Veritas Asteroid Family: Remarkable Spectral Differences Inside a Primitive Parent Body [1]

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Abstract

In this paper we report first optical reflectance spectra in the wavelength range 3800–9000 Å for seven members of the Veritas asteroid family, as determined by Zappalà *et al.* (1994, *Astron. J.*, **116**, 291–314). The observed asteroids are 490 *Veritas*, 844 *Leontina*, 1086 *Nata*, 2428 *Kamenyar*, 2934 *Aristophanes*, 5592 *Oshima*, and *1985* TQ_1. In addition, we observed also the object 5107 *1987* DS_6, which joins the Veritas family when a slightly more relaxed criterion of selection is adopted. The obtained spectra show a surprising slope gradient spanning from 0 to about 8%, a range which includes the slopes characteristics of all the low albedo, primitive bodies (from C to D–type). Taking into account the very compact structure of the family – the probability of finding interlopers inside the defined clustering is practically zero –, this result seems to confirm the suggestion by Vilas and Sykes (1996, *Icarus*, in press) about the presence of thermally altered large asteroids inside the outer belt population. However, the hypothesis of possible space weathering processes cannot completely ruled out. A tentative representation of the post–impact velocity field has been also obtained, showing a possible peculiar ejection of the fragments.

1 Introduction

The evolution of the Solar System has been greatly dominated by high-energy collisional impacts, leading to complete fragmentation of minor bodies as well as to the cratering of the surface of the largest planets. However, while the importance of catastrophic fragmentations is widely accepted, knowledge of the physical mechanisms following an impact is still an open problem. Laboratory experiments play an important role in defining the main parameters involved in the process, but their exact quantification is very difficult to obtain: this is mostly due to the unsolved "scaling" problem (Fujiwara *et al.* 1989). In fact, it is not obvious how to extrapolate the results obtained on targets of few tens of centimeters to objects of some hundreds of kilometers in size. On the other hand, in the Solar System there exists a quite large sample of fragments produced in high–velocity catastrophic impacts, in principle able to clarify most of the unsolved problems related to the fragmentation mechanisms. They are the so–called "asteroid families", clusterings of some tens to hundreds of minor planets having quite similar orbital elements. They represent the outcomes of mutual collisions among asteroids, which involved objects whose sizes ranged from few tens to hundreds of kilometers. Even though known from the beginning of this century, asteroid families have not yet been conveniently studied from a detailed physical point of view, due the low reliability of past procedures and techniques used to define them. Recently some new and objective statistical identification methods have been applied to a much larger sample of data (to date about 12,500 asteroids), together with the simultaneous improvements of the computation techniques of asteroid proper elements (Knežević and Milani 1994, and references therein). The final result is the identification of a group of families (about 30) with a very high statistical reliability, whose memberships appear stable versus the method used for family identification (Zappalà *et al.* 1995). Therefore, it is possible now to start systematically quantitative investigations of the main physical and chemical characteristics of these groupings, which represent the best example of the outcomes of catastrophic fragmentations still observable in the solar system. The main analyses include mass and velocity distributions, mineralogical surface compositions of the members, dependence of the various parameters from the size of the target and from the impact energy, etc..

Visible and near–infrared (up to wavelengths of about 3 μm) reflectance

spectroscopy is the most fruitful remote sensing technique for characterizing many cosmically important mineral phases, and has been used extensively to determine the likely surface compositions of the largest asteroids (Gaffey *et al.* 1989). Thus, by comparing the optical properties and the inferred surface compositions of several members of the same family, one can aim at "reconstructing" the parent body like a 3–D jigsaw puzzle – thus finding out whether it was made of primitive, unheated material or it was melted and differentiated, and in the latter case trying to obtain constraints on its internal layering, and the compositions of its core/mantle/crust. Moreover, spectroscopic data in turn would allow us to discriminate in many cases between the "real" members and the chance interlopers, which can affect the reconstruction of the velocity field (Migliorini *et al.* 1995, Zappalà *et al.* 1996).
In this paper we present the results obtained from visible spectroscopic observations of seven Veritas family members (plus one "captured" by the family at 20 m/sec up the Quasi-Random-Level as defined by Zappalà *et al.* 1995), and we have outlined a possible representation of the post–impact velocity field, showing a possible peculiar ejection of the fragments.

2 The Veritas Family

Veritas family is located in the outer part of the main belt with an average proper semimajor axis of about 3.17 AU. Veritas membership, from a statistical point of view, has a very high level of reliability, it is well defined and very compact in the proper elements space (Zappalà *et al.* 1994, 1995); We recall that some members of the present family were already enclosed in family 106 as defined by Williams (1979). Figure 1 shows the family membership in the planes $a' - e'$, $a' - sin\ i'$, and $e' - sin\ i'$, where the size of the different circles is proportional to the diameter of the corresponding objects and the black dots refer to objects observed in this survey. The available data for Veritas family members are summarized in Table 1, which lists, from column 1 to 8, the asteroid number, the proper semimajor axis, eccentricity and sine of the inclination (Milani and Knežević 1994), the IRAS albedo, and, as computed taking into account different sources of error in the absolute magnitude, the diameter and the relative 2σ error. For the asteroids not observed by IRAS

the diameters have been estimated by assuming an albedo of 0.069, which is the average value of the IRAS observed objects.
As shown in Table 1, the Veritas family, determined by Zappalà *et al.* (1995), is composed of 22 objects; ten of them are numbered and only three have a diameter larger than the completeness limit, i.e. the diameter beyond which all the existing bodies are likely to have been already discovered. This limit has been estimated by Zappalà and Cellino (1994) to be 27.5 km. According to Migliorini *et al.* (1995) it's very unlikely that any of the family members can be chance interlopers, in fact in the diameter range $0 - 28$ km, applying Poisson statistical analysis, the probability that no interlopers exist is 73%. In the 28–75 km range we expect no interlopers with a probability of 92%. In the last range, *i. e.* 75–130 km, no background objects are available near the family proper element space for a correct estimation of interlopers.
Until now, only few physical data about the Veritas family members have been available. Besides the IRAS albedos of some objects, we know that 490 Veritas belongs to the C taxonomic class (Tholen 1989), but no other objects have been yet classified. For 490 Veritas a 24-colors spectrum is also available (Chapman and Gaffey 1979).
Recently Milani and Farinella (1994) have analysed the stability of the orbits of the Veritas family members, integrating them back for 72 million years, and conclude that $\approx 5 \times 10^7$ years after the birth of the family, the proper elements of two objects become widely dispersed. 490 Veritas' orbit has been proved to be very chaotic as well as that of 3542 on timescales of 50 million years. Therefore they concluded that this timescale would be comparable with the age of the family, making it very probably one of the youngest in the belt. The other family members are sometimes slightly chaotic, but they remain well inside the borders of the family. Due to the practically void area around the family, the above considerations do not affect the reliability and compactness of the clustering.

3 Observations and Data Reduction

The observations have been carried out from April 1994 to November 1995 in three different sites: European Southern Observatory (ESO, La Silla, Chile) by the 1.52–m telescope, Bologna Observatory (Loiano observing station, Italy) by the 1.5–m telescope and Padova–Asiago Observatory (Cima Ekar observing station, Italy) by the 1.82–m telescope. The circumstances of the observations and the aspect data of the observed asteroids are listed in Table 2 and Table 3, respectively.

The ESO telescope was equipped with a Boller & Chivens spectrograph and as detector a CCD 2048×2048 (windowed at about 300×2048). The CCD has a 15 μm square pixel, yielding a dispersion of 4.9 Å/pixel in the wavelength direction. The grating used was a 225 grooves/mm with a dispersion of 330 Å/mm in the first order. The useful spectral range is from about 5000 Å to 9000 Å with an instrumental FWHM of 9.8 Å. At the Bologna Observatory the *Bologna Faint Spectrograph and Camera* (BFOSC) has been used. It is equipped with a 1024×1024 Thomson coated CCD with a pixel dimension of 19 μm, yielding a dispersion of 4.2 Å/pixel in the wavelength direction. The spectral range is from about 5200 Å to 9000 Å, with an instrumental FWHM of 8.4 Å. At Padova–Asiago Observatory we have used a Boller & Chivens spectrograph and as detector a CCD Thomson TH7882 thick UV–coated 580×388 pixels, each of them with dimensions of $23\mu\text{m} \times 23\mu\text{m}$, giving a dispersion of about 7.8 Å/pixel . The grating had 150 grooves/mm with a dispersion of 339 Å/mm in the first order. In order to prevent the second order contamination, a yellow filter was used ($\lambda_T(\text{Å}) > 6200$ Å) to perform the observations at ESO and Padova–Asiago observatories. The 490 Veritas spectrum has been obtained in a different wavelength range, namely from 3800 Å to 7500 Å. Observations of solar–analog stars (Hardorp 1978), as simultaneously as possible with those of asteroids, have been made in order to calibrate the asteroid relative reflectance spectra (when possible we used 16 Cyg B and 64 Hyades) and of spectrophotometric standard stars to monitor changes in atmospheric extinction. Wavelength calibration was performed by using He–Ar or Fe–Ar lamp spectra.

Data reduction has been performed by using *IRAF* package following the standard procedure, as described in Di Martino *et al.* (1995), which includes subtraction of bias level, flattening of data, removal of the cosmic rays, subtraction of sky, wavelength calibration, collapsing the two–dimensional spectra, extinction correction, and division of the asteroid spectrum by the solar analogs spectra.

The spectra obtained are shown in Fig. 2, in which to the spectrum of 490 Veritas the 24–colors spectrum, taken from Chapman and Gaffey (1979), has been overlapped.

4 Spectroscopic Results

Considering that the Veritas family is one of the more compact and statistically reliable grouping of asteroids, a surprising result of this study consists in the wide range of slopes (from 0 to about 8%, the values typical of C–type to D–type) shown by the spectra of the observed objects. We really expected a more similar slope for each member considering the primitive taxonomic type of the largest remnant as well as of the region where the clustering is located. To check this finding, we have compared in Fig. 3 the spectra of the family members with the available 8–colors spectra (Zellner *et al.* 1985) of background asteroids having sizes comparable with that of the Veritas parent body (i.e., larger than about 100 km) and semimajor axes included between 3.1 to 3.3 AU. We considered only asteroids belonging to low albedo taxonomic classes (in accord with the taxonomic type of 490 Veritas), excluding the objects belonging to other families located in the same region (Themis, Hygiea, and Meliboea). The result is very intriguing: Veritas members show a much greater slope range with respect to that shown by the background asteroids. Trying to add some more information to this problem, in Fig. 3 we have plotted also the 8-colors spectra of background objects having sizes smaller than 100 km. They should represent more likely fragments of relatively recent impacts. Indeed, they show a dispersion of spectral slopes more similar to that shown by the Veritas family members. An inspection of SMASS survey spectra performed by Xu *et al.* (1995) confirms these results. Therefore, we can outline a general scenario for the whole outer region of the main belt, which takes into account the previous observational evidences: the large majority of the "old" large asteroids seem to show a surface composition which fit quite well a spectrum typical of C–type (very probably this was also the case of the Veritas parent body). Then, more or less catastrophic impacts produce fragments, which are smaller, "younger" (their age depends obviously on the age of the break-up event) and come – for the most – from the interior of their parent bodies. There is an evidence that these younger, smaller, and "core" fragments show a wide variety of spectral slopes, ranging from C– to D–types.

In order to explain this scenario, we hazard two possible hypotheses: i) as in

the case of S-type asteroids, in which supposed space weathering processes have been confirmed by Gaspra and Ida observations by the Galileo spacecraft (Chapman 1996), also in the case of low albedo, carbonaceous objects similar processes could be effective, as some preliminary laboratory studies seem to show (Korochantsev *et al.* 1996, Moroz *et al.* 1992). In this view, "core" fragments, which have been originated in different break–ups, can show a different spectral slope depending on the age of the event. However, we have to take into account that some small fragments can also come from the parent body surface and therefore they could partly show the original weathering suffered by the parent body itself. ii) the original parent bodies have been already altered in their interior by extended thermal episodes (Vilas and Sykes 1996, and reference therein). In this case, the role of the impact has been only that of exposing pieces coming from different regions inside the target, which suffered different degrees of thermal metamorphism leading to different spectrum signatures.
The first hypothesis can be applied to non–altered parent bodies, the different spectral signatures of the fragments being only due to their corresponding exposure age. The second one can be applied to altered parent bodies without any weathering processes affecting the fragment surfaces. Obviously, the two mechanisms can work together.
The Veritas case, which very probably refers to a single episode, implying the same exposure age for all the fragments, seems to fit better the second hypothesis and it is in good agreement with the conclusions by Vilas and Sykes (1996), who suggest that fragments coming from the interior of a large parent body should exhibit a greater range of compositional diversity than the large asteroids. However, as already pointed out, the first one cannot be completely ruled out, since one can assume that some pieces come from the parent body surface and therefore can partly have an older exposure age with respect to that of the "core" fragments. Among the 8 observed objects, 3 of them, namely 1086 Nata, 2934 Aristophanes, and 1985 TQ1, appear to have a practically flat spectrum, i.e. a trend very typical of C-type asteroids. Vilas et al. (1993,1994) have shown that objects belonging to this class present a shallow and wide absorption band centered around 7000 Å, which is attribuited to an $Fe^{2+} \rightarrow Fe^{3+}$ charge transfer transition in oxidized iron in phyllosilicates. Vilas and Sykes (1996) discussed deeply the presence of this feature in terms of primordial heating events. In particular, they concluded that at a given heliocentric distance the fraction of C–asteroids that

possess this feature should decrease with decreasing size. This absorption band is well recognizable in the spectrum of 1086 Nata, while is less evident in the spectrum of 1985 TQ_1. The same band could be also present in the spectrum of 2934 Aristophanes, but the spectrum it is too noisy to reveal a feature as weak as that present in the 1086 Nata spectrum. Figure 4 shows these spectra, where for evidencing the feature the method described by Vilas et al. (1993) has been applied. These results are not in conflict with the conclusion of Vilas and Sykes (1996) quoted before, if we consider the C–type fragments of the family as survivor pieces of the surface of the original larger parent body. However, it remains hard to explain why the largest remnant of the family (490 Veritas) does not present the same feature. May be that the catastrophic disruption which originated the family has been "core–type" (Fujiwara *et al.* 1989), i.e. a shattering process in which the outer layers of the target are spalled off leaving a large central core, followed by a considerable reaccumulation. Anyway, to confirm this hypothesis, it could be very interesting to perform spectroscopic observations of 490 Veritas at different rotational phases, in order to check the possibility of a compositional diversity in its surface. More in general, we have to say that future spectroscopic observations under 5000 Åand in the IR spectral domain, as well as laboratory experiments on space weathering processes on primitive materials, are highly reccommended for drawing more definitive conclusions on a topic which appears of the highest importance for the understanding of the thermal history and the collisional evolution of the asteroidal population as a whole.

5 A Possible Collisional Model

In order to understand what kind of catastrophic event could have formed the Veritas family, we try to reconstruct the original velocity field of the family applying the method described in Zappalà *et al.* (1996). Unfortunately, a major problem prevents us from drawing any definitive conclusion. In fact, due to the chaotic motion of 490 Veritas itself (containing more than 80 percent of the total mass) as described by Milani and Farinella (1994), the position of the barycenter of the family (i.e., the origin of the velocity field) cannot be determined. It follows that no really quantitative conclusion about the relative velocities of the fragments can obviously be obtained. However, some information about the qualitative behaviour of the overall velocity field can still be extracted by the present data. Let us assume that the position of 490 Veritas is the real one, not affected by any kind of chaotic motion. It means that the barycenter of the family turns out to be very close to the position of Veritas itself. Under this assumption we apply the method by Zappalà *et al.* (1996) and we obtain (with some very large uncertainty on the computed angles due to the peculiar structure of the velocity field) that the true anomaly f and the argument of perihelion $w + f$ at the moment of breakup should be about 70 deg and 45 deg respectively. Identifying the direction of the projectile (i.e., the direction of the impact) with the axis of symmetry of the overall velocity field [see Zappalà *et al.* (1996) for a more detailed discussion of the procedure to adopt], we obtain the representation of the velocity field reported in Fig. 5. Apart from quantitative conclusions (unrealistic due to the inescapable uncertainty connected with the barycenter, as stated before), an interesting result appears: the velocity field is well represented by a kind of "jet–like" structure lying in the plane $v_{imp} - v_{norm1}$. This behaviour is not affected by changing the angles f and $w + f$ by some 20-30 deg as well as by changing the barycenter of the family. In the latter case what we can obtain is to alter the shape of the "jet", but we cannot avoid the fact that almost all the fragments are located in a well defined plane. It is very interesting to note that this kind of planar ejecta (even if not very common) has been obtained in some laboratory simulation of hypervelocity impacts (Martelli *et al.* 1993). Finally, we have to note that the second largest object of the family (844 Leontina) seems to be not connected with the rest of the fragments. However, its "isolated" position could be due to the chaotic motion of Veritas and consequently to the adopted barycenter of the family.

6 Conclusion

We have performed spectroscopic observations in the visual band of 8 members of the Veritas family and the result we obtained is quite unexpected. In fact, considering that this family is one of the more compact and statistically reliable grouping of asteroids, the slope of the spectra we obtained shows a slope gradient ranging from 0 to 8% within which the slope characteristics of the major low albedo asteroid types (C, P and D–types) are included.

The family slope range shows a larger gradient when it is compared with the available 8–colors spectra of background asteroids larger than 100 km. On the contrary, the slope range of background asteroids smaller than 100 km, which at least in part are fragments of catastrophic fragmentations, is quite similar to the family one. These observational evidences allow us to outline the following two alternative hypotheses, which can be applied to the whole population of the outer main belt asteroids:

- the parent bodies had an already altered interior, due to local or extended thermal episodes, and its fragmentation exposed pieces of different composition. This hypothesis fits well the case of Veritas' family.
- low albedo asteroids can be affected, as S–type objects, by some kind of "space weathering", so spectral differences among smaller, collisionally generated asteroids could be related to the different age of the catastrophic impact that originated the fragments.

Three of the observed asteroids (1086 Nata, 2934 Aristophanes, and 1985 TQ_1) show flat spectra characteristic of the C–type taxonomic type objects. At least two of them (1086 Nata and 1985 TQ_1) show a shallow and wide absorption band centered around 7000 Å, which is attributed to the presence of aqueous alteration products on the asteroid surface. These results can anyway agree with the conclusions drawn by Vilas and Sykes (1996), if we consider that these objects are fragments coming from the parent body surface. These evidences and the fact that the spectrum of the largest remnant of the family do not present the same feature suggest the hypothesis that the catastrophic fragmentation that originated the family has been "core–type". More definitive issues can be drawn by further spectroscopic observations in the UV and IR domains and by laboratory studies on the space weathering of carbonaceous materials.

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Figure Captions

Figure 1. Veritas family asteroids in the proper element space. Filled circles show the observed objects (excluded 5107), whereas empty circles show not–observed members. The dimension of the circles is proportional to the asteroid diameter.

Figure 2. Spectra of the observed asteroids (normalized at 7000 Å). To the spectrum of 490 Veritas the 24–colors spectrum, taken from Chapman and Gaffey (1979), has been overlapped.

Figure 3. (Top) Spectra of background asteroids having sizes larger than 100 km and semimajor axis included between 3.1 and 3.3 AU. (Center) Spectra of Veritas family members. (Bottom) Spectra of background asteroids having sizes smaller than 100 km and semimajor axis included between 3.1 and 3.3 AU. The objects belonging to other families located in the Veritas region (Themis, Hygiea, and Meliboea) have been excluded from background population.

Figure 4. Residual spectra of asteroids 1086 Nata, 2934 Aristophanes, and 1985 TQ_1 created as a result of the smoothing with a five–point running box average of the original ones and divided by the linear backgrounds with overlapped the continuum in order to evidence the absorption band centered around 7000 Å.

Figure 5. Velocity field of the Veritas family as computed by using the method developed by Zappalà *et al.* (1996).

Table 1: Membership, proper elements, absolute magnitude (H), albedo (p_v), and diameter of the Zappalà Veritas family member asteroids.

Number	a'	e'	sin i'	p_v	D(km)	$2\sigma_D$
490	3.17504	0.0646	0.1576	0.0622	115.53	12.24
844	3.19689	0.0687	0.1605	—	60.79	26.18
1086	3.16589	0.0603	0.1616	0.0767	60.42	25.65
2147	3.17137	0.0632	0.1607	0.0439	26.45	11.04
2428	3.17068	0.0620	0.1617	0.0864	26.02	10.81
2934	3.16743	0.0597	0.1596	0.0780	24.98	10.49
3090	3.16983	0.0618	0.1604	—	17.53	7.55
3542	3.17484	0.0638	0.1609	—	19.22	8.28
5107	3.13628	0.0724	0.1559	—	18.31	7.62
5592	3.16905	0.0589	0.1630	—	24.20	10.42
5594	3.16880	0.0575	0.1617	—	22.07	9.50
1976 QL_2	3.17075	0.0626	0.1626	—	15.99	6.89
1981 ES_9	3.16529	0.0595	0.1626	—	7.31	3.15
1985 TQ_1	3.16652	0.0616	0.1604	—	21.08	2.61
1981 EE_4	3.17507	0.0573	0.1617	—	6.64	2.88
1981 EM_{10}	3.17225	0.0602	0.1631	—	10.47	1.29
1981 ER_{34}	3.16584	0.0582	0.1592	—	6.54	0.81
1991 PW_9	3.16492	0.0612	0.1615	—	11.58	4.99
2123 PL	3.17613	0.0672	0.1611	—	7.62	0.94
4573 PL	3.17328	0.0688	0.1622	—	8.38	0.98
4107 T_1	3.16442	0.0604	0.1617	—	13.12	1.62
1118 T_3	3.17811	0.0681	0.1616	—	5.81	2.50
1122 T_3	3.18297	0.0527	0.1603	—	7.65	3.30

Table 2: Circumstances of the observations.

Object	Place	Date	UT [Start]	T_{exp}	Airmass
490	Ekar	11–04–95	19h 10m	32 min.	1.44
844	ESO	17–04–94	06h 21m	40 min.	1.00
1086	ESO	18–04–94	09h 18m	50 min.	1.28
2428	Ekar	27–10–94	01h 00m	32 min.	1.67
2934	Loiano	30–10–94	19h 36m	45 min.	1.48
5107	ESO	09–11–95	00h 15m	120 min.	1.07
5592	ESO	18–04–94	06h 21m	40 min.	1.12
1985 TQ_1	ESO	18–04–94	02h 23m	60 min.	1.20

Table 3: Aspect data of the observed asteroids at 0^h UT of the observation day.

Object	R.A.	Decl.	Long.	Lat.	r	Δ	Phase	V
	[2000]		[2000]		[AU]	[AU]	[deg]	[mag]
(490) Veritas	$07^h\ 55^m.9$	$+13^\circ\ 44'.3$	$117^\circ.5$	$-6^\circ.9$	3.28	3.00	$17^\circ.6$	14.2
(844) Leontina	$15^h\ 09^m.3$	$-28^\circ\ 19'.4$	$231^\circ.9$	$-10^\circ.2$	3.24	2.32	$8^\circ.26$	14.4
(1086) Nata	$20^h\ 54^m.4$	$-20^\circ\ 24'.1$	$309^\circ.6$	$-2^\circ.8$	3.33	3.40	$17^\circ.11$	15.5
(2428) Kamenyar	$01^h\ 01^m.0$	$+10^\circ\ 17'.7$	$17^\circ.2$	$+3^\circ.5$	2.91	1.94	$5^\circ.33$	15.2
(2934) Aristophanes	$00^h\ 46^m.7$	$+05^\circ\ 42'.4$	$12^\circ.2$	$+0^\circ.6$	3.20	2.26	$7^\circ.10$	16.0
(5107) 1987 DS_6	$22^h\ 12^m.1$	$-09^\circ\ 12'.6$	$330^\circ.9$	$+1^\circ.7$	3.19	2.77	$17^\circ.43$	17.6
(5592) Oshima	$19^h\ 11^m.7$	$-16^\circ\ 45'.5$	$286^\circ.5$	$+5^\circ.6$	3.03	2.68	$18^\circ.98$	16.9
1985 TQ_1	$11^h\ 58^m.2$	$+3^\circ\ 53'.9$	$177^\circ.3$	$+3^\circ.3$	3.39	2.48	$8^\circ.51$	17.1