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Peculiar Near-Earth Objects

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Abstract. In this paper we present visible and near-infrared spectroscopy of 7 peculiar NEOs. These objects have been observed within the SINEO (Spectral Investigation of Near-Earth Objects) survey, which have produced more then 100 spectra of NEOs. Among the objects presented here, five of them result to be spectrally peculiar, belonging to the rare V and R classes. The other two have peculiar orbits being comet-like. Their spectroscopy gives a B- and a X-type which is compatible with the scenario of being objects which originated in the outer Solar System.

Key words. minor planet – asteroids – near-Earth objects

1. Introduction

Much progress in understanding the origins of near–Earth objects (NEOs) has been accomplished in the last three decades. NEOs have in general chaotic, short–living orbits (typical life–times of the order of a few million years), suggesting that they have to be continuously resupplied from an external reservoir. Two major sources have been identified (for a review see Morbidelli et al. (2002)). The principal one is the Main Belt, where gravitational perturbations, mainly by Jupiter and Saturn, create dynamically resonant regions which provide escape routes (in this case we refer to near–Earth asteroids, NEAs). The second (by far less important) source is represented by extinct comets: a certain number of NEOs may represent the final evolutionary state of comets, i.e. a devolatilized nucleus.
In this paper we present the spectroscopy of some peculiar NEOs: five peculiar igneous bodies and two having comet-like orbits and a primitive composition.

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2. Igneous bodies

2.1. V-type

In figure 1 the visible spectra of four V-types observed NEOs are shown. For each body, the spectrum of the asteroid 4 Vesta has been overplotted for a direct comparison.

They exhibit an excellent spectral match with Vesta. We also report the range of variation concerning the previously defined V–type asteroids on the basis of 39 V–type objects found within SMASSII (Bus 1999). The presented NEAs are significantly more similar to 4 Vesta than the previously known V–type MB asteroids. The same is true within the sample of V–type NEAs (a total of 15 bodies, see Binzel et al. (2002)). The main differences between 4 Vesta and the other V–types are the slopes in the range 0.4-0.72 μm (from moderately to much redder than Vesta) and the depth of the 1

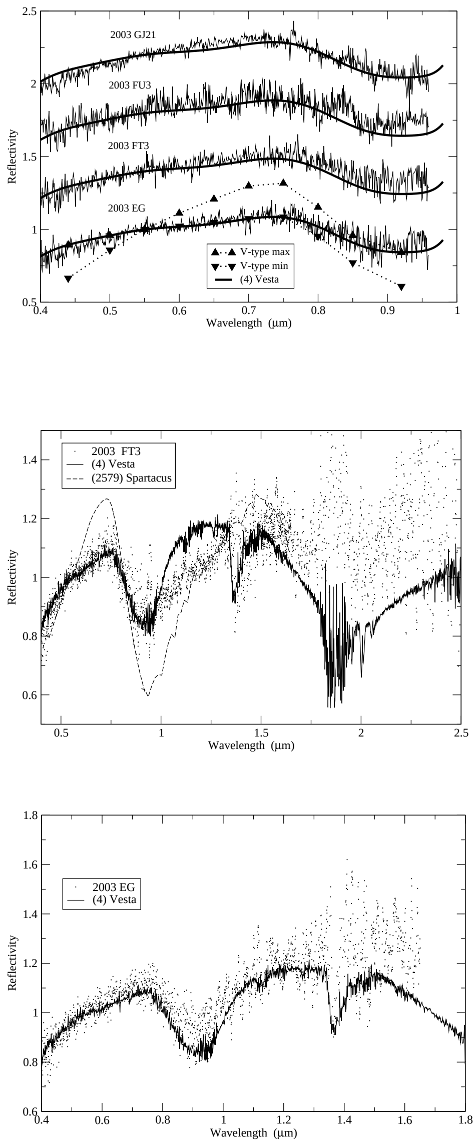

Fig. 1. Upper panel: Comparison between the observed NEOs (namely, 2003 EG, 2003 FT3, 2003 FU3, and 2003 GJ21) and 4 Vesta in the visible region. The spectra are shifted vertically for clarity. For 2003 EG the maximum and minimum spreading among V-types (Bus 1999) is also shown. Middle panel: Comparison between 2003 FT3 and 4 Vesta. The Main Belt asteroid 2579 Spartacus is also overplotted (Burbine et al. 1997). Lower panel: Comparison between 2003 EG and 4 Vesta. The smoothed specrtum of 2003 EG is also shown, for a easier comparison.

μm band (deeper than Vesta's: see Florczak et al. (2002); Burbine et al. (2001); Binzel & Xu (1993)). We are aware that neither differences in slope do necessarily indicate differences in composition, as shown by Kelley et al. (2003), nor the similar spectral behaviour between two objects necessarily establishes a genetic link. However, the similarity between 4 Vesta and the NEOs, whose observations are presented in this paper, stands as a striking feature. For this reason, in the following we shall compare our data not only to V–types in general, but also often to Vesta.
For two NEAs in our sample, namely 2003 FT3 and 2003 EG, we performed also NIR observations; unfortunately these spectra are too noisy for a quantitative analysis of bands position and depth, which would be necessary for a detailed compositional analysis.

The composite visible-NIR spectrum of 2003 EG (Fig. 1, lower panel) resembles that of 4 Vesta throughout all the observed range, and in particular the shape of the 1 μm band is similar. However, the depth of the 1 μm band is not the same, being deeper on Vesta than on 2003 EG, perhaps indicating a different content of pyroxene and/or olivine. Unfortunately, the 2 μm band is out of the measured range, thus preventing any detailed compositional analysis. Anyway, the high reflectivity level of 2003 EG at 1.6 μm suggests a lower content of pyroxene with respect to Vesta.
The overall NIR spectrum of 2003 FT3 (Fig. 1, middle panel) is consistent with the V–type, but the right–hand limb of the 1μm band is very peculiar and much different from other V-types (and from Vesta as well). Moreover the 2 μm band is less deep than that of Vesta. Similar features, for the first time detected among NEOs, have been observed at least in another MB V–type object, namely 2579 Spartacus (Burbine et al. 2001). We stress that the spectra of Vesta, Spartacus and 2003 FT3 are rather different one from each other. However, the broad 1 μm bands of Spartacus and 2003 FT3 may suggest a compositional similarity (note also that no similar features have been detected among HED meteorites). The peculiar spectral features can be seen (here as for 2579 Spartacus, see Burbine

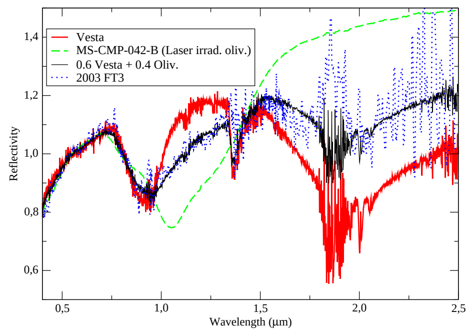

Fig. 2. Linear combination of Vesta's spectrum with laser irradiated olivine. The percentages which give the best fit are 60% Vesta and 40% olivine (see text for further details).

et al. (2001)) as diagnostic of an excess of olivine and/or plagioclase, compared to typical V–types. Indeed, olivine has a broad profile at the right side of the 1 μm band and has no 2 μm band (e.g. see Hiroi & Sasaki (2001)) while plagioclase has a wide band that extends from 1 to 1.5 μm, and has no 2 μm band. In order to investigate such hypotesis, we computed a linear combination (e.g. see Hiroi et al. (1993)) of Vesta spectrum with the spectrum of olivine (taken from RELAB, http://www.planetary.brown.edu/relab/). The result is shown in fig. 2. Although the linear combination could represent a oversimplification of the actual 2003 FT3 surface (it holds only if the diverse species have separate locations on the surface), an excellent match has been achieved. We recall that a spot of olivine has been identified (Gaffey (1997); Thomas et al. (1997); Cochran & Vilas (1998)) on the surface of Vesta: 2003 FT3 might originate from a surface layer of Vesta, close to the spot.
For a more detailed analysis see also Marchi et al. (2005).

2.2. R-type

In Fig. 3 the visible spectrum of 2001 XR31 is shown. Its spectrum presents the overall behavior of igneous, V-like, objects. However its visible spectrum also presents many common aspects with another group of igneous bodies, those belonging to the R-class. Tholen et al. (1989) introduced the distinction between V- and R-class on the basis of the spectra of two peculiar MBAs, 4 Vesta and 349 Dembowska, respectively (for further details, see Gaffey et al. (1993)). Recently Bus (1999), still kept this distinction, although he provided new spectra in both classes increasing the spreading between each class. In particular he found 3 more objects similar to 349 Dembowska, and hence classified as R-types. However, a detailed inspection of all the visible spectra of V- and R-types show that this division is somewhat weaker than that introduced by Tholen. According to this classification, 2001 XR31 would be at the border between V- and R-class (see Fig. 3, upper panel). However, we underline also that the spectrum of 2001 XR31 surprisingly overplots exactly the R-types in the range 0.4-0.85 μm. Moreover, we point out another similarity between the R-types and our NEO, namely on the basis of their behavior within the range 0.86-0.95 μm. In fact, the reflectivity of all the R-type objects in this interval is noticeably constant (see Fig. 3, upper panel) while for the V-types it is generally slightly decreasing. In other words, the bottom of the 1μm band is almost flat. Now, it is difficult to understand the origin of this behavior, but it is believed to be significant for compositional differences. We point out that it could be due to mixture of compounds which have the peak of the 1 μm band at slightly different wavelengths, for example by a mixture of olivine and pyroxene or a mixture of pyroxenes with different contents of Fe (e.g. see Gaffey (1997)). To better show the differences between V-types and R-types, in Fig. 3 we also report the object 3155 Lee which, among the V-types, is the one which closer resembles 2001 XR31. Fig. 3 clearly shows that although the overall behavior of these two objects is quite similar, there are differences in slope and the shape of the 1 μm band, reasons for which the spectrum of 2001 XR31 is best fitted by the R-types, instead of V-types.

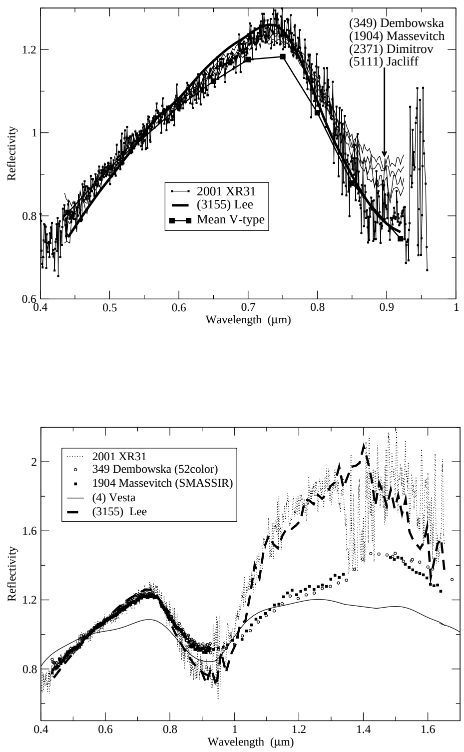

Fig. 3. Upper panel: Comparison of 2001 XR31 with R-type MBAs (taken from Bus 1999) in the visible region. The mean V-type and 3155 Lee are also shown (both from Bus (1999)). Lower panel: Comparison of 2001 XR31 with R-type asteroids. On the same plot, 4 Vesta and 3155 Lee are also shown. The NIR of 1904 Massevitch and 3155 Lee are from SMASSIR (Burbine et al. 1997), while the NIR of 349 Dembowska is from 52-Color survey (Bell et al. 1988).

However, the NIR (see Fig. 3, lower panel) of 2001 XR31 does not resemble those of the only two available R-types. Anyway, the 2001 XR31 high values of reflectivity in the range 1.3-1.5 μm with respect to 349 Dembowska is likely the same kind of discrepancy shown by the V-types and Vesta. For the latter a possible explanation has been found in grain size effects (Burbine et al. 2001): smaller particle sizes produce higher values of reflectivity. Other possible reasons able to increase the reflectivity could be compositional differences or space weathering. If 2001 XR31 is a fragment of 349 Dembowska, their differences could be affected both by a different degree of space weathering and/or compositional differences. Finally, the steep right-hand limb of the 2μm band of 2001 XR31 would indicate a greater concentration of pyroxene on 2001 XR31 with respect to 349 Dembowska.

Concerning the intriguing possibility that 2001 XR31 (having an estimated diameter of about 1.3 km) is related to R-type instead of V-type, notice that the only possible known parent body is 349 Dembowska. This is because it has a diameter of about 140 km, while the other main belt R-types have diameter in the range 6-12 km, unless they are remnants of a larger R-type body which suffered a collision, but there is no evidence for that at the moment. Nevertheless other sources cannot be excluded. The surface of 349 Dembowska is still poorly known. The only information about its shape comes from the analysis of the light curves (e.g. see Zappalà et al. (1979)). As pointed out by Abell & Gaffey (2000), the light curves and spectral variations seem to indicate the presence of an albedo spot near the equator. Possibly it could be a trace of a cratering event, as also noted by Abell and Gaffey. If so, the differences observed in the NEOs spectra with respect to the R-types can results from NEOs being fragments of deepen layers which should have different composition considering the spot albedo variation.

However, it has a proper semi-major axis of 2.925 AU which falls inside the 5:2 and 7:3 mean motion resonances. These resonances are probably not too efficient to produce NEOs, because they tend to push objects into high eccentricity orbits and eventually, when they reach a critical eccentricity for becoming Jupiter crosser, the objects are subsequently removed from the inner solar system by close encounters with Jupiter (see Moons & Morbidelli (1995); Gladman et al. (1997); Morbidelli & Gladman (1998)). However this possibility cannot be ruled out, because for eccentricity lower than the critical value, some objects can

have close encounter with Mars and the Earth (see Moons & Morbidelli (1995); Morbidelli & Gladman (1998)), and eventually, they can be trapped in near-Earth space, as maybe indirectly prove by the presence of many C-types among NEOs. Moreover, notice that fragments released from Dembowska could easily enter the 7:3 resonance, for which a velocity of about 0.1 km/s is sufficient; while higher velocity (∼0.5 km/s) are needed to reach the 5:2 resonance. Also taking into account possible semi-major axis mobility, i.e. the Yarkovsky effect (Farinella & Vokrouhlicky 1999), it seems unlikely that the 5:2 has played a role in delivering fragments from 349 Dembowska.
For further details see Marchi et al. (2004).

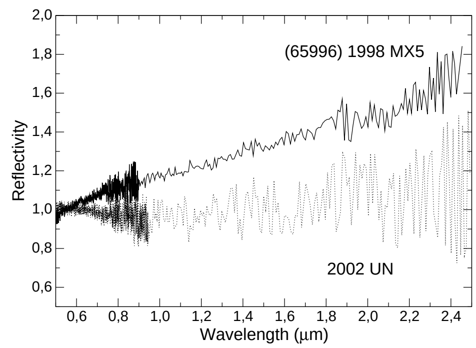

Fig. 4. Visible and NIR spectroscopy of two NEOs having comet-like orbit.

3. Primitive bodies

In this section we present the spectroscopy of two primitive NEOs (i.e. 1998 MX5 and 2002 UN), having comet-like orbits. They, in fact, have Tisserand invariants with Jupiter (T_J) of 2.95 and 2.81, respectively. We remind that objects with $T_J < 3$ are usually considered comet-like asteroids. This dynamical condition has been strengthened by our observations: both objects are indeed B- X-types. The reddish and featureless spectra of 1998 MX5 and 2002 UN are typical of primitive objects, cometary nuclei and most asteroids in cometary orbits studied in the 0.5-2.4 μm range. Unfortunately the very few cometary nuclei spectroscopically observed in this wavelength range did not show any kind of peculiar absorption feature (e.g. Lazzarin et al. (1996), De Sanctis et al. (2000), Licandro et al. (2002), Licandro et al. (2003)). Licandro et al. (in preparation), also observed 17 asteroids in cometary orbits, and found that 15 of them present featureless, slightly red spectra, and failed to find any feature that could distinguish between them and main belt primitive asteroids.
For further details see Lazzarin et al. (2005).

4. Conclusions

- Four NEOs (2003 EG, 2003 FT3, 2003 FU3 and 2003 GJ21) have been classified as V–type. Moreover, considering their good spectral match with 4 Vesta they can be defined as Vesta analogues. They are among the objects which more closely resemble Vesta itself observed so far; in particular 2003 EG shows a striking spectral similarity to Vesta both in the visible and in the NIR.
- Due to the spectral match with Vesta and considering their dimensions, the presented objects could be fragments from the surface layer of 4 Vesta. 2003 FT3 shows the presence of an excess concentration of olivine. Its properties might be consistent with an origin close to the known olivine spot on the surface of Vesta.
- 2001 XR31 resembles V-type bodies, but we point out its possible link with the R-class. If this would be confirmed by other observations, it will be the first R-type discovered among NEO so far. Considering the possibility that 2001 XR31 is R-type, we point out that it could have been injected in near-Earth space by the 7:3 mean motion resonance with Jupiter.
- Two other NEOs having comet-like orbits, have been revealed to be primitive, confirming their possible origin in the outer Solar System.

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