

Spectroscopic investigation of near-Earth objects at Telescopio Nazionale Galileo

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ABSTRACT

In this paper we present new results obtained from our spectroscopic survey of near-Earth objects (called SINEO). We show a set of 36 visible and near-infrared spectra, recorded with the 3.5-m Italian Telescopio Nazionale Galileo at La Palma (Canary Island). We discuss their taxonomic classification (resulting in 25 objects belonging to the S-complex, five to the C-complex and six to the X-complex), and their overall compositional linkage with the principal source of near-Earth objects, namely the Main Belt. Moreover, for some near-Earth objects we found good spectral fit among meteorites. In particular, we achieved an excellent fit for chondrites of different clans. Finally, we discuss the influences of space weathering among small S-type near-Earth objects.

Key words: minor planets, asteroids.

1 INTRODUCTION

The near-Earth object (NEO) population comprises asteroids and extinct comet nuclei in orbits with perihelion distances $q < 1.3$, which periodically approach or intersect the orbit of the Earth. Given their vicinity to the Earth, NEOs are believed to be a source for most meteorites which arrive on Earth.

Despite the first NEO being observed more than a century ago, only in the last three decades have significant steps in understanding their origins been achieved. It is now clear that NEOs are removed from the inner Solar system either by collision with the Sun or terrestrial planets or by gravitational interactions mainly with Jupiter. Because this removal time is short compared with the age of the Solar system, and the NEO population is essentially stationary in number, they must be continually resupplied. Even if it is accepted that most NEOs come from the Main Belt (MB) and only a small fraction are dead or dormant comets (see Harris & Bailey 1998; Weissman, Bottke & Levison 2002), their proportions are not well defined yet. A detailed comprehension of the sources and mechanisms of the resupply of the NEO population is one of the principal aims of NEO investigations. Although a global picture of the origin of NEOs is now widely accepted, a detailed knowledge of their physical properties has been obtained only for few bodies, i.e. less than 10 per cent. From the available data, the NEO population is very heterogeneous in all aspects of their physical properties: very different rotation periods and complex rotation states, different shapes

(some very elongated), some binary systems, etc. Moreover, almost all taxonomic classes identified among MB asteroids have been also found among NEOs, including the C, P and D classes that are typical of outer MB asteroids. Although C-type asteroids dominate the MB, this is not the dominant class among NEOs even after bias corrections (Stuart & Binzel 2004). NEOs in fact are dominated by S-types. This could indicate that asteroidal NEOs are contributed mostly by the inner MB, via the ν_6 resonance, where S-types are the most common asteroids. The other principal source of NEOs, i.e. the 3 : 1 resonance (see, for example, Morbidelli et al. 2002), is surrounded by C- and S-type asteroids in almost equal quantity. Other peculiar findings among NEOs, such as for example numerous V-type possible fragments from Vesta (see, for example, Marchi et al. 2005), give further constraints on the relationship between MB asteroids and NEOs.

As stated before, another possible source of NEOs is represented by dead or dormant comets, i.e. devolatilized comets and/or comets whose surfaces still have icy materials but are covered by a subtle non-volatile crust. Owing to this crust, no cometary emission would be detected from these bodies and they would show a spectral behaviour typical of cometary nuclei (featureless and flat to reddish spectrum).

Finally, understanding the sources of NEOs means also to understand the origin locations for most meteorites, because NEOs are considered a link between meteorites and their parent bodies.

Almost all the issues outlined above (mineralogy, taxonomic classification, origin, relations with comets, MB asteroids and meteorites) can be studied by performing spectroscopic investigation of NEOs. In this paper we present the analysis of 36 spectra obtained with the Telescopio Nazionale Galileo of La Palma. This work is

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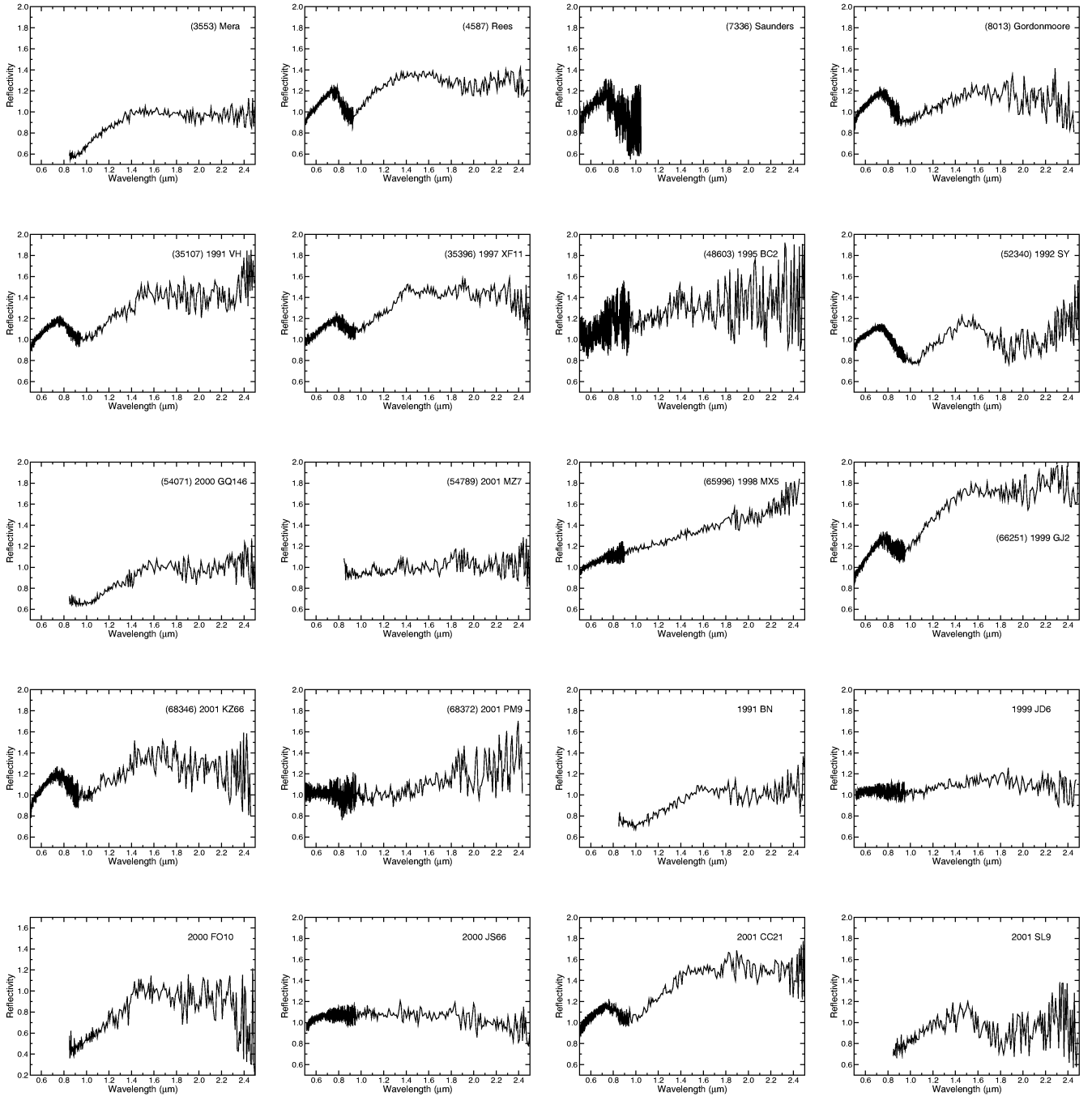


Figure 1. NEOs observed.

the continuation of a programme we started some years ago and performed also with the European Southern Observatory (ESO) New Technology Telescope (NTT) of La Silla (Chile). For details on the first results, see Lazzarin et al. (2004), Marchi et al. (2005) and Marchi, Lazzarin & Magrin (2004).

2 OBSERVATIONS AND DATA REDUCTION

The spectra presented here have been recorded with the Telescopio Nazionale Galileo (TNG) at La Palma in the course of three runs performed in 2002 December, 2003 July and 2004 May for a total of nine nights, four in the visible and five in the near-infrared (NIR;

see Fig. 1). In the visible, we used the Low-Resolution Spectrograph (LRS) with the LR-R grism, which provides a resolving power of about 300, in the 0.5–0.95 μm range. We used a slit aperture of 5 arcsec in order to minimize effects due to atmosphere differential refraction. For the same reason, for the solar analogues the slit was then oriented along the parallactic angle. For the NEOs, as they are very fast moving objects, we preferred to orient it along the direction of their motion in order to reduce the possibility of losing the objects while tracking.

In the NIR, we used the Near-Infrared Camera Spectrometer (NICS) equipped with the AMICI prism, which provides a resolving power of about 50 almost constant through out the range

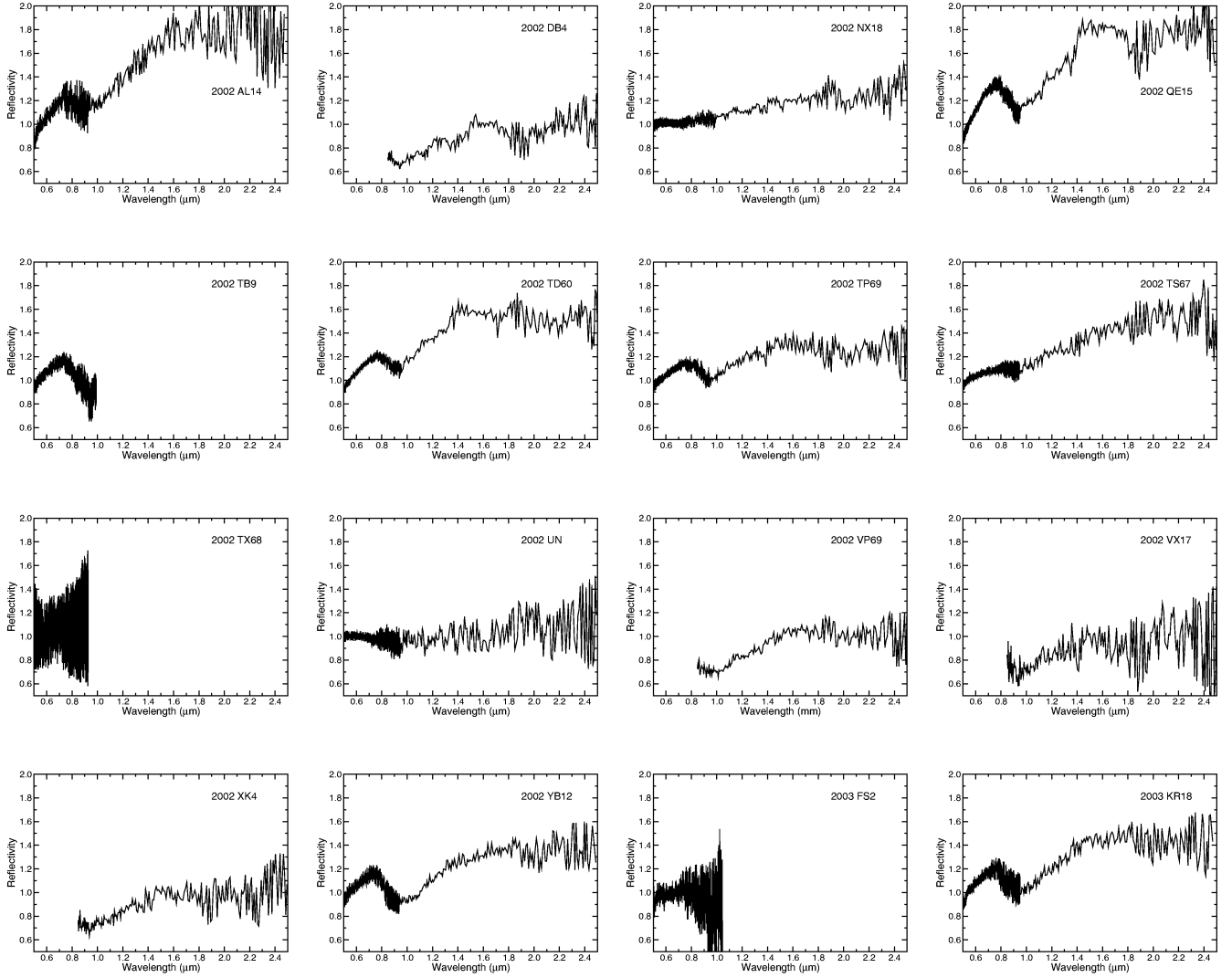


Figure 1 – continued

0.8–2.5 μm . In the NIR we used a 2-arcsec slit width, with the same method described for the visible. For both visible and NIR, to minimize the possibility of losing objects, we decided to check the position of each moving target on the slit every 15–20 min, depending on the velocity of the asteroid. Longer exposures, needed on fainter objects, have been split into shorter exposures, repeated as many times as needed to reach the required signal-to-noise (S/N) ratio.

The reduction was carried out with the usual reduction techniques, and for details we refer, for instance, to Lazzarin et al. (2004) and Licandro, Ghinassi & Testi (2002a). To obtain the relative reflectance, several Landolt G stars (Landolt 1973) and Hyades 64 were observed during the nights at different airmasses (see Table 1). All these stars showed negligible differences. They were also observed in previous runs together with the solar analogue star P330E (Colina & Bohlin 1997) and they present similar spectra in the IR region, so we used them as solar analogues for both visible and NIR.

3 TAXONOMIC CLASSIFICATION

The taxonomic classification of the observed NEOs has been obtained by performing a best fit between our data and the mean spec-

tra of each spectral class proposed by Bus (1999) on the second phase Small MB Asteroid Spectroscopic Survey (SMASSII) data. Because Bus taxonomy was restricted to visible data, we applied this analysis only to NEOs for which visible measurements were available. We looked for a best fit between each of our spectra (the range considered was 0.52–0.92 μm) and each of the Bus mean types restricted to the same range. Finally we simply chose the best solution as the ‘right’ taxonomic class.

Afterwards, we applied the principal component analysis (PCA) technique to the data, in a modified version of that proposed by Bus (1999). In the original technique, each spectrum is simplified by interpolating it with a cubic spline in the range 0.44–0.92 μm with a step of 0.01 μm (49 channels). We proved that, by taking a shorter spectral interval, compatible with our visible range, the lack of information due to a lesser number of points in a spectrum did not affect the statistical result of the analysis. Moreover, the mean types are still located in different zones on the (slope, PC2’) plot. Fig. 2 shows a plot of these two components, in the 0.52–0.92 μm range, computed on a set that includes all the SMASSII MB data, all TNG NEOs visible spectra published in this paper, and all the ESO-NTT NEOs visible spectra in Lazzarin et al. (2004). In the plot we also show the position of the Bus mean types. It is clear that

Table 1. NEOs observed with the TNG. For each asteroid, the orbit type, inferred taxonomy, absolute magnitude, spectral range (v = visible, n = NIR), meteorite analogue, and solar analogue are reported. In column 2, AM denotes amor, AP denotes apollo and AT denotes aten. In column 3, the NEO spectra for which only the NIR was available have been classified by visual checking and divided only in terms of complexes (S, C, X), as a detailed classification cannot be done. Among them, only 2001 SL9 has been classified Q-type in the light of its distinctive spectral features. In column 6, OC denotes ordinary chondrites, EC denotes enstatite chondrites, CC denotes carbonaceous chondrites, SW denotes possibly space weathered objects, and ‘–’ means no analogue was found (see text for further details).

NEO	Orbit	Tax	H	Spectral range	Meteorite analogue	Solar analogue
(3553) Mera	AM	S	16.49	n	OC	Land 112-1333
(4587) Rees	AM	Sr	14.98	v+n	SW	Land 112-1333
(7336) Saunders	AM	Sr	18.77	v	–	Land 115-271
(8013) Gordonmoore	AM	Sr	16.63	v+n	OC	Land 115-271
(35107) 1991 VH	AP	S	16.57	v+n	SW	Land 98-978
(35396) 1997 XF11	AP	K	16.76	v+n	SW	Land 98-978
(48603) 1995 BC2	AM	Xe	17.42	v+n	–	Land 115-271
(52340) 1992 SY	AM	Q	17.65	v+n	OC	Land 98-978
(54071) 2000 GQ146	AM	S	17.28	n	OC	Land 98-978
(54789) 2001 MZ7	AM	X-	14.67	n	EC	Land 98-978
(65996) 1998 MX5	AM	Xk	18.22	v+n	–	Land 115-271
(66251) 1999 GJ2	AM	Sa	16.82	v+n	SW	Land 112-1333
(68346) 2001 KZ66	AP	S	16.48	v+n	SW	Land 107-98
(68372) 2001 PM9	AP	B	18.71	v+n	CC	Land 112-1333
1991 BN	AP	S	18.99	n	AC	Hyades 64
1999 JD6	AT	Cg	16.99	v+n	CC	Land 107-98
2000 FO10	AT	S	17.30	v	–	Land 112-1333
2000 JS66	AP	Xc	18.64	v+n	CC	Land 107-98
2001 CC21	AP	Sk	18.39	v+n	SW	Land 98-978
2001 SL9	AP	Q	17.43	n	OC	Land 115-271
2002 AL14	AT	Sl	17.67	v+n	SW	Land 115-271
2002 DB4	AT	S	16.41	n	OC	Land 98-978
2002 NX18	AM	C	17.24	v+n	CC	Land 98-978
2002 QE15	AM	A	16.19	v+n	SW	Land 98-978
2002 TB9	AP	Sk	16.22	v	–	Land 107-98
2002 TD60	AM	S	19.24	v+n	SW	Hyades 64
2002 TP69	AM	Sk	21.63	v+n	SW	Hyades 64
2002 TS67	AM	Xe	18.71	v+n	–	Hyades 64
2002 TX68	AM	X	17.91	v+n	–	Land 112-1333
2002 UN	AM	B	17.12	v+n	CC	Land 115-271
2002 VP69	AP	S	17.79	n	AC	Land 115-271
2002 VX17	AM	S	21.76	n	OC	Land 98-978
2002 XK4	AP	S	15.53	n	OC	Land 98-978
2002 YB12	AP	Sq	18.34	v+n	SW	Land 115-271
2003 FS2	AM	Cg	18.78	v	–	Land 115-271
2003 KR18	AM	S	17.76	v+n	SW	Land 115-271

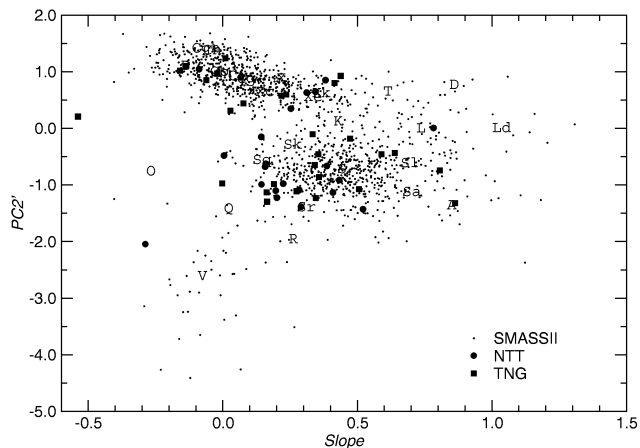


Figure 2. PCA of SMASSII and the newly observed NEOs. NEOs observed in previous runs are also shown (see Lazzarin et al. 2004).

we can still distinguish between the C- and X-complexes, and the S-complex. Moreover, all S subclasses are still well separated. As a result, we found an excellent compatibility between the taxonomic classification obtained by the best fit with the mean types and the location of the NEOs in the (slope, PC2') plane, as predicted by the PCA.

For some NEOs we did not have visible measurements, and for this reason they were excluded from the previous analysis. However, the ‘taxonomic’ information contained in a NIR spectra are so important that we attempted a rough classification by visual inspection. For this purpose, we restricted the analysis only to distinguish among the three (S, C, X) main complexes, as reported in Table 1. Some of the investigated NEOs were previously classified. We find small differences compared with our classification, and in general the complexes are the same. These differences could be due to surface inhomogeneities. In only one case, 1999 JD6, Binzel et al. (2004) suggested K-type while we found Cg-type.

3.1 Peculiar objects

Among the observed NEOs, 1991 VH, 2001 SL9, 1998 MX5, 2002 UN and 2002 QE15 present peculiar characteristics. The first two NEOs are likely binary asteroids (see Pravec, Wolf & Sarounova 1998; Pravec, Kusnirak & Warner 2001). Their companions have diameter ratios with the primary of 0.40 and 0.31, respectively.

1998 MX5 and 2002 UN have comet-like orbits. In fact, they have Tisserand invariants with Jupiter (T_J) of 2.95 and 2.81, respectively. We note 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- and X-types. The 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, Barucci & Doressoundiram 1996; De Sanctis et al. 2000; Licandro et al. 2002b, 2003). Licandro et al. (in preparation) also observed 17 asteroids in cometary orbits, and found that 15 of them present featureless, slightly red spectra; they failed to find any feature that could distinguish between them and MB primitive asteroids.

2002 QE15 has been classified as an A-type on the basis of its very red spectrum. This class has only two other members among NEOs (see Binzel et al. 2004; Lazzarin et al. 2004) detected so far. Few others have also been observed among the adjacent class of Mars-crossers (Binzel et al. 2004; de León et al. 2004). The existence of olivine-rich asteroids is of interest because olivine is an igneous mineral that proceeds from highly differentiated objects. Their existence indicates the occurrence of secondary events on asteroids, such as collisions, and their visibility requires the exposure of asteroid interiors.

4 LINKS WITH METEORITES

In this section we deal with the problem of finding possible meteorite analogues. This topic has been widely discussed in the literature (see, for example, Burbine et al. 2002a).

For this task, we have developed a code which is able to automatically perform a least-squares fit between our NEO spectra and the vast meteorite spectral data base available on RELAB (<http://www.planetary.brown.edu/relab/>). We used all the public spectra cataloged as ‘XT’ (i.e. extraterrestrial), for a total of 847 spectra. Some of them correspond to the same meteorite, but obtained in different conditions (different grain size, laser irradiation dose, different portion, etc.). For each NEO of which we had NIR measurements, we selected 20 meteorites in order of descending fit quality. We did not use any automatic cut-off for the quality of the fit because this can be sometimes misleading, as it strongly depends on the S/N ratio. The best fit was chosen through visual inspection, to avoid possible mistakes, especially in the case of too noisy NEO spectra, and to check if there was a real acceptable solution or not; in some cases, we did not find a good meteorite analogue in the data base. NEOs with only the visible part of the spectrum have not been considered, as the fit in this interval does not tell much of their relationships with meteorites (see also Lazzarin et al. 2004). In Fig. 3, we report those NEOs for which a good fit has been achieved. We found possible ‘analogues’ for eight ordinary chondrite meteorites (OCs). OCs represent about 80 per cent of all falls on Earth. Despite this, the detection of OC-like asteroids for a long time has been problematic (e.g. Gaffey, Burbine & Binzel 1993). Only recently, it has been shown that OC-like asteroids indeed exist among small

size asteroids (see, for example, Burbine et al. 2002b). Among our OC-like NEOs, we found one H5, one L5, one L6, two L4 and three LL6. We point out that, among these NEOs, we found quite large compositional variations (also observed among OCs) as clearly appears from the depth and shape of the 1- and 2- μm bands due to olivine and pyroxene. So, for instance, 1992 SY has a high content of pyroxene (deep 2- μm band) while 2000 GQ146 has virtually no pyroxene (it does not exhibit the 2- μm band). We stress that even if this is a result of particular interest, the fit for those objects for which we have only the NIR should be taken with caution. While there is no doubt about their OC-like composition, possible influences of space weathering (see the following) could have been masked by the normalization at 1.5 μm .

Moreover, one NEO (2001 MZ7) has a good fit with an enstatite chondrite (EC) of type E6. Although this was the best fit achieved, we stress that owing to the flat, featureless spectral behaviour of 2001 MZ7, it is difficult to clearly establish if it is really an EC, an aubrite or an iron meteorite, which also present flat, featureless spectra.

Notice that two NEOs (1991 BN and 2002 VP69), observed only in the NIR, have been best fitted by a shergottite martian achondrite. However, the NIR of both objects is also not too different from some OC meteorites. Indeed, it is not easy to distinguish between these two groups of meteorites, but important indications could come from visible measurements, because shergottite is considerably different from OCs in this interval.

Finally, we also found good match with five carbonaceous chondrites (CCs), and within them one CV3, one C2, two CM2 and one CO3 (see Table 2). Some of the NEOs (e.g. 1999 JD6) compared with these CCs show shallow absorption bands centred around 1 μm , probably due to olivine. CCs are only ~ 5 per cent of all falls. They are generally linked with C-complex type asteroids, which are mainly in the outer MB. Therefore, the existence of CC-like NEOs is an important link between CC and their source region.

For seven other NEOs, the fit, even if not completely bad, was not satisfactory. Typically, the shape and/or the band positions are slightly different. Several processes could be invoked to explain the differences observed, such as slight compositional variations and/or grain size effects, just to mention some.

For 12 other S-type objects, the fit was really bad, indicating that for these objects we are dealing either with large compositional differences having no analogues among meteorites, or we are in the presence of large alteration processes. We think the latter is more likely, because if such large compositional differences were so common among S-types we would expect to find some similar meteorite samples. While their overall composition should not greatly differ from that of OCs (all basically made of olivine and pyroxene, as witnessed by the presence of typical olivine/pyroxene bands), the spectra of these NEOs are moderate to much redder than typical OCs. As pointed out by several works (see, for example, Pieters et al. 2000;) such red slopes can be achieved by increasing the content of metal (Fe–Ni) with respect to that of silicates. The origin of this metal is not easily determined by remote analysis, and it could be both primordial or due to some alteration process, such as the so-called space weathering. In fact, as described in Pieters et al. (2000), silicate grains under the flux of micrometeorites and solar wind sputtering develop nanophase iron rims, which alter the optical properties of silicates. In order to quantify this mismatch, we determined the spectral slopes of all S-type NEOs and a large sample (about 300) of OCs in the range 0.52–2.4 μm . The results are reported in Fig. 4. As expected, the vast majority of OCs have small slopes, although some OCs exhibit a red spectrum.

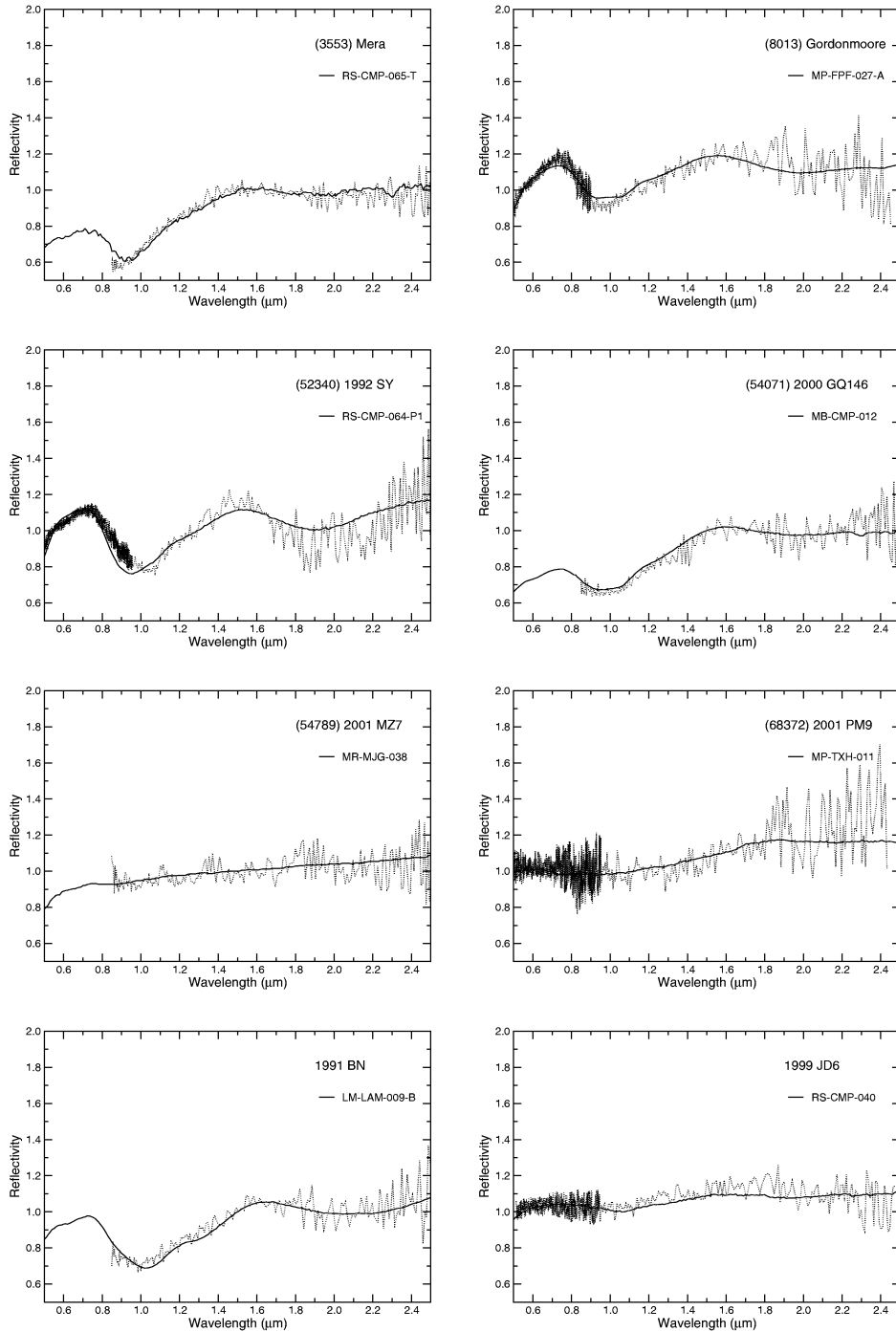


Figure 3. Fit of some NEOs with meteorites. For each asteroid the best-fitting meteorite is shown. Meteorite names refer to the RELAB Catalogue nomenclature.

95 per cent of OCs are below a slope of 20.8 per cent μm^{-1} . So, in this analysis we assumed this value of slope (S_w) as an indicator for the space weathering process. The striking feature is that in comparison with OCs, many NEOs are redder than S_w . On the basis of these considerations, NEOs having a slope greater than S_w have been considered to be space weathered, as reported in Table 1. As the investigated NEOs have diameters ranging from about 100 m to 5 km (on the basis of their absolute magnitude and average albedo), this result is of particular interest because it clearly shows that space weathering may alter also the surface

spectral properties of small size asteroids, usually considered little weathered.

Moreover, we point out that the red spectrum of the A-type asteroid 2002 QE15 (Fig. 4) could be due to a high concentration of olivine as stated before, but also to the presence of highly space weathered silicates (Hiroi & Sasaki 2001). The same consideration may hold for the less red Sa-type 1999 GJ2.

However, it is not yet possible to say whether we are in the presence of space weathering or not, and a final discernment between these two different origins can only be obtained with the help of

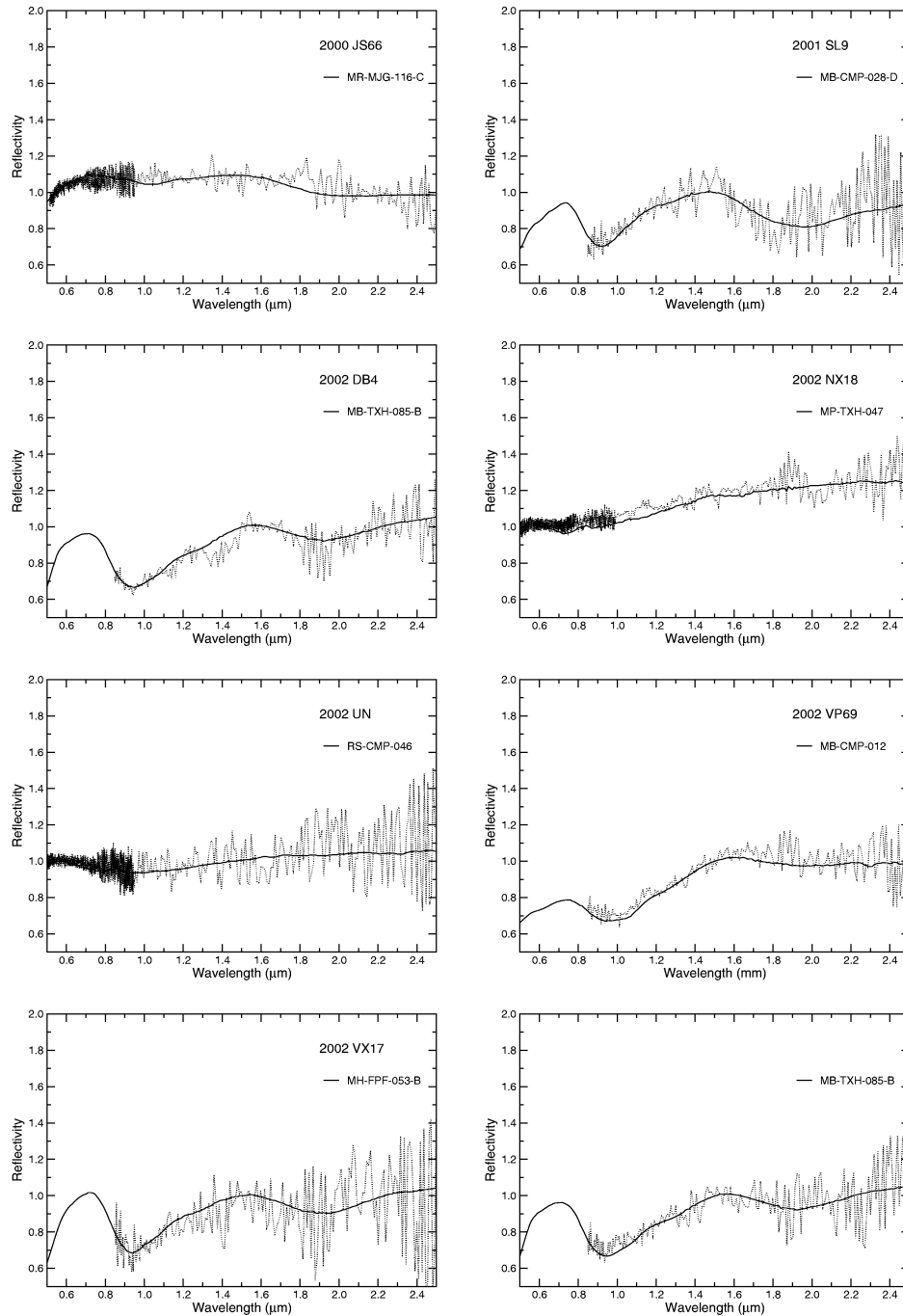


Figure 3 – continued

more data of NEOs, and also with asteroid albedos. Unfortunately, albedo measurements are not yet available for any of the observed NEOs, and further research is needed.

5 CONCLUSIONS

In this paper we have discussed the spectral properties of 36 NEOs observed with the TNG telescope at La Palma. From the analysis of the spectra we have obtained indications about the surface composition of these objects. Moreover, all the visible spectra have also been parametrized in terms of Bus taxonomy (Bus 1999). From this

analysis, it has been possible to classify the observed NEOs, obtaining 21 S-type objects, six X-type, three C-type, two B-type, two Q-type, one A-type and one K-type. The NIR part of the spectrum indicated that in some cases the classification performed using only the visible part could sometimes be uncertain. We also observed two NEOs in cometary orbits, and both present featureless spectra in the 0.5–2.5 μm range.

By comparing the NEOs observed in the full spectral range and a large set of meteorites (847 spectra), we obtain a good match in many cases, also providing information about the relationships between chondrites meteorites and NEOs.

Table 2. Meteorites best fit. For each meteorite we report the RELAB sample identity, the meteorite name, class and petrologic type, the sample texture and the grain size range in case of powder texture. In column 4, OC denotes ordinary chondrites, EC denotes enstatite chondrites, CC denotes carbonaceous chondrites, and AC denotes achondrites (see text for further details).

NEO	Sample ID	Name	Class	Type	Texture	Size (μm)	Comments
2001 SL9	MB-CMP-028-D	Saratov	OC	L4	Powder	94–200	
1999 JD6	RS-CMP-040	Allende	CC	CV3	Powder	0–45	
2002 UN	RS-CMP-046	Boriskino	CC	C2	Powder	0–45	
1992 SY	RS-CMP-064	Pervomaisky	OC	L6	Slab	–	
Mera	RS-CMP-065-T	Tsarev 15384,3-2	OC	L5	Thin Section	–	
2002 VX17	MH-FPF-053-B	Nuevo Mercurio	OC	H5	Powder	0–150	Olivine-bronzite
Gordonmoore	MP-FPF-027-A	Bjurbole top	OC	L4	Powder	0–1000	
1991 BN	LM-LAM-009-B	ALHA77005,112	AC			–	Shergottite martian
2002 VP69	LM-LAM-009-B	ALHA77005,112	AC			–	Shergottite martian
2001 MZ7	MR-MJG-038	Pillistfer	EC	E6		–	
2000 GQ146	MR-MJG-073	Manbhoom	OC	LL6		–	Amphoterite, no rust
2000 JS66	MR-MJG-116-C	Warrenton	CC	CO3	Slab	–	Whole rock
2002 DB4	MB-TXH-085-B	Y-74646	OC	LL6	Powder	25–45	Dry-sieved
2002 XK4	MB-TXH-085-B	Y-74646	OC	LL6	Powder	25–45	Dry-sieved
2001 PM9	MP-TXH-011	Y-74662,101	CC	CM2	Powder	0–125	
2002 NX18	MP-TXH-047	MAC88176,16	CC	C2	Powder	0–125	

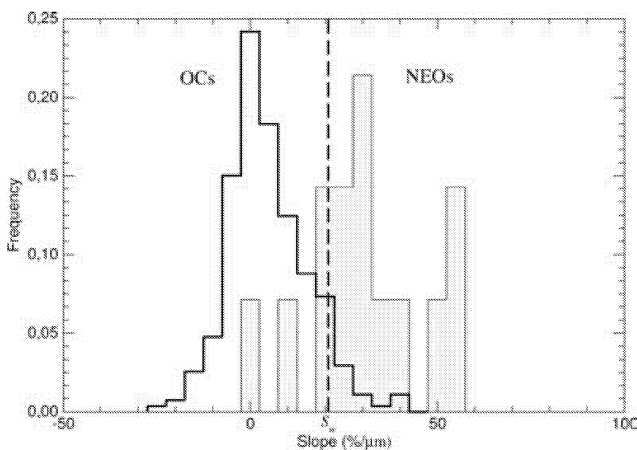


Figure 4. In this plot we report the distributions of OC slopes and S-type NEO slopes (shaded area). The vertical dashed line represents the limit of 95 per cent between non-weathered and weathered objects, as determined from the OC slope distribution. The corresponding slope value is 20.8 per cent μm^{-1} . Both distributions have been normalized to unity area (see text for further details).

Finally, for 12 S-type objects, no fit with meteorites has been achieved and this could be due to space weathering. This result is of particular interest because, as the objects observed have dimensions in the range of 100 m to 5 km, it clearly shows that space weathering may modify the surface spectral properties also of small size asteroids.

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