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Two new basaltic asteroids in the Outer Main Belt⋆

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ABSTRACT

Aims. The identification of other basaltic objects in the asteroid belt is mandatory to explain the diversity in the collection of basaltic meteorites. This diversity requires more than one differentiated parent body, a fact that is consistent with the diversity of differentiated parent bodies implied by the iron meteorites.

Methods. Based on a list of previously identified candidate basaltic (V-type) asteroids, two asteroids in the outer main belt, (7472) Kumakiri and (10537) 1991 RY16, were spectroscopically observed during an observational run in Calar Alto Observatory, Spain.

Results. We confirm the V-type character of these two asteroids that, together with (1459) Magnya, become the only known traces of basaltic found in the outer main belt up to now. We also demonstrate that the searching for candidate V-type asteroids using a photometric survey, like the Sloan Digital Sky Survey, produces reliable results.

Key words. Minor planets, asteroids

1. Introduction

A few years ago, most of the known basaltic asteroids, classified as V-type in the common taxonomical classification schemes, were members of the Vesta dynamical family. Nowadays, several V-type asteroids are know to reside outside the Vesta family (e.g. Burbine et al., 2001; Florczak et al., 2002), and several NEAs with basaltic mineralogical surface composition have been recognized (e.g. McFadden et al., 1985; Cruikshank et al., 1991; Binzel et al., 2004; Duffard et al., 2006). The asteroid (1459) Magnya, a basaltic object in the outer asteroid belt (Lazzaro et al., 2000), is too far away from the Vesta family to have a real probability of being a fragment from the Vesta's crust (Michtchenko et al., 2002).

Concerning the meteorite collection, the realization that most of the Howardites, Eucrites and Diogenites (HED) have similar isotopic composition provides evidence of a possible common origin (Clayton & Mayeda, 1983, 1996; Mittlefehldt et al., 1998). Although a direct link between the

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HED meteorites and the asteroid (4) Vesta is generally acknowledged, several issues continue to be actively examined.

Regarding this point, the oxygen isotope data provide evidence that most of the HEDs derive from a common well-mixed pool. However, more detailed studies recently indicate that some HEDs would be inconsistent with a unique origin. Among these we can mention the eucrites Northwest Africa 011 (Yamaguchi et al., 2002), Ibitira, Pasamonte, Caldera and ALHA 78132 (Wiechert et al., 2004). In particular, the fairly typical eucrite Ibitira has an ^{17}O value indistinguishable from the angrites, which is another suite of ancient basaltic meteorites. These meteorites are geochemically distinct from the HEDs and are clearly resolved on the basis of oxygen isotopes as well. The meteorite collection could actually represent several dozen parent bodies, considering also the abundance of iron meteorites which should have been part of the nucleus of distinct differentiated bodies (Burbine et al., 2002). In short, the diversity in the collection of basaltic meteorites requires more than one basaltic parent body, which is consistent with the abundance of differentiated parent bodies implied by the iron meteorites. In a recent work, Bottke et al. (2006), demonstrated that small differentiated parent bodies (and their fragments) should be common in the Main Belt.

Having this in mind, Roig & Gil-Hutton (2006) presented the possibility of searching yet unknown V-type asteroids using data from large photometric surveys, like the Sloan Digital Sky Survey (SDSS). A sub-product of this survey is the Moving Objects Catalog (MOC), which in its third release provides five band photometry for 43424 asteroids of which 15472 have been observed twice or more (Ivezić et al., 2001; Jurić et al., 2002). In Roig & Gil-Hutton (2006) it was introduced a systematic method to identify possible candidate V-type asteroids from the SDSS-MOC, applying the Principal Components Analysis (PCA) to the data, combined with some criteria of segregation based on direct comparison to the available spectroscopic data. They found 263 V-type candidates that are not members of the Vesta dynamical family. The most interesting result is the presence of 8 V-type candidates in the middle/outer asteroid belt with a > 2.5 AU: (7472), (10537), (21238), (40521), (44496), (55613), (66905) and 2000 KO41. These asteroids are quite isolated in proper elements space and do not belong to any of the major dynamical families. They are not close in proper elements space to (1459) Magnya either.

In a recent paper, Masi et al. (2006, submitted) introduced yet another systematic method that also allows the identification of V-type candidates from the SDSS colours. They present spectroscopic observations of four candidates, already identified by Roig & Gil-Hutton (2006), and confirmed their basaltic nature. Their most interesting result is the confirmation of (21238), a V-type asteroid located at about 2.54 AU, far away from the outer edge of the Vesta family.

As part of a more extensive campaign to search V-type asteroids outside the Vesta family, we selected 5 candidates from Roig & Gil-Hutton's list to be observed through reflectance spectroscopy. This letter is devoted to describe the observations of two of these candidates: (7472) Kumakiri and (10537) 1991 RY16, which are located in the outer asteroid belt. Our aim is to determine the taxonomic classification (indicative of the surface composition) and to proof the efficiency of Roig & Gil-Hutton's method to identify V-type candidates. In the next sections, we first describe the observations and the reduction procedures, then we present the identification of the taxonomic type, and finally, we briefly discuss the results obtained.

Table 1. Observational circumstances for the targets in November 14 and December 29, 2006: Universal Time (UT), heliocentric distance (r), geocentric distance (Δ), phase angle (ϕ), visual magnitude (V), airmass and total exposure time (T_{exp}).

Asteroid	UT	r [AU]	Δ [AU]	ϕ [deg]	V [mag]	airmass	T_{exp}
November 14							
(7472) Kumakiri	03:25:00	2.920	2.123	13.5	16.6	1.037	3400 sec
(10537) 1991 RY16	00:05:08	3.040	2.053	1.8	17.1	1.091	4000 sec
December 29							
(7472) Kumakiri	21:48:52	2.873	1.901	3.8	15.9	1.094	3600 sec

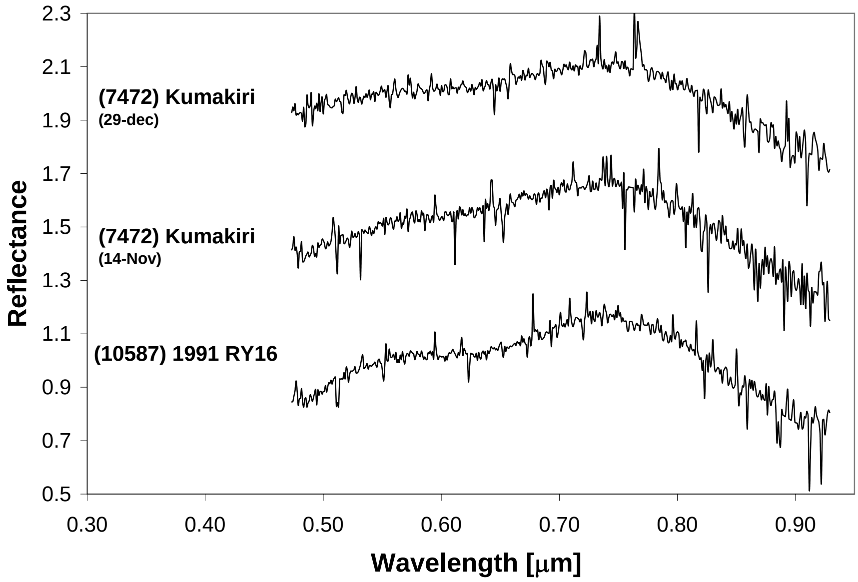

Fig. 1. Reflectance spectra of (10537) 1991 RY16 (below) and (7472) Kumakiri (above) shifted by 0.5 units for clarity.

2. Observations

Low resolution spectroscopy of (7472) Kumakiri and (10537) 1991 RY16 were obtained on November 14, 2006, as part of a 4 nights observational run, and (7472) Kumakiri was observed again on December 29, 2006, in Director's Discretionary Time (DDT) using the Calar Alto Faint Object Spectrograph (CAFOS) at the 2.2m telescope in Calar Alto Observatory, Spain. Table 1 summarizes the observational circumstances.

CAFOS is equipped with a detector consisting of a SITe-1d 2k x 2k chip (24 μm/pixel, i.e. 0".53/pixel). The grism R400 was used (see http://www.caha.es/alises/cafos/cafos22.pdf for more details), allowing to obtain an observable spectral range between 0.50 and 0.92 μm. For calibration purposes, spectra of the solar analog stars HD 191854, HD 20630 and HD 28099 (Hardop, 1978)

Table 2. Proper elements and non linear secular resonant frequencies of V-type asteroids in the outer belt. Frequencies are in "/yr. For (1459), the last column gives the diameter from Delbo et al. (2006). For (7472) and (10537), the diameter was computed assuming an albedo of 0.40.

Asteroid	a_p [AU]	e_p	$\sin I_p$	gs_{57}	gs_{66}	gs_{77}	D [km]
(1459) Magnya	3.14986	0.2183	0.2651	-5.664	-6.299	-4.493	17.0 ± 1.0
(7472) Kumakiri	3.01033	0.1372	0.1562	-3.588	-4.195	-2.388	8.5
(10537) 1991 RY16	2.84958	0.1023	0.1101	-1.570	-2.207	-0.400	7.3

were also taken at similar airmasses as the asteroids' spectra. At each night of observations, at least two solar analogs were observed in order the estimate the quality of the night. The ratios between the spectra of the solar analogs in each night show no substantial variation. Bias frames, spectral dome flat fields and calibration lamps spectra were also taken at each night. Spectrum exposures for each asteroid were splitted into two exposures at two different slit positions, A and B, separated by 20" (the width of the slit was 2.0"). The observations were performed with the telescope tracking at the proper motion of the asteroid. Hence by subtracting A from B and B from A, a very accurate background removal is achieved. Finally, standard method for spectra extraction was applied.

The final result for (7472) and (10537) is shown in Fig. 1. The spectra were normalized at 0.55 μm and shifted up in reflectance for clarity purposes. To remove the solar contribution from the reflectance spectra, we used the solar analog HD 191854 in both asteroids for the night of November 14 and the solar analog HD 28099 for the night of December 29.

3. Results and Conclusions

The reflectance spectra of (7472) Kumakiri and (10537) 1991 RY16 correspond to that of a V-type asteroid. Both spectra show a steep slope shortwards of 0.7 μm and a deep absorption band longwards of 0.75 μm, typical of a basaltic composition. Figure 2a compares the spectra of the two asteroids to that of (4) Vesta, taken from the SMASS survey (Bus & Binzel, 2002), and to that of (1459) Magnya, taken from the S3OS2 survey (Lazzaro et al., 2004). Figure 2b compares the obtained spectra to the corresponding observations from the SDSS-MOC. The good agreement demonstrate that taxonomy predictions based on the photometry of the SSDS are reliable, at least concerning the identification of V-types.

Besides the 1 μm absorption band, the spectrum of (10537) 1991 RY16 also shows an appreciable absorption band around 0.6-0.7 μm, whose origin is unclear. Such kind of absorption feature is usually believed to arise from the $Fe^{2+} \rightarrow Fe^{3+}$ charge transfer absorptions in phyllosilicate (hydrated) minerals (Vilas & Gaffey, 1989; Vilas et al., 1993). It is difficult to explain the presence of a hydrated mineral in the surface of a basaltic object, because the heating and melting that produce the basalt also eliminate any traces of water. In a recent paper (Shestopalov et al. 2007) analyzed faint absorption bands in the reflectance spectra of vestoids.

They proposed a origin of trace amounts of ferric iron in pyroxene's asteroid surface may be connected with effect of the shock-induced oxidation of Fe^{2+}. In other words, Fe^{3+}-containing material could be introduced into vestoid regolith due to impacts with other asteroids or comets. On the other hand, Shestopalov and Golubeva (1998) do not rule out Fe^{3+} in the Vesta pyroxenes, and Rivkin et al. (2005) cannot formally rule out a shallow water band in the Vesta spectrum.

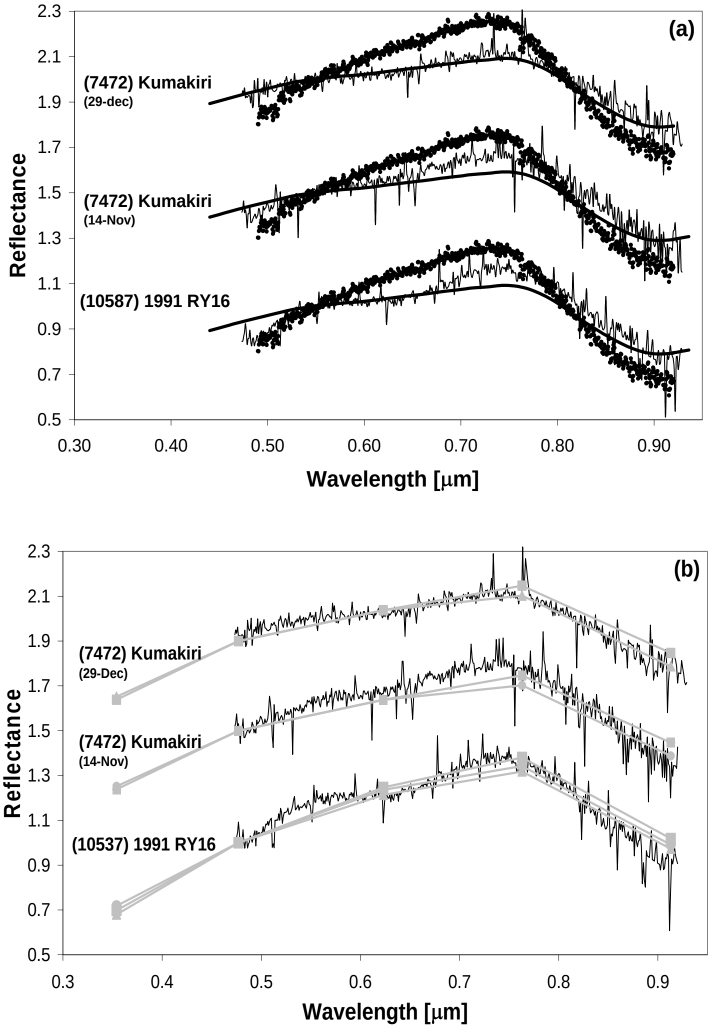

Fig. 2. (a) Reflectance spectra of (10537) 1991 RY16 (below) and (7472) Kumakiri (above) compared to the spectra of (4) Vesta (full line) and (1459) Magnya (dotted line). The spectra are normalized to 1 at 0.55 μm. (b) Same as (a), but compared to the photometric observations of the SDSS-MOC. The normalization has been done at 0.477 μm to be consistent with the g band of the SDSS photometry and to avoid the shallow band at 0.6 μm. The errors in the SDSS fluxes are less than 3%.

Shestopalov and collaborators concluded that Fe^{3+} appears to be in the vestoid material. Since similar impact events could occur with other asteroids, Fe^{3+}-absorptions in the asteroid spectra should be ubiquitous in the asteroid belt wherever pyroxene absorptions are found. They propose that the trace amounts of Fe^{3+} on vestoids surfaces may be due to oxidation from impacts by icy bodies, a fact that is more probable in the outer main belt where Kumakiri and 1991 RY16 are.

Other probable explanation to this feature is the presence of olivine. It is know that the reflectance olivine spectra contain a wide absorption near 0.6 μm. Golubeva et al. 2007 (personal comunication, abstract to LPSC 2007) listed a set of 4 V-type asteroids with a faint isolated absorption near 0.6 μm. This fact sugest that olivine appears to be (< 10 vol. %) on the surface of (2468) Repin, (2640) Hallstrom, (4188) Kitezh, and (4993) Cossard.

In conclusion, it is difficult to interpret this broad band. If it is the olivine band (Fe^{2+} in olivine) in the spectrum of an olivine-pyroxene mixture, it's necessary to see the 0.9 μm band position. In our spectra this is the noisest part of the spectra and the setup of the spectrograph allows signal until 0.93 - 0.94 μm. Doing a polynomial fit of several different grades, we obtained a minimum of 0.94 ± 0.05 for (10537) 1991 RY16 and 0.96 ± 0.03 for (7472) Kumakiri. With this data in mind the option of the presence of olivine is more razonable, but the shift of the 0.9 band to 1.0 μm can be also caused by high calcium pyroxene.

Up to now, the most plausible evidence for the fragmentation of a differentiated asteroid in the outer belt has been provided by Mothé-Diniz et al. (2006). These authors used different techniques to analyse the spectra of 22 asteroids members of the Eos family. These spectra in the 0.8-2.5 μm range are characterized by the presence of a broad absorption feature around 1 μm and a weaker-to-absent absorption feature at 2 μm, suggesting an olivine-rich composition with a minor pyroxene component. In principle, this kind of minerals would come from the mantle of a differentiated body, but they might also have condensed in the primordial nebula. Therefore, whether Eos is a differentiated family or not is still an open problem. Can the discovery of the two new basaltic asteroids presented here help to clarify the scenario?

The analysis of the orbital distribution of (7472) and (10537) show several peculiarities. Table 2 gives the proper elements and diameter of the two asteroids together with (1459), which is the other known V-type asteroid in the outer belt. All the three asteroids are too small to be differentiated bodies by themselves, so they would be candidates to be the fragments of one or several differentiated parent bodies. Unfortunately, they are well separated from each other in terms of proper elements, and none of them belong to any of the known asteroid families, although (7472) is relatively close to the Eos family, and (10537) is relatively close to the Koronis family. Under this evidence, the hypothesis of being fragments of the same parent body is difficult to support.

On the other hand, both (7472) and (10537), as well as (1459), share a common dynamical property: they are located very close to the same bunch of non linear secular resonances. This kind of secular resonance is formed by a linear combination of the proper frequencies of perihelion and node that is close to zero. In the case under study, the main combinations are $g + s - g_5 - s_7$, $g + s - g_6 - s_6$, and $g + s - g_7 - s_7$ (which we will name here as gs_{57}, gs_{66} and gs_{77}, respectively), where g and s are the frequencies of the perihelion and node variation of the asteroid, respectively, and g_i, s_i are the frequencies of the perihelion and node of the planets ($i = 5$ for Jupiter, $i = 6$ for Saturn, and $i = 7$ for Uranus). These secular resonances have been already identified and described by Milani & Knežević (1992), who also pointed out that they cross through the Eos family (located at $a_p \sim 3.0$ AU, $e_p \sim 0.08$, $\sin I_p \sim 0.18$). Table 2 provides the values of the resonant frequencies for the three asteroids.

It is worth noting that all the V-type candidates identified by Roig & Gil-Hutton (2006) in the outer belt are also located very close to the bunch of non linear secular resonances mentioned above. In fact, they appear aligned along these resonances in the a_p vs. $\sin I_p$ space (see figure 4b of that paper). Since the resonances also cross the Eos family, one would be tempted to claim that the V-type asteroids in the outer belt may be genetically related to this family. These V-type asteroids may have slowly evolved from the Eos family up to their present locations, chaotically diffusing along the secular resonances with the aid of the Yarkovsky effect. The scenario may be analogous to what happens in the inner belt, where some V-type asteroids outside the Vesta family, like (809) Lundia and (956) Elisa, may be fugitives of this family evolving via chaotic diffusion along secular resonances (Carruba et al., 2005). However, in the case of the outer belt, this scenario has two major drawbacks.

First, it is not clear whether the non linear secular resonances mentioned above would be strong enough to allow the change in proper elements that would be necessary to explain the present orbits of the observed V-type asteroids. Even accounting for the Yarkovsky effect, this should produce a drift of about 10^{-4} AU/My, which is too large for asteroids in the outer belt and in the size range shown in Table 2[1]. Moreover, we cannot say whether the alignment shown in figure 4b of Roig & Gil-Hutton (2006) is real or it simply happens by chance due to the poor statistics. In any case, these two issues may deserve a more detailed analysis.

Second, and more important, if we assume that the V-type asteroids in the outer belt are fugitives from the Eos family, then we should expect to detect several V-type candidates within the family. In fact, the breakup of a differentiated parent body is expected to produce a large amount of basaltic fragments, most of which should remain in the family while only a few are allowed to escape. This is precisely what happens in the inner belt, where about half of the V-type candidates identified by Roig and Gil-Hutton (2006) are members of the Vesta family. Notwithstanding, not a single V-type candidate can be identified among the members of the Eos family from the SDSS photometry, even if about 10% of the family members have been observed by the SDSS-MOC.

A possible explanation to this lack of basaltic material within the Eos family could be that the basaltic crust of Eos' parent body was too thin while the mantle was too thick. Therefore, the crust was mostly pulverized during the breakup, and most of the large surviving fragments came only from the mantle. But only the discovery of a significant amount of small basaltic asteroids (which, by now, is out of the observational possibilities) may help to support this hypothesis. Meanwhile, we cannot rule out the possibility that the V-type asteroids in the outer belt might not be related to the Eos family and that their origin must be explained by some other scenario.

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[1] Recall that the Yarkovsky effect decreases with increasing size and increasing distance to the Sun.

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