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A successful search for hidden Barbarians in the Watsonia asteroid family★

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ABSTRACT

Barbarians, so named after the prototype of this class (234) Barbara, are a rare class of asteroids exhibiting anomalous polarimetric properties. Their very distinctive feature is that they show negative polarization at relatively large phase angles, where all 'normal' asteroids show positive polarization. The origin of the Barbarian phenomenon is unclear, but it seems to be correlated with the presence of anomalous abundances of spinel, a mineral usually associated with the so-called calcium–aluminium-rich inclusions (CAIs) on meteorites. Since CAIs are samples of the oldest solid matter identified in our Solar system, Barbarians are very interesting targets for investigations. Inspired by the fact that some of the few known Barbarians are members of, or very close to, the dynamical family of Watsonia, we have checked whether this family is a major repository of Barbarians, in order to obtain some hints about their possible collisional origin. We have measured the linear polarization of a sample of nine asteroids which are members of the Watsonia family within the phase-angle range 17°–21°. We found that seven of them exhibit the peculiar Barbarian polarization signature, and we conclude that the Watsonia family is a repository of Barbarian asteroids. The new Barbarians identified in our analysis will be important to confirm the possible link between the Barbarian phenomenon and the presence of spinel on the surface.

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

1 INTRODUCTION

The degree of linear polarization of sunlight scattered by an asteroid towards an observer depends on the phase angle, namely the angle between the asteroid–Sun and the asteroid–observer directions. The phase-polarization curves of all atmosphereless bodies of the Solar system exhibit qualitatively similar trends, but their detailed features vary according to the specific properties (including primarily the geometric albedo) of individual surfaces. In the phase-angle range ∼0°–20°, asteroids exhibit the so-called branch of *negative polarization*, in which, in contrast to what is expected from simple single Rayleigh scattering or Fresnel-reflection mechanisms, the plane of linear polarization turns out to be parallel to the plane of scattering (the plane including the Sun, the target and the observer). The plane of linear polarization becomes perpendicular to the scattering plane, a situation commonly described as *positive polarization*, at phase angle values larger than the so-called *inversion angle*, which is generally around 20°.

A few years ago, Cellino et al. (2006) discovered a class of asteroids exhibiting peculiar phase-polarization curves, characterized by a very unusual extent of the negative polarization branch, with an inversion angle around 30°, much larger than the values commonly displayed by most objects. Since the prototype of this class is the asteroid (234) Barbara, these objects have been since then commonly known as *Barbarians*. Only half a dozen Barbarians are known today: (234) Barbara, (172) Baucis, (236) Honoria, (387) Aquitania, (679) Pax and (980) Anacostia (Cellino et al. 2006; Gil-Hutton et al. 2008; Masiero & Cellino 2009).

The polarimetric properties of the Barbarians are fairly unexpected. The observed large negative polarization branch is not predicted by theoretical models of light scattering, but in fairly special situations, including surfaces composed of very regularly shaped particles (spheres, crystals) or surfaces having considerable microscopic optical inhomogeneity (Shkuratov et al. 1994). Although Barbarians are certainly uncommon, they do exist, and the interpretation of their polarization features may lead to important advances in our understanding of both light-scattering phenomena, and of the origin and evolution of these objects. Potential explanations range

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from peculiar surface composition and/or texture to the possible presence of anomalous properties at macroscopic scales due to the presence of large concavities associated with big impact craters (Cellino et al. 2006). For instance, (234) Barbara has a very long rotation period, which might be the effect of a big collision. Delbò et al. (2009) suggested that (234) Barbara could have a surface characterized by large-scale craters. This is confirmed by an analysis of still unpublished occultation data by one of us (PT).

In terms of taxonomy based on spectrophotometric data, all known Barbarians are classified as members of a few unusual classes, including *L*, *Ld* and (in only one case) *K*. (234) Barbara itself is an *Ld* asteroid (here we use the taxonomic classification of Bus & Binzel 2002). However, there are *L*-class asteroids which are 'normal' objects not exhibiting the Barbarian properties. This fact seems to rule out a direct relationship between taxonomic class (based on the reflectance spectrum) and polarimetric properties. On the other hand, *L*, *Ld* and *K* classes are located, in a principal component analysis plane, along adjacent locations, which although non-overlapping seem to represent some kind of continuous spectral alteration surrounding the most common *S*-class complex. The fact that the six known Barbarians identified so far all belong to one of these three classes suggests that surface composition could be responsible for their polarimetric properties. Even more important, two *L*-class Barbarians, (387) Aquitania and (980) Anacostia, exhibit very similar reflectance spectra, both sharing the rare property of displaying the spectral signature of the spinel mineral (Burbine, Gaffey & Bell 1992). Actually, it was exactly the fact that (980) Anacostia was found to be a Barbarian that led Masiero & Cellino (2009) to observe polarimetrically (387) Aquitania, and to discover that also this object shares the same polarimetric behaviour.

Spinel ([Fe,Mg]Al_2O_4) is a mineral characterized by indistinct cleavage and conchoidal, or uneven fracture properties. In terms of optical properties, the $MgAl_2O_4$ form of spinel has a fairly high refractive index ($n = 1.72$), which becomes even higher in the spinel variety having a high iron content (hercynite) ($\sim$1.8, i.e. much above the values characterizing the most common silicates present on asteroid surfaces; Sunshine et al. 2008). Spinel is an important component of calcium–aluminium-rich inclusions (CAIs) found in all kinds of chondritic meteorites. CAIs are refractory compounds which are thought to be among the first minerals to have condensed in the proto-solar nebula. They are the oldest samples of solid matter known in our Solar system, and they are used to establish the epoch of its formation (Sunshine et al. 2008). In terms of spectroscopic properties, spinel is characterized by the absence (or extreme weakness) of absorption bands around 1 μm, and by the presence of a strong absorption band at 2 μm. Sunshine et al. (2008) concluded that, to model the available near-IR spectra of spinel-rich asteroids, it is necessary to assume abundances of the order of up to 30 per cent of CAI material on the surface. This extreme abundance, which causes a high refractive index, might also be responsible for the anomalous polarization properties. Such high CAI abundances have never been found in meteorite on Earth (so far, the richest CAI abundance, found on CV3 meteorites, is about 10 per cent). Therefore, Sunshine et al. (2008) conclude that spinel-rich asteroids 'might be more ancient than any known sample in our meteorite collection, making them prime candidates for sample return' missions.

Many interesting questions are certainly open. Which processes are involved in the onset of physical mechanisms which produce the Barbarian polarimetric behaviour? Are Barbarians really among the oldest objects accreted in our Solar system? If so, why are they the only one class of primitive objects being characterized by an anomalous polarimetric behaviour? Why are they so rare? Are they unusually weak against collisions and fragmentation? Do space-weathering phenomena affect their polarimetric properties? Are the taxonomic classifications of some *L*, *Ld*, *K* objects possibly wrong (in such a way that all Barbarians might be member of a unique class and not spread among three of them)? It is clear that an important pre-requisite to improve our understanding of these objects, and to draw from them some possible inferences about the origin, composition and subsequent evolution of the planetesimals orbiting the Sun at the epoch of planetary formation, is to find new members of the Barbarian class, but where to look for them?

An aid to a Barbarian search comes from the fact, recently confirmed by Novaković, Cellino & Knežević (2011), that the spinel-bearing Barbarian (980) Anacostia belongs to a family of high-inclination asteroids. This family is named Watsonia from its lowest numbered member (729) Watsonia. (980) Anacostia belongs to a small grouping which is included in the Watsonia family and merges with it at larger values of mutual distances between the members. In other words, (980) Anacostia belongs to a distinct sub-group of the Watsonia family, but the possible independence of this sub-group from the rest of the family is highly uncertain and questionable (Novaković et al. 2011). Another known Barbarian, (387) Aquitania, though not being a member of the Watsonia family, is also located in close vicinity in the space of proper orbital elements (see Section 3). Finally, a member of the Watsonia family, asteroid (599) Luisa, is not a known Barbarian (no published polarimetric measurements are available for it), but it is known to be one of the few spinel-rich asteroids identified so far (thus sharing some common properties with both Anacostia and Aquitania).

One should also note that the distribution of albedos of the members of the Watsonia family observed at thermal IR wavelengths by the *WISE* satellite (Masiero et al. 2011) is strongly peaked around values between 0.10 and 0.15 with only a few likely interlopers, suggesting that the family is not a statistical fluke.[1] A possible common collisional origin of these asteroids opens new perspectives for the search of new Barbarians and for the interpretation of their properties. Asteroid families are the outcomes of fragmentation of single parent bodies disrupted by catastrophic collisions. Therefore, if (980) Anacostia, and possibly also (387) Aquitania, were issued from the disruption of a common parent body exhibiting the rare properties which produce the Barbarian polarization phenomenon, it would be natural to expect that also the other, still not observed members of the Watsonia family should be found to be Barbarians. Moreover, among the Watsonia family members at least one, (599) Luisa, is a known spinel-rich asteroid, like Anacostia and Aquitania. Finally, *WISE* albedo values in the same range of those of Watsonia family members have also been derived for most Barbarian asteroids known so far, namely 234, 172, 236, 679 and 980.

2 NEW OBSERVATIONS

Our target list includes nine objects that are members of the Watsonia family (not limited to the Anacostia sub-group) according to Novaković et al. (2011). These objects are listed in Table 1. We note that a more recent family search whose results are publicly available at the AstDys web site[2] also identified a Watsonia family, but using a more conservative value of the critical level of mutual distances

[1] We examined the *WISE* albedo distribution of the Watsonia family by using the MP^3C web facility available at URL http://mp3c.oca.eu/

[2] http://hamilton.dm.unipi.it/astdys/index.php?pc=5

Table 1. Polarimetry of nine asteroids of the Watsonia family in the special Bessell *R* band. 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. It is therefore identical to the parameter often indicated as P_r in asteroid polarimetry studies. The last column lists, when available, the albedo value according to *WISE* thermal IR measurements

Date (yyyy mm dd)	Time (UT) (hh:mm)	Exp (s)	Object	Phase angle (°)	P_Q (per cent)	P_U (per cent)	*WISE* albedo
2013 07 05	23:41	480	5492	18.79	-1.14 ± 0.10	0.05 ± 0.10	0.14 ± 0.02
2013 07 29	01:44	960		18.31	-1.01 ± 0.09	0.00 ± 0.09	
2013 06 03	09:40	2000	42365	23.30	-0.83 ± 0.15	-0.06 ± 0.15	0.17 ± 0.02
2013 08 03	09:08	960		18.55	-1.73 ± 0.12	-0.06 ± 0.12	
2013 07 12	23:50	960	56233	17.83	-1.07 ± 0.16	-0.09 ± 0.16	0.19 ± 0.03
2013 08 05	01:03	2200		19.31	-1.09 ± 0.12	-0.07 ± 0.12	
2013 07 30	00:38	2000	106059	18.30	-1.06 ± 0.30	-0.15 ± 0.31	
2013 08 04	01:09	4000		18.82	-0.94 ± 0.14	0.00 ± 0.14	
2013 08 28	01:24	4800		19.64	-0.84 ± 0.20	-0.09 ± 0.20	
2013 07 06	01:33	1400	106061	20.21	-0.94 ± 0.11	0.06 ± 0.11	
2013 08 09	02:46	4000		23.97	-0.57 ± 0.12	-0.05 ± 0.12	
2013 07 06	02:05	960	144854	21.30	-0.81 ± 0.12	0.13 ± 0.12	
2013 08 05	02:06	4000		24.19	-0.15 ± 0.12	-0.13 ± 0.13	
2013 08 13	06:28	4000	236408	18.31	-0.97 ± 0.15	0.22 ± 0.15	0.14 ± 0.04
2013 07 07	02:40	3440	247356	19.97	0.10 ± 0.15	-0.33 ± 0.15	
2013 04 17	08:58	4800	320971	23.78	0.11 ± 0.31	-0.06 ± 0.31	
2013 06 03	07:08	3440		20.53	-0.03 ± 0.22	-0.06 ± 0.21	

between family members to be adopted to define the family. As a consequence, the AstDys version of the Watsonia family has a smaller membership list, and does not include our target objects 42365, 144854, 247356 and 320971.

We observed our targets using the VLT FORS2 instrument (Appenzeller et al. 1998) in imaging polarimetric mode, and obtained 17 broad-band linear polarization measurements in the *R* special filter from 2013 April to September. The choice of an *R* filter (instead of the standard *V* filter traditionally used in many asteroid polarimetric observations) was dictated by the need of improving the S/N ratio. 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 cumulated over all exposures varied from 8 min (for 5492) to 1 h and 20 min (for 320971). Data were then treated as explained in Bagnulo et al. (2011), and our measurements are reported adopting as a reference direction the perpendicular to the great circle passing through the object and the Sun. In this way, P_Q represents the flux perpendicular to the plane Sun–object–Earth (the scattering plane) minus the flux parallel to that plane, divided by the sum of these fluxes. It is therefore identical to the parameter indicated as P_r in many asteroid polarimetric studies. In these conditions, for symmetry reasons, P_U values are expected to be zero, and inspection of their values confirms that this is the case for our observations.

At small phase angles ($\ll 20°$), all asteroids exhibit negative polarization, whereas at phase angles $\gtrsim 20°$, nearly all asteroids exhibit positive polarization. By contrast, at phase angle $\simeq 20°$, Barbarians still exhibit a relatively strong negative polarization (~ -1 per cent). Therefore, to identify Barbarians, we decided to measure the polarization at phase angles $\geq 17°$, and establish whether the measured polarization plane is found to be parallel or perpendicular to the scattering plane.

3 RESULTS

The results of our polarimetric measurements are given in Table 1 and shown in Fig. 1, in which a comparison is also made with the phase-polarization curve of (234) Barbara and (12) Victoria, a big, non-Barbarian *L*-class asteroid. In the figure, each target is represented by a different symbol, and some targets have more than one measurement. In the observed phase-angle range, seven of our targets show a polarization value ~ -1 per cent, consistent with the value exhibited by (234) Barbara. In fact, (234) Barbara exhibits marginally higher polarization values (in absolute value) than our targets, possibly due to the different filter in which the observations were performed.

The striking result of our observing campaign is that seven out of nine asteroids of our target list are Barbarians. The two exceptions are 247356 and 320971. However, we know a priori that all family member lists are expected to include some fraction of random interlopers (Migliorini et al. 1995), and then we conclude that both non-Barbarian objects in our target list may be family interlopers. For instance, asteroid 320971 is listed as a Watsonian member by Novaković et al. (2011), but it is not included among the Watsonia members identified in the new AstDys list of asteroid families. On the other hand, three other targets not included in the AstDys member list, but present in the Novaković et al. (2011) member list, are found to be Barbarians. We conclude therefore that, apart from some details concerning family membership, the Watsonia family is an important repository of Barbarian asteroids. This is the immediate and most important result of our investigation. We also note that the number of Watsonia Barbarians identified in our observing campaign is larger than the whole sample of Barbarians previously known. We also note that, except in the case of 236408 and 247356 (only a single

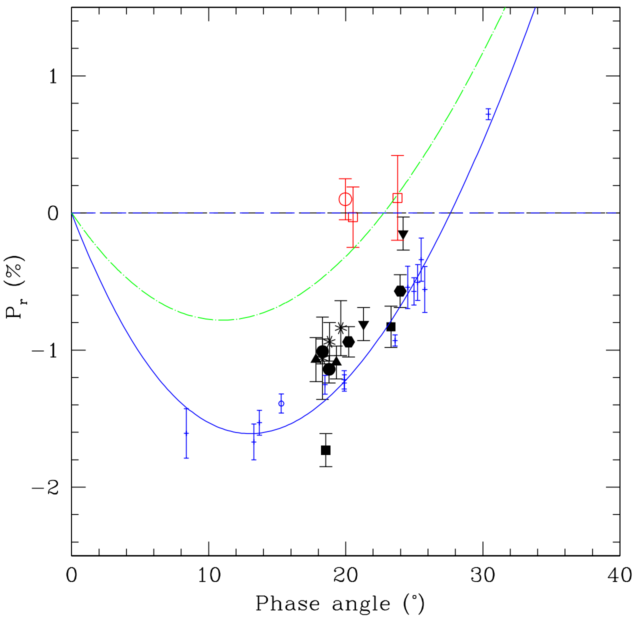

Figure 1. Phase-polarization data (in *R* light) for the targets of the present investigation, compared with the polarization curves (in *V* light) of the (234) Barbara, and of (12) Victoria, a large *L*-class asteroid which does not exhibit the Barbarian behaviour. Black symbols: the seven targets exhibiting the Barbarian polarimetric behaviour; red symbols: our two targets that display a 'normal' polarimetric behaviour; small blue symbols and blue curve: available data for (234) Barbara (Masiero & Cellino 2009), and the corresponding best-fitting curve using the linear exponential relation $P_r = A[e^{\alpha/B} - 1] + C \cdot \alpha$, where α is the phase angle in degrees; dashed green curve: the best-fitting curve for the *L*-class asteroid (12) Victoria (for the sake of clearness, individual observations of this asteroid are not shown).

measurement each), the resulting P_U values are always well consistent with zero.

4 DISCUSSION AND FUTURE WORK

Our results confirm once again that asteroid polarimetry can provide an important contribution to asteroid taxonomy, as noted in the past by several authors (see, for instance, Penttilä et al. 2005).

Several problems, however, are now open, and deserve further theoretical and observational efforts.

The first issue to be addressed is the relationship between the Barbarian polarimetric features and the unusual amount of spinel measured via spectroscopy in some of the known Barbarians. In other words, the new Barbarians that we have found in our investigation must be spectroscopically observed in the visible and near-IR wavelengths in order to check whether they exhibit the spinel features. We do believe that this will be the case, since we already know three objects that are both spinel rich and Barbarians (234 Barbara, 387 Aquitania and 980 Anacostia), and we also know that the Watsonia family includes at least one other spinel-rich asteroid (599 Luisa) (Sunshine et al. 2008), but we clearly need confirmation from new observations.

Similarly, we need to search for the Barbarian polarimetric feature in other spinel-rich asteroids. In particular, we are interested not only in 599 Luisa, but also in the Henan family, which is known to include at least three spinel-rich asteroids (Sunshine et al. 2008).

Next, we need to understand why the Barbarian and the anomalous spinel abundance phenomena are so rare. Apparently, only a handful of Barbarian parent bodies existed, and only their disruption into many fragments made it possible to identify today larger numbers of these objects. In principle, one might wonder whether the unusual properties displayed by these objects might also be in some (still obscure) way a consequence of the collisional events themselves.

Another open problem is the origin of (387) Aquitania. This asteroid is not included in any family list, including both the most recent classification available at the AstDys site and the Novaković et al. (2011) classification of high-*I* families. Yet, this object is quite close, in terms of orbital elements, to (980) Anacostia and the rest of the Watsonia family. The values of proper elements for (387) Aquitania and (980) Anacostia (available in the AstDys data base) are $a = 2.739\,16$, $e = 0.230\,25$, $\sin I = 0.282\,45$ for (387) Aquitania, and $a = 2.741\,02$, $e = 0.139\,72$, $\sin I = 0.298\,05$ for (980) Anacostia, where a is the proper semimajor axis, e is the proper eccentricity and I is the proper inclination. The only one relevant difference, which prevents any family search to include them in an acceptable group, is the proper eccentricity. One should conclude that there is no relation between (387) Aquitania and (980) Anacostia, and that the similarity of their orbital semimajor axes and inclinations is just a coincidence. Moreover, both asteroids display stable orbits in terms of characteristic Lyapunov exponents, and any possible evolution due to non-gravitational forces (e.g. the Yarkovsky effect) seems also very unlikely, because both asteroids are fairly large, with sizes of the order of 80–100 km according to thermal radiometry data. Finally, the collision which could have produced a family including two fragments of this size had to be extremely energetic, and should have produced a huge family, of which there is no evidence today.

On the other hand, Aquitania and Anacostia exhibit too many relevant similarities in their physical properties, which suggests that they may come from a unique parent body fragmented by a collision. A very tentative scenario is that, in a very early epoch, a violent collision destroyed a big parent body which was the progenitor of the Barbarians we see today in this zone. Most of the first-generation fragments produced by the event are now gone due to gravitational perturbations and Yarkovsky-driven drift in semimajor axis. The current Watsonia family could be the product of a more recent disruption of one of the original fragments of the first event. This region could still include several first-generation fragments, preferentially the biggest ones which, due to their size, experienced no or extremely weak Yarkovsky evolution, like (387) Aquitania and (980) Anacostia. Some gravitational perturbations could have also played some role. If one looks at the a–e or a–$\sin I$ plots making use of the facility available at the AstDys site,[3] it is easy to see that the Watsonia family is crossed, in semimajor axis, by a couple of thin resonances, one of which is located close to the value of a of both (387) Aquitania and (980) Anacostia. So, we cannot rule out entirely the idea that some limited evolution in eccentricity of these objects could be due to these perturbation effects and the two objects might have been originally closer in the proper element space. We stress again that this kind of scenario is only eminently speculative and deserves further analysis before it can be accepted as a plausible one.

We point out that a so large relative fraction of observed members of the Watsonia family turning out to be Barbarians has a further implication to be taken into account. If the parent body was differentiated, or had some gradient of composition as a function of depth, with the presence of CAI material limited to some thin shell, then the spinel signature would be present only in a minority of

[3] http://hamilton.dm.unipi.it/astdys2/Plot/

the family members. This is in disagreement with what we observe, indicating that the anomalous composition of the parent body was not limited to some thin region. In conclusion, we are not looking simply at some kind of surface process (like alteration by space weathering or impacts), but at the properties displayed by asteroids originated from different depths inside a single parent body which was anomalously spinel rich in most of its volume (this can be even more true if the Watsonia family is a secondary event derived by a first-generation destruction of a larger body).

The issues of Section 1 are still open and deserve careful attention. The immediate result of our investigation is that we have now a much larger sample of Barbarians than before at disposal for future physical investigations (including photometric, spectroscopic and polarimetric campaigns). At the same time, our results definitively confirm the family of Watsonia as a sizeable group of Barbarians having a common collisional origin, and open new perspectives for the development of models in order to try and sort out in a coherent scenario several pieces of observational evidence which appear now to form a complicated puzzle.

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