± 0.05

an inversion angle which in this case is $\sim 25^\circ$. The two independent CAPS (Calern Asteroid Polarimetric Survey) measurements of (606) Brangäne perfectly fit the trend exhibited by the other family members.

A more detailed analysis of Fig. 3 shows that the Brangäne family members very closely mimic the behaviour of (234) Barbara in an interval of phase angles $\sim 17^\circ \div \sim 25^\circ$. At the highest values of phase angle, however, we note that the behaviour of (234) Barbara is not clearly defined because the four measurements at phase angle $\gtrsim 30^\circ$ are not in a good agreement among each other. In particular, the measurement obtained at a phase of 30.4° obtained by Cellino et al. (2016) fits very well the data obtained for the members of the Brangäne family, but is high when compared with the other measurements obtained at similar or near phase angles, which suggest a much gentler increase of polarization in the positive branch. More observations are needed to better characterize the behaviour of (234) Barbara around phase angle 30° . Based on the observations presently available, the inversion angle could be from 25° (very similar to the inversion angle for the Brangäne family) to about 30° .

In any case it is evident that our measurements of a sample of members of the Brangäne family definitively show that this is a family of Barbarians, and the observed behaviour of its members suggest an inversion angle of polarization between 25° and 27° . Interestingly enough, according to Devogèle et al. (2018), such a value would suggest a relatively low abundance of CAI abundances, possibly smaller than 5 per cent. Moreover, although our data do not allow us to derive a robust estimate of the extreme value of negative polarization P_{\min} , the visible trend seems to suggest a fairly deep value for this parameter. According to Devogèle et al. (2018) this would also correspond to small abundances of nano-phase iron particles on the surface (see fig. 13 of Devogèle et al. 2018). Further spectroscopic data in the visible and near-IR spectral regions will help to confirm or rule out these tentative inferences.

The existence of a variety of values for the inversion angle of polarization of different Barbarians can be important, and may correspond to significant differences in terms of surface properties and composition, according to preliminary inferences by Devogèle et al. (2018). This means that a possible difference of about five degrees between the inversion angle of the Brangäne family and (234) Barbara suggests that the small population of objects that we call Barbarians might be more heterogeneous than currently believed. As shown by Devogèle et al. (2018), the reflectance spectra of different Barbarians may also exhibit differences that in some cases might represent more than subtle nuances among objects sharing a given set of properties. In other words, the data currently available suggest that the Barbarians might include objects having non-negligible differences in terms of surface properties and

composition. Only by obtaining new data we can confirm or rule out this possibility.

Devogèle et al. (2018) claimed that the polarimetric properties of Barbarians are a consequence of the high content of spinel-bearing minerals in their surfaces, confirming previous results by Sunshine et al. (2008). This may suggest a formation dating back to epochs when the solid matter accreted into growing planetesimals was characterized by a much higher abundance of refractory components, the first compounds to solidify during the very early cooling of a hot proto-planetary disc. Barbarians could therefore be very old, having possibly survived the very chaotic early phases of evolution of our planetary system.

According to the so-called ‘Grand Tack’ model (Walsh et al. 2011, 2012), the very early history of the Solar system was characterized by episodes of back and forth migration of the giant planets, producing a huge depletion (by more than 99 per cent) of the planetesimals originally accreted in the region of the current main asteroid belt. The subsequent evolution, up to the end of the so-called Late Heavy Bombardment phase, about 3.9 Gyr ago, is described by the so-called ‘Nice’ Model (Gomes et al. 2005; Morbidelli et al. 2005). It is believed that this was also an era of instability for the small bodies, subject to perturbations that led many objects to move from the outer regions to smaller heliocentric distances. At the end of this era, the major planets achieved their current configuration, and the populations of small bodies orbiting at different heliocentric distances started to be more stable, their further evolution being mainly determined by mutual collisions and, in the current asteroid belt, by a steady removal of the smallest objects due to a progressive drift of their orbital semimajor axes determined by thermal emission mechanisms [Yarkovsky effect, see, for instance, Rubincam (1995) and Farinella et al. (1998)]. So, the lucky survivors of an earlier age are expected to be rare, and larger than a few tens of km.

This could explain why Barbarians are so rare and relatively big: apart from the members of the *Watsonia* and *Brangäne* families, there are currently only 17 identified Barbarians in the whole main belt, and all of them are above 40–50 km in size. Smaller objects could have avoided detection so far simply because they are fainter, but if they were common it is unlikely that a large number of them would not have been identified in spectroscopic surveys like the one carried out by DeMeo et al. (2009), taking into account that the L taxonomic class is characterized by some evident features in the near-IR region of the reflectance spectrum.

Among the few known Barbarians, moreover, there are reasons to believe that four objects, namely (387) *Aquitania*, (729) *Watsonia* and (980) *Anacostia*, as suggested by Cellino et al. (2014), and also (599) *Luisa*, found more recently to be another nearby Barbarian, could be the surviving members of a previous, first-generation family produced by the collisional disruption of a much bigger Barbarian parent body, occurred presumably in very ancient times. The idea is that the parent body of the *Watsonia* family was likely a fragment from an earlier, first-generation collision involving a much bigger parent body. According to Cellino et al. (2014), this event produced, in addition to the parent body of the *Watsonia* family, also a few other big Barbarian asteroids [including (387) *Aquitania* and (980) *Anacostia*, see also Masiero & Cellino (2009)]. After a very long time since their origin, these objects have orbits still similar to each other and to those of the *Watsonia* family, but not sufficiently close to each other and to *Watsonia* to form an identifiable, unique family. In other words, according to Cellino et al. (2014) we would have here the first recognized example of an eroded and dispersed family that was formed during or just

later than the early, chaotic phases of the Solar system history, characterized by strong perturbations due to processes of migration of the giant planets. The few survivors of this very old family are still recognizable today as siblings sharing the same origin, only as a consequence of their peculiar physical properties.

The age of this first-generation family that supposedly produced (729) *Watsonia* and the big Barbarian asteroids nearby, must be older than the upper limit found by Spoto et al. (2015) for the ages of families still recognizable today using current techniques of family identification and dating. The techniques of family identification are purely based on the vicinity in the proper elements space, while the ages are derived from the measurement of a size-dependent spreading in proper semimajor axis of family members due to the Yarkovsky effect, derived from analysis of the so-called ‘V-shaped’ diagrams of families.² In other words, the ages are estimated by means of an analysis of the time needed to produce the observed, size-dependent spreading in orbital semimajor axis of the family members, as a consequence of the Yarkovsky effect (Spoto et al. 2015; Milani et al. 2017). In the case of the *Watsonia* family, an estimate of the age is uncertain, due to the asymmetric structure of the family. The age turns out to range between about 0.8 and 1.2 Gyr, depending on the unknown density of its members. Such an age, in spite of the large uncertainty, supports the assumption that the supposedly big primordial family that produced the *Watsonia* parent body could have an age of the order of, if not larger than, 2×10^9 yr, older than any other known family.

If the few existing Barbarians (apart from the small members of more recent families) are long-sought survivors from a very early epoch, we might be close to have found some pieces of the Holy Grail in asteroid science. In this respect, many primitive, low-albedo asteroids that are abundant in the current asteroid main belt are thought to have been originally accreted at much higher heliocentric distances (Gomes et al. 2005; Morbidelli et al. 2005). Recently, Delbò et al. (2017) found indications of the existence in the inner asteroid belt of low-albedo objects that might be the survivors of at least one asteroid family possibly originated as early as 4 billion yr ago. It is not clear whether the supposed parent body of this family can be representative of a population of dark planetesimals accreted at relatively small heliocentric distances, or might have been a member of a migrating population of planetesimals originally accreted at larger heliocentric distances.

However, the Barbarians look different with respect to low-albedo objects, whatever their origin might be. In particular, Barbarians seem to have significantly higher albedos (mostly between about 0.15 and 0.20, according to Cellino et al. 2016), and are found in the current asteroid main belt in a wide interval of heliocentric distances.

Devogèle et al. (2018) found that the 2.5 μm absorption band which characterizes the reflectance spectra of Barbarians seems to be diagnostic of the presence of iron-enriched spinel mineral present in CAIs. In particular, they proposed that Barbarians are characterized by a composition rich in fluffy-type CAIs. The production of this mineral assemblage seems to require a mild, but not negligible degree of thermal alteration, whereas a strong thermal alteration would be expected to destroy the fluffy-type, iron-enriched variety of spinel. The interior of planetesimals big enough to include a significantly large amount of Al_{26} seems not to be a favourable

²Plots of the V-shaped diagrams of asteroid families can be displayed using the *Plotting the asteroids* facility available at <http://hamilton.dm.unipi.it/astdys2/Plot/>

environment. In this respect, the existence of a big Barbarian parent body from which a first generation of fragments including (729) *Watsonia* and its nearby Barbarian siblings (*Aquitania*, *Anacostia*, etc.) originated can be a problem, since the required size of such parent body cannot be less than 200 km. Of course, more detailed models of the internal structure and evolution of such a body is needed to confirm or rule out the compatibility with the presence and survival up to our days of large amounts of fluffy-type, spinel rich CAI materials.

In general terms, a composition enriched in refractory minerals can be more compatible with an origin in a hot environment at moderate heliocentric distances, because in a colder environment a larger variety of minerals can exist in the solid state, making it more difficult to explain a strong enrichment in refractory compounds.

The determination of the most likely astrophysical environment to explain the origin of Barbarians is an open question, due to our insufficient understanding of the composition of these objects. Devogèle et al. (2018) obtained reasonable fits of the observed spectroscopic properties of Barbarians by considering a mineral assemblage composed by a mixture of fluffy CAI, MgO-rich olivine and minerals present in the matrix of a couple of CV3 meteorites. The CV3 are low-albedo, primitive meteorites, and for some of them the presence of aqueous alteration cannot be ruled out, something that is in tension with an origin in a hot environment. Mg-rich silicates, however, are predicted by thermodynamical models to condense in a hot gas at temperature above 1200 K, whereas the reaction with Fe occurs at lower temperatures. According to Hanner and Bradley (2004), Mg-rich olivine (forsterite) and pyroxene (enstatite) may have formed by direct condensation in the inner primordial nebula, although both forsterite and enstatite have been found by the Giotto and Vega missions to be present in comet 1P/Halley (Schultze, Kissel & Jessberger 1997), and, more recently, in comets Hale-Bopp (Crovisier et al. 1997) and 9P/Tempel (Lisse et al. 2007), based on thermal IR spectra. They have been also directly found in samples of comet 81P/Wild2 collected by the Stardust mission (Clemett et al. 2007).

All this suggests that we cannot rule out the possibility that Barbarians may be the few survivors of a pristine population of moderate-sized, early planetesimals accreted at the beginning of planetary formation at moderate heliocentric distances. The situation, however, is still strongly ambiguous and we have not yet a sufficient body of evidence to allow us to draw firm conclusions about the origin of these bodies, and we cannot yet discriminate among very different, possible scenarios.

The identification of a new family of Barbarians is in any case an important result. The total number of identified Barbarians increases by many tens of objects, if we assume that, apart from some fraction of random interlopers (Migliorini et al. 1995), most members of the Brangäne family, including those that have not yet been observed, are Barbarians. On the other hand, all the members of any given family (apart from possible special cases of mutually-overlapping multigeneration events) are fragments produced by the disruption of one single parent body. This means that all the members of a given family normally correspond to one single asteroid of a previous generation. The *Watsonia* and Brangäne family members are fragments of two, larger Barbarians that were disrupted in relatively recent times. In particular, there is evidence that the Brangäne family is very young (Spoto et al. 2015).

It is worth noting that the two impacts that produced the Brangäne and *Watsonia* families did not cause a widespread alteration of the polarimetric properties of their members, despite the fact that one was a catastrophic event and the other a cratering (which would

create fresh-looking ejecta but leave the largest remnant having on the average a much older surface). This may imply that the long inversion angle property that characterizes Barbarians is not affected by compaction, weathering, regolith size, or other time-dependent effects, in agreement with results of other studies.

The recent production of small Barbarian fragments in the asteroid main belt is interesting, because it means that at least some of these objects can have chaotically evolved, being subject to the Yarkovsky effect, up to possibly achieving near-Earth asteroid-like orbits. As a consequence, it is possible that at least a few Barbarians might exist today among the near-Earth asteroid (NEA) population. This is exciting, because the identification of some Barbarian NEAs would possibly permit to conceive space missions of exploration and sample-return, making it possible to retrieve to the Earth some materials which might date back to the very early epochs of planetary growth.

In most general terms, the number of existing families of Barbarians and the sizes of their parent bodies put critical constraints on the interpretation of the physical properties and the possible origin of these objects (Devogèle et al. 2018). In particular, the number of Barbarian families may put some constraints on the initial inventory of these bodies, having been subject, since the end of the era of Late Heavy Bombardment, to the general process of collisional evolution of the asteroid population that can be investigated by means of numerical models (Bottke et al. 2015).

There are many reasons to conclude that the study of the Barbarian asteroids is an important topic in modern planetary science, and can shed some light on the processes of early formation and subsequent evolution of planetesimals in our Solar system. Further investigations are needed to solve some of the open questions concerning these interesting objects. This is also another example of the importance of polarimetric studies of asteroids. This discipline has been somehow underexploited for a long time, until recent years that have seen not only the discovery of Barbarians, but also the possibility to use polarimetric properties to infer information about possible links between asteroids and comets, as recently demonstrated in the case of polarimetric observations of (101955) *Bennu* (Cellino et al. 2018).

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