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Discovering New V-Type Asteroids in the Vicinity of 4 Vesta[1]

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We present results on the identification of two new V-type asteroids, 809 Lundia and 956 Elisa. These asteroids are located in the neighborhood of Asteroid 4 Vesta, but they do not belong to Vesta's dynamical family. Their spectra in the visible wavelength are consistent with the spectra of the Vesta family members (Vestoids) and of other V-type objects in the nearby region too. The possible existence of two spectroscopic groups of V-type asteroids in the Vesta region is discussed. © 2002 Elsevier Science (USA)

Key Words: **asteroids; asteroids, Vesta; asteroids, composition; spectroscopy; surface composition.**

1. INTRODUCTION

It has long been recognized that the spectrum of Asteroid 4 Vesta exhibits the 1- and 2-μm pyroxene features, similar to those of the HED meteorites (McCord *et al.* 1970, McFadden *et al.* 1977). The uniqueness of this kind of spectrum in the asteroid main belt led to the association of the HED meteorites with 4 Vesta, in spite of the difficulties in identifying the possible mechanisms of transport from 4 Vesta to the Earth. Later on, the identification of a Vesta dynamical family (Williams 1989, Zappalà *et al.* 1990), the discovery of near-Earth asteroids having the same spectral signature, and the discovery of a 460-km-diameter crater in 4 Vesta (Binzel *et al.* 1997) contributed to reinforce the link between 4 Vesta and the HED meteorites. The subsequent identification (Binzel and Xu 1993) of several small asteroids, either members of the Vesta family or close to it, having visible spectra similar to that of 4 Vesta, and the discovery of the transport mechanisms from the Vesta region to near-Earth orbits (Marzari *et al.* 1996, Migliorini *et al.* 1997), consolidated this hypothesis (Drake 2001).

In recent taxonomies, asteroids showing a spectrum similar to that of 4 Vesta have been classified as V-type (Tholen and Barucci 1989, Bus 1999). The name "Vestoids" was initially used by Binzel and Xu (1993) to refer to all the asteroids in the region near 4 Vesta having a V-type spectrum. Recently, it has been found that all the Vestoids have near-infrared spectra consistent with a unique origin (Burbine 2000, Burbine *et al.* 2001). The exception is Asteroid 2579 Spartacus, which not only has a spectrum very similar to those of V-class objects but also shows features indicating the presence of a significant amount of olivine. This suggest either that 2579 Spartacus contains sample material from the mantle of 4 Vesta or it is not a Vesta fragment at all.

The spectroscopic link among the Vestoids, the V-type near-Earth asteroids (NEAs), and the HED meteorites seems to be quite consistent, especially if we take into account that basaltic material is very rare in the asteroid belt. However, some problems still remain open. For example, the cosmic ray exposure time observed in the HED meteorites seems to be incompatible with the transport dynamical time of the NEAs (Migliorini *et al.* 1997). The spectra of all the HED meteorites show a subtle absorption feature, which is observed only on some V-type asteroids in the Vesta region (Vilas *et al.* 2000, Hiroi *et al.* 2001). Finally, the recent identification of a basaltic asteroid, 1459 Magnya, in the outer main belt (Lazzaro *et al.* 2000), which is not related to the Vesta family, provides another possible source for the V-type NEAs and HED meteorites (Michtchenko *et al.* 2002).

In this paper, we present the recent identification of two new V-type asteroids: 809 Lundia and 956 Elisa. These asteroids are located in the region near Vesta but far away from the limits of the Vesta dynamical family. Actually, one of them is classified as a member of the nearby Flora clan. It is worth recalling that another asteroid with a V-type spectrum, 4278 Harvey, has already been discovered among the same clan (Florczak *et al.* 1998). In view of the increasing number of objects with a

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V-type spectrum for which a clear link to 4 Vesta has not been yet established, we will adopt the following convention from here on: All the asteroids in the Vesta region showing a Vesta-like spectrum will be referred to as V-type asteroids; all the V-type asteroids belonging to the Vesta family will be specifically called Vestoids.

In the next section we present observations and results for the two V-type asteroids recently discovered plus the other V-type asteroid in the Flora family. The discussion on the origin and evolution of these asteroids, as well as the possible scenarios that may support the observed distribution of V-type bodies in the Vesta region, is presented in the last section.

2. OBSERVATIONS AND RESULTS

The observations were performed at the European Southern Observatory, La Silla, as part of the Small Solar System Spectroscopic Survey (Lazzaro *et al.* 2001). We used a 1.5-m telescope, equipped with a Boller and Chivens spectrograph and a 2048 × 2048 CCD. Using a 225 gr/mm grating with a 330 Å/mm dispersion, we obtained a useful spectral range from 0.49 to 0.92 μm, with a FWHM of 10 Å. The spectra were taken through a 5-arcsec slit, oriented in the East–West direction to minimize the consequences of atmospheric differential refraction and to reduce the loss of light at both ends of the spectra. It is worth noting that a substantial loss of light may lead to an erroneous spectral characterization of the objects. The observational circumstances are listed in Table I. The table shows date, number of exposures, airmass during observation, heliocentric and geocentric distances, solar phase angle, estimated visual magnitude, and solar analog used.

The spectral data reduction was performed using the Image Reduction and Analysis Facility package, following standard procedures. Wavelength calibration was performed using an He–Ar lamp, and spectra were corrected for airmass using the mean extinction curve of La Silla (Tüg 1977). At least two solar analogs (Hardorp 1978) were observed in each observational run, and their influence on the resulting spectra led to differences smaller than $1\%/10^3$ Å. A full description of the data reduction process is given in Florczak *et al.* (1998). By convention, the asteroids' spectra were normalized around 5500 Å.

TABLE I
Observational Circumstances

Asteroid	UT Date	Exp.	Airmass	R (AU)	Δ (AU)	α	Mag ν	Solar analog
809 Lundia	26/05/01	2	1.0	2.19	1.27	14.4	14.8	HD144585
	27/05/01	1	1.0	2.19	1.26	14.0	14.8	HD144585
956 Elisa	26/05/01	1	1.1	1.91	1.16	26.6	15.5	HD144585
	27/05/01	2	1.1	1.90	1.15	26.4	15.5	HD144585
4278 Harvey	08/01/97	1	1.4	2.06	1.71	15.9	16.8	HD44594

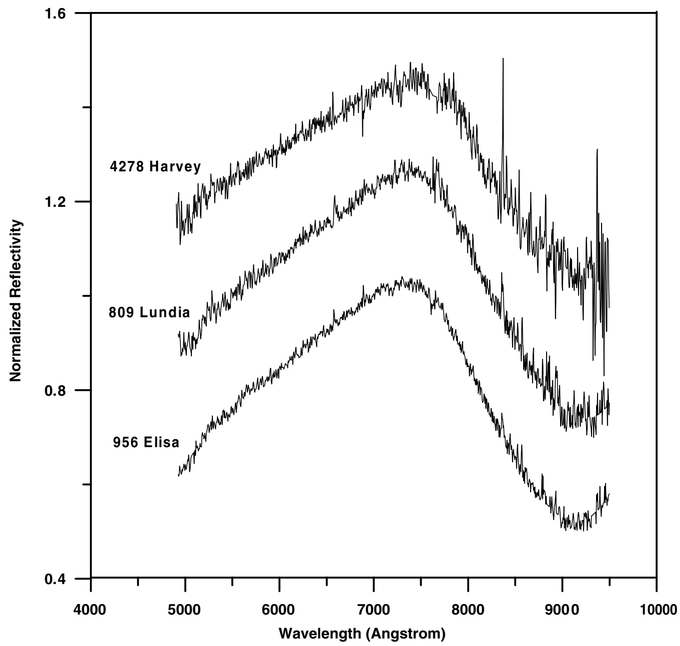

FIG. 1. The spectra of Asteroids 4278 Harvey, 809 Lundia, and 956 Elisa. The spectra have been vertically shifted for better comparison.

The spectra of 809 Lundia, 956 Elisa, and 4278 Harvey are shown in Fig. 1. The 9200- to 9400-Å deep absorption band, characteristic of V-type asteroids, is appreciable in the three spectra. Due to the limited range in the blue part of the spectra, it is difficult to recognize whether the subtle 5065-Å absorption feature described by Vilas *et al.* (2000) is present or not.

To analyze the possible link of these asteroids to 4 Vesta, the Vestoids, and the other V-type asteroids, their spatial distribution is shown in Fig. 2. The gray, filled triangles and circles denote the members of the Vesta and Flora dynamical families (Zappalà *et al.* 1995), respectively. Open triangles denote the Vestoids, and open circles are the V-type members of the Flora dynamical family. Twenty V-type asteroids belonging neither to the Vesta family nor to the Flora family are shown by black stars. Their spectra were used for comparison with the three new V-type bodies. Seven of these V-type asteroids (1273, 2442, 2579, 2653, 2763, 2851, and 4188) were taken from Burbine *et al.* (2001). Ten bodies (2566, 2640, 2704, 2795, 2912, 3307, 3849, 4434, 4796, and 5379) were taken from the SMASS survey (Binzel *et al.* 2001), such that they were located in the Vesta region (arbitrarily defined by $2.2 \leq a \leq 2.5$ and $e \leq 0.2$). Finally, three of these V-type asteroids (2113, 3153, and 3869) were taken from Binzel and Xu (1993).

The spectral distribution of the asteroids in our sample is shown in Fig. 3. In Fig. 3a, we show the polynomial best fits of the spectra of all the selected V-type asteroids in the Vesta region, including the three new ones. We can see that all the spectra have the same shape, with a quite red slope and a 9200- to 9400-Å

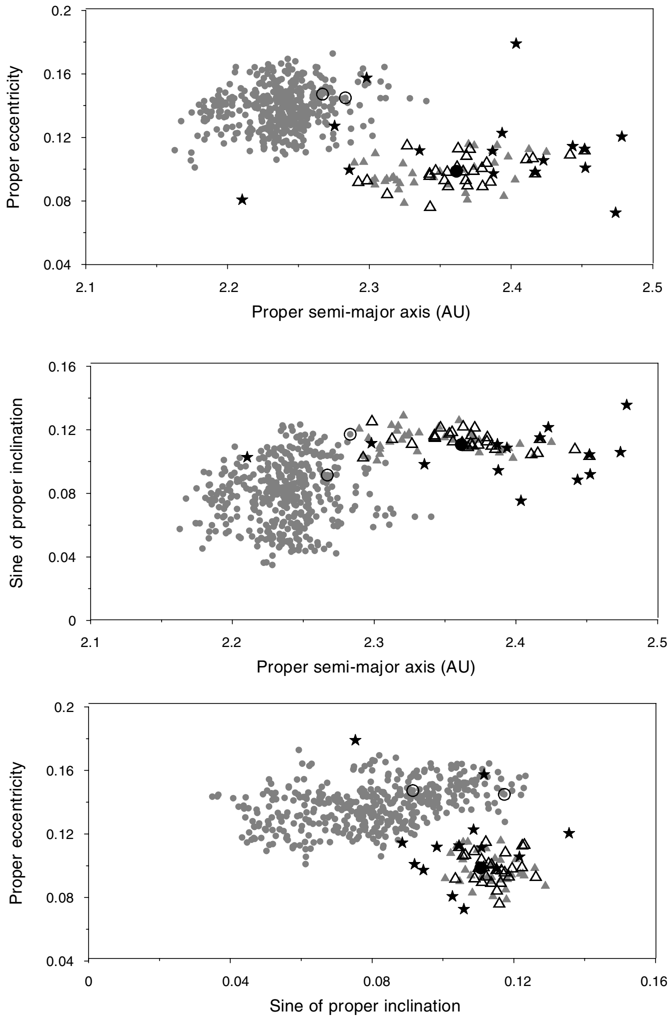

FIG. 2. The spatial distribution (proper elements) of the asteroid members of the Vesta family (gray, filled triangles), members of the Flora clan (gray, filled circles), and selected V-type bodies (black stars). The members of the Vesta family having a V-type spectrum (Vestoids) are detached as open triangles. The V-type members of the Flora clan are denoted by open circles. The position of 4 Vesta is indicated by the black, filled circle.

deep absorption band. In Fig. 3b, we show the polynomial best fits of the spectra of new V-type asteroids, together with those of the selected Vestoids. Two spectroscopic groups seem to coexist in this figure. From the 11 Vestoids shown there, only 3 or 4 seem to have a spectrum similar to that of the new V-type bodies: They present a steeper slope and a deeper absorption band. It is worth noting that the actual existence of these two groups needs to be confirmed by more detailed mineralogical studies, which depend on the data in the near-infrared wavelength.

3. DISCUSSION

The first point we stress is that not only are Asteroids 809 Lundia and 956 Elisa the lowest numbered V-type asteroids, but they are among the largest ones yet discovered. Assuming an albedo of 0.42 (equal to that of 4 Vesta), the estimated diameters of 809 Lundia, 956 Elisa, and 4278 Harvey are 9.1, 6.3, and 3.3 km, respectively. Still more relevant, these asteroids are among the V-type bodies in the Vesta region that are further away from 4 Vesta. To these peculiar characteristics, Asteroids 809 Lundia and 4278 Harvey add the fact of being classified as members of the Flora family.

The spectral characterization of Asteroids 809 Lundia and 4278 Harvey seems to link these bodies to the Vesta family. However, from the dynamical point of view they belong to the

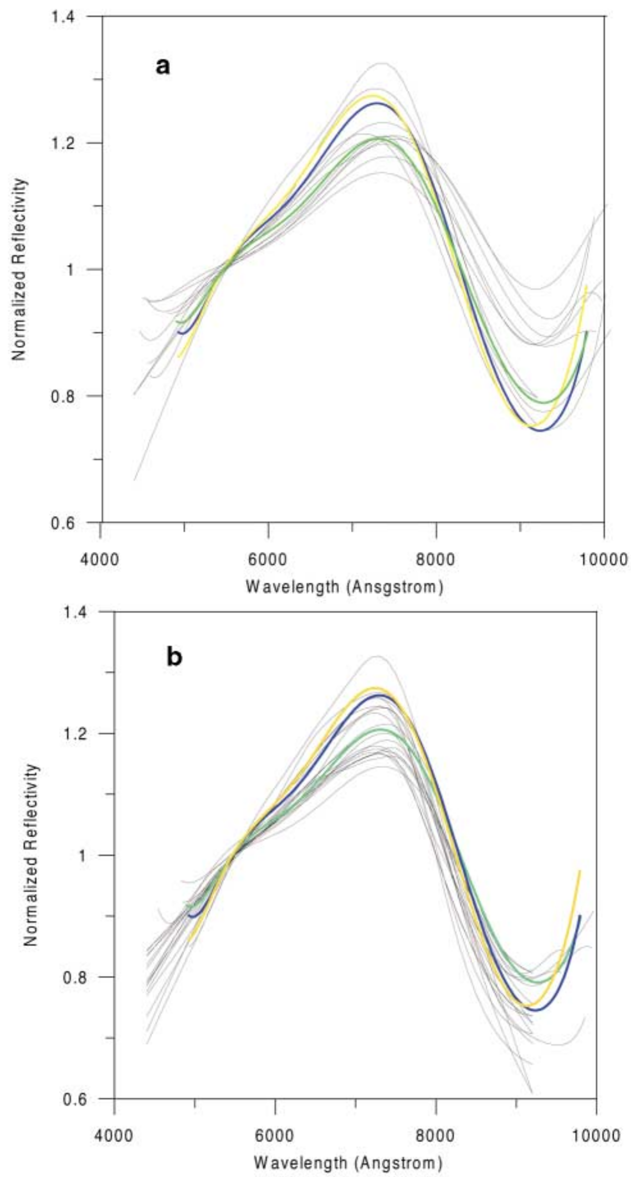

FIG. 3. Spectral distributions of the selected Vestoids (a) and V-type asteroids (b), and comparison with the spectra of 809 Lundia (yellow line), 956 Elisa (blue line), and 4278 Harvey (green line). The spectra are represented by their polynomial best fits.

Flora clan. Could these asteroids have been formed by the single or multiple fragmentations that form the Flora clan? It is worth recalling that the spectral distribution of some 40 members of the Flora family has been analyzed in a previous work (Florczak *et al.* 1998). This study showed that the spectra of the members of the Flora family span a continuous but limited range of reflectivities, consistent with the effects of a space-weathering process on S-type asteroids. This distribution is incompatible with a V-type spectrum, and it seems very improbable that Asteroids 809 Lundia and 4278 Harvey were genetically linked to most members of the Flora clan. However, we note two facts: (i) The Flora region is quite complex to analyze because clustering analyses (Zappalà *et al.* 1995) identify several groups, and (ii) the number of members of the Flora clan with observed spectra is still very small. Our current understanding suggests that Asteroids 809 Lundia and 4278 Harvey are genetically linked to 4 Vesta. Notwithstanding, we cannot rule out the hypothesis that a differentiated body, other than Vesta, existed in this region and was catastrophically disrupted.

The other important property we stress concerns the spectral distribution of the V-type asteroids analyzed in this paper. We can see in Fig. 3 that all the V-type asteroids in the Vesta region—including 809 Lundia, 956 Elisa, and 4278 Harvey—show a 1-μm band deeper than most of the Vestoids and 4 Vesta itself. This suggests the possible coexistence of two distinct mineralogical groups among the V-type asteroids, either probing different layers of 4 Vesta or coming from different bodies. Subtle spectral differences among 4 Vesta, its neighboring V-type asteroids, and the HED meteorites have already been detected by Vilas *et al.* (2000) and Hiroi *et al.* (2001), leading to the hypothesis of different rocky groups.

If all the V-type asteroids actually come from 4 Vesta, then the two apparently different groups might be explained by a scenario where two large impacts on 4 Vesta excavated layers of different materials (Marzari *et al.* 1996). The distinct groups might also be explained by a single energetic impact, which ejected fragments from the inner layers of Vesta's crust. It is worth recalling that the crust of the HED's parent body is associated with two different mineralogies: (i) a diogenite lower crust and (ii) a eucrite upper crust (Takeda 1997). Hydrocode models simulating the fragmentation of 4 Vesta (Asphaug 1997) indicate that material from both the crust and the mantle may actually be ejected. A very interesting result of these simulations is that the most plentiful fast fragments (with diameters larger than 1 km) are extracted from the crust, while the fastest fragments come from beneath the surface. Surprisingly, the largest escaping fragment (15 km in diameter) is extracted from the mantle. A recent study (Kelly *et al.* 2001) confirmed that at least one Vestoid, 1929 Kollaa, has compositional characteristics compatible with cumulate eucrite, which suggests that it has been formed deep inside the eucritic crust of Vesta.

Assuming that the V-type asteroids are genetically linked to 4 Vesta we are faced with another problem: How did they arrive to their presently observed locations? We may think that either the cratering impacts on 4 Vesta generated ejection velocities much larger than the values presently suggested (Binzel *et al.* 1999), putting the fragments directly where we observe them now, or the fragments were driven to their present locations by some dynamical transport mechanism.

According to Binzel *et al.* (1999) the orbital distribution of the Vestoids known by that time (rather spread out in semimajor axes but limited in eccentricities and inclinations) could be reproduced assuming that they originated from an impact on 4 Vesta, with random ejection velocities. The maximum ejection velocities required to reproduce such an orbital distribution would be about 1 km/s. However, higher ejection velocities would be necessary to put the newly discovered V-type asteroids in their present location. This would be also the case of other recently discovered asteroids, like 2763 Jeans, which has an eccentricity of 0.18, much larger than the 0.1 average eccentricity of the Vestoids. It is worth noting that hydrocode simulations do not predict such large ejection velocities. Actually, simulations by Asphaug (1997) provided a maximum ejection velocity of only 0.6 km/s.

What about the presence of some transport mechanism able to drive objects of several kilometers in diameter from the Vesta neighborhood to their present, far away locations? The dynamical analysis of the main belt performed by Milani and Knezevic (1994) indicated the presence of a subtle secular resonance which "cuts" the Vesta family. This secular resonance may be responsible for driving objects from the Vesta region to higher eccentricity regions (e.g., Flora region). A detailed dynamical analysis of the region around 4 Vesta is especially urged and will be the subject of a forthcoming paper.

On the other hand, if the V-type asteroids in the Vesta region resulted from the catastrophic disruption of a large body other than 4 Vesta, then we have to find the "other" pieces of such an event. A better mineralogical characterization of the Flora clan asteroids is necessary, together with a detailed analysis of the kind of fragmentation that may have occurred. It is worth stressing that we already have two pieces of evidence about the possible fragmentation of another basaltic asteroid in the asteroid belt: (i) Asteroid 1459 Magnya (Lazzaro *et al.* 2000) and (ii) the meteorite Northwest Africa 011 (Yamaguchi *et al.* 2001). The first one is a basaltic asteroid of nearly 30 km in diameter, located in the outer main belt (3.14 AU), for which the link to 4 Vesta is highly improbable (Michtchenko *et al.* 2002). The second one, in spite of its having a texture and mineralogy similar to some basaltic eucrites, shows a ^{16}O-rich isotopic composition, which suggests that this meteorite is genetically unrelated to the other HED meteorites.

Finally, we stress that the three asteroids analyzed in this paper have been observed in the visible wavelength, but only observations in the near-infrared wavelength will allow a precise mineralogical characterization and may put stronger constraints on their origin.

In summary, we list the main characteristics of the newly discovered V-type asteroids:

1. They are the lowest numbered V-type asteroids yet discovered.
2. They are among the largest V-type asteroids yet discovered.
3. They are among the objects furthest away from Vesta yet discovered.
4. They are embedded in the Flora clan.
5. They have a surface composition more similar to that of other V-type asteroids than to that of the Vestoids.

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