Mem. S.A.It. Suppl. Vol. 5, 21

Memorie della
Supplementi

SINEO: Spectroscopic Investigation of Near Earth Objects

M. Lazzarin, S. Marchi, S. Magrin and C. Barbieri

Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio, 2 - 35122 Padova e-mail: lazzarin@pd.astro.it

Abstract. Near-Earth objects (NEOs) represent one of the most intriguing populations of Solar System bodies. These objects appear heterogeneous in all aspects of their physical properties, like shapes, sizes, spin rates, compositions etc. Moreover, as these objects represent also a real threat to the Earth, a good knowledge of their properties and composition is the necessary first step to evaluate mitigation techniques and to understand their origin and evolution. In the last few years we have started a long-term spectroscopic investigation in the visible and near-infrared (NIR) region of NEOs. The observations have been performed with the ESO NTT in La Silla and the TNG in Canary Islands, obtaining about 80 spectra so far. We discuss the taxonomic classification of the observed NEOs, their links with meteorites and possible influences of space weathering.

Key words. Asteroids, composition; Asteroids, surface; Visible, Infrared, Observations; Spectroscopy; Meteorites.

1. Introduction

Little is still known on near-Earth object properties and origins. These objects, comprised by asteroids and extinct comet nuclei in orbits with perihelion distances q <1.3, periodically approach or intersect the orbit of the Earth, and are believed to be on the same dynamical routes which deliver meteorites to the Earth. The importance of studying NEOs has been recognized worldwide, and a great deal of resources are being used for this task, both for ground-based facilities and space missions. Space probes can provide very detailed information about most of the physical, dynamical and geological characteristics of the target, however, they can only visit a very limited number of objects. So, a picture of the whole NEO population, in order to study their global properties and their diversity, can be obtained only with ground-based observations. From the available data, the NEO population is very diverse in nature: some objects have very elongated shapes, others have complex, non-principal axis rotation states (*tumbling* asteroids), very long and very short rotational periods are observed, and even binary systems are known. NEO diversity is also emphasized by the different taxonomic types found within the population. Another interesting issue is the relationship between NEOs and meteorites, in particular the ordinary chondrites (OCs), that are thought to represent samples of the prim-

Send offprint requests to: M. Lazzarin
Correspondence to: Vicolo dell'Osservatorio, 2 - 35122 Padova

itive solar nebula that have undergone modest thermal evolution over the age of the Solar System (Binzel et al. 1996; Lazzarin et al. 1997; Binzel et al. 2001, 2002). The question of NEOs origins also is not well understood. Currently, two sources for NEOs have been identified. The principal one is the main belt, where gravitational perturbations by the major planets and Mars cause dynamical resonances which provide escape routes. The second source is represented by extinct comets. A certain number of NEOs may represent the final evolutionary state of comets, that is, a devolatilized nucleus (Harris et al. 1998).
One way of addressing many issues related to NEOs is to characterize these objects spectroscopically in order to derive their mineralogy, to classify them taxonomically, to address their origin and their relations with comets, main belt asteroids and meteorites.
In this context we started few years ago a spectroscopic investigation of NEOs (that we called SINEO) in the visible and near infrared region. So far, four observing runs have been performed using the ESO NTT in La Silla and three using the TNG in Canary Islands. In the following sections we describe the data reduction and the obtained results.

2. Data analysis

In this section we describe the analysis we have performed with the main aim to find out the taxonomic types and possibly the link between the observed NEOs and meteorites. We recall that our work, based mainly on statistical analysis, is in progress, being a long term observational program.

2.1. Taxonomical classification

This task has been performed by the comparison of the obtained spectra with the largest sample of main belt asteroids spectra available in the literature: the Small Main-Belt Asteroid Spectroscopic Survey phase II (SMASSII, Bus 1999). It consists of 1341 visible spectra of main belt asteroids having estimated diameters less than 30 km, taken between 1993 and 1999. The SMASSII data were analysed by means of principal component analysis (PCA), in order to remain as compatible as possible with Tholen's taxonomy (Tholen 1984), the developments of which was partially based on this technique. We followed the procedure described in Bus (1999) and Bus & Binzel (2002b) to calculate the PCA parameters and determine taxonomic classification. Although we have NIR data, in the following we limit the discussion to the visible part used in SMASSII (0.44 to 0.92 μm) in order to make a comparison with it (indeed our visible spectra cover a slightly larger interval, from 0.40 to 0.95 μm).

The procedure described was applied using the same program to our data and to the SMASSII main belt object spectra in order to obtain comparable results. The principal components used are the so called *slope*, PC2', PC3'. To better understand the meaning of these variables see Lazzarin et al. (2004). The spectra distribution on the (*slope*, PC2') plane clearly shows a broad bimodal distribution being the most part of the asteroids clustered into two regions. One of these is called the S–complex, and the other has been divided into two regions for which the terms C–complex and X–complex have been introduced (see Bus 1999).

The three major complexes are not the final product of the Bus taxonomy. Many objects lie outside of the nominal ranges defined for the C, X and S–complexes and also with the help of the large SMASSII data set, it has been possible to identify many subclasses within the three major complexes. By performing a least square fit between our NEOs spectra and the mean spectra of the several classes of the main belt asteroids of SMASSII, we were able to get a first "rough classification" of our data. After that, we considered the NIR spectra (when available) in the attempt to verify the visible classification, by the presence of the characteristic NIR features of each class, or to discriminate among different classes in case of ambiguity. The inferred taxonomic classes are reported in Tab. 1.

The main results of this analysis can be summarized as follows:

Table 1. NEOs observed with TNG. For each asteroid are reported the orbit's type, inferred taxonomy, visual magnitude, airmass, and spectral range (v=visible, n=NIR). The NEOs observed in previous runs are in Lazzarin et al. (2004) and they are not repeated here. Others 25 NEOs are presently under analysis.

NEO	Orbit	Tax.	V	air	Spectral range
1996 HW1	AMO	B	17.5	1.58	v+n
1991 BN	APO	S	16.5	1.00	n
2002 UN	AMO	B	18.0	1.10	v+n
2002 VP69	APO	S	17.5	1.09	n
2002 VX17	AMO	S	17.7	1.36	n
2000 GQ146	AMO	S	17.4	1.67	n
1995 BC2	AMO	X	18.5	1.36	v+n
2001 MZ7	AMO	X	16.8	1.29	n
2002 XK4	APO	S	17.2	1.05	n
2002 DB4	ATE	S	17.3	1.72	n
1992 SY	AMO	Q	16.6	1.06	v+n
2002 TS67	AMO	Xe	16.9	1.24	v+n
2002 QE15	AMO	A	15.9	1.70	v+n
2001 CC21	APO	Sk	16.7	1.08	v+n
2002 NX18	AMO	Ch	16.1	1.22	v+n
2002 TP69	AMO	Sk	17.2	1.16	v+n
1997 XF11	APO	K	16.4	1.22	v+n
1991 VH	APO	S	17.1	1.39	v+n
2002 TD60	AMO	S	15.7	1.04	v+n
2002 YB12	APO	Sq	17.6	1.0	v+n
2001 PM9	APO	Cb	18.2	1.1	v+n
1998 MX5	AMO	Xk	16.8	1.2	v+n
1999 GJ2	AMO	Sa	16.8	1.1	v+n
4587 Rees	AMO	Sr	17.6	1.5	v+n
2002 TB9	APO	Sr	18.3	1.5	v
8013 Gordonmoore	AMO	Sr	17.4	1.2	v+n
2003 KR18	AMO	S	17.5	1.2	v+n
7336 Saunders	AMO	Sr	19.3	1.1	v
2001 KZ66	APO	S	17.5	1.5	v+n
2003 FS2	AMO	C	19.3	1.0	v
2002 AL14	ATE	Sl	18.6	1.2	v+n
2001 SL9	APO	Q	18.1	1.1	n

- We found 32 S-type objects, 3 Q-types, 3 K-types, 1 A-type, 6 C-types, 2 B-types, 9 X-types;
- the observed NEOs are widely distributed over the SMASSII spectra, except for the classes at right hand of the plot (A, L, D–type);
- Many NEOs are in the region of Sq–type asteroids, and few objects are Q–type. This is an important result (also found by Binzel et al. 2001, 1996; Di Martino et al. 1995), since it allows us to establish a link among OCs and NEOs. This task will be discussed further in the next section;

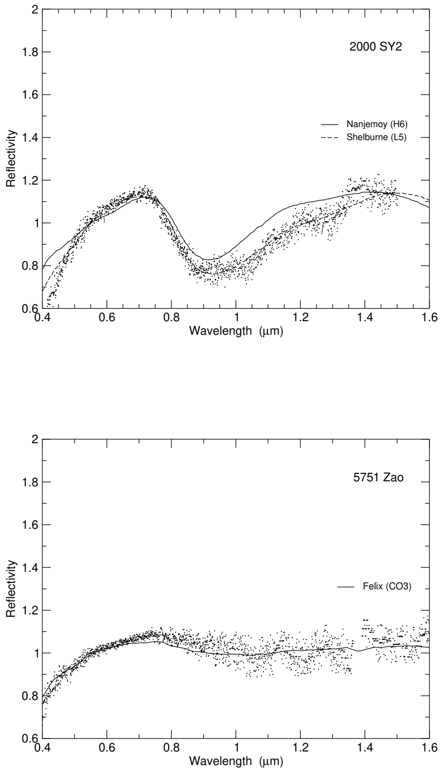

Fig. 1. Examples of good fits achieved with meteorites.

– Two of the Xe-type objects, (3103) Eger and (4660) Nereus, are already classified as E-types on the basis of their albedo.

2.2. Links with meteorites

As previously discussed, a long-standing problem in the Solar System science is the origin of meteorites and their extraterrestrial sources. With our data we can contribute to the study of this problem, NEOs being the bodies closest to the Earth. Extremely interesting for this purpose is the NIR information, because the visible part of the spectrum alone does not give the possibility to analyse in detail the link between a meteorite and an asteroid. We compared the NIR spectra with those of meteorites.

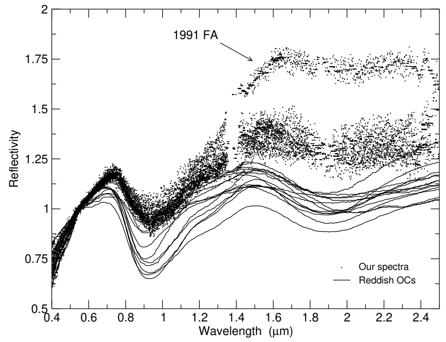

Fig. 2. Space weathering among S–type NEOs.

We used the visible plus NIR spectra of a large sample of meteorites (Gaffey 1976). In Fig. 1 the best meteoritic counterparts, obtained with a least square fit, for two objects are shown. Of particular interest is 2000 SY2, which has a good match with the Shelburne OC over the full available range. The object (5751) Zao (K–type) is in good agreement with the proposed CO3 carbonaceus chondrite meteorites (see Fig. 1; see also Burbine et al 2001). In these cases, and in other not shown here, our spectra fit quite well with those of the meteorites, and we can conclude that the observed NEOs could be possible sources of those meteorites. On the other hand, for other NEOs we did not find any match with meteorites. Let us deal with these objects.

2.3. Space Weathering

Regarding the counterpart of the OCs we know the possibility that an asteroid's spectrum can be affected by space weathering, the size of the regolith grain and also mineralogic differences. A recent work by Ueda et al. (2002), has shown how the space weathering and the grain size effects influence the Band I center versus BandI/BandII area ratio plot. Their results can be summarized as follows:
i) space weathering alters mainly the BandI/BandII area ratio toward higher values; *ii)* the grain size effects reduce both

the Band I center and the BandI/BandII area ratio; *iii)* mineral diversity (namely different olivine–orthopyroxene mixtures) alters mainly the Band I center. Although these effects are far from being well understood, they clearly indicate the difficulties of inferring mineral information from spectral data, and also to identify effects of space weathering by comparison between asteroids and laboratory (or meteoritic) spectra. In Fig. 2 we report some of our NEOs' spectra possibly altered by space weathering ((3102) Krok, (3753) Cruithne, (7341) 1991 VK, (719) Albert and (11054) 1991 FA). In the same figure, 14 OCs meteorites chosen among the reddest ones are also plotted. From the figure we can notice some aspects.

First of all, it clearly appears evident the importance of the NIR part of the spectrum and in particular all the range down to 2.5 μm. In fact, although it is possible to find reasonable meteorite analogues for some asteroids' spectra in the range 0.4–1.6 μm, if we take also into account the interval from 1.6 to 2.5 μm there is no spectral match. Then, we see that those meteorites that better fit our data have a Band I center position slightly shifted towards lower wavelengths with respect to NEOs' spectra. On the other side, meteorites with deeper 1.0 μm absorption are closer to NEOs' Band I center position. Regarding the Band II depth, both NEOs and meteorites are quite similar. A possible explanation for such behavior is that if really the S–types are parent bodies for the OCs, they have to suffer space weathering and be covered by regolith.

3. Discussion and Conclusion

In this work we discussed the taxonomic classification of some NEOs observed so far. From the analysis of the spectra we have obtained indications about the surface composition of these objects. Moreover, all the visible spectra have been also parametrized in terms of a new taxonomy developed for main belt asteroids (Bus 1999). From this analysis, it has been possible to classify the observed NEOs, obtaining 32 S-type objects, 3 Q-types, 3 K-types, 1 A-type, 6 C-types, 2 B-types, 9 X-types. The NIR part of the spectrum indicated that in some cases the classification performed using only the visible part could be uncertain. Moreover, from the NIR (and in particular the 1.6–2.5 μm region) we also get strong indications about the possible presence of space weathering among S-type NEOs.

Some peculiar bands have been revealed (eg. on three Xe–types) around 0.5 μm probably due to the presence of troilite, found until now in other very few objects (Fornasier & Lazzarin 2001).

Finally, we made a comparison between the NEOs observed in the full spectral range and a large set of meteorites (more than 200), obtaining a good match in most cases and providing also new information about the relationships between ordinary chondrite meteorites and aubrites with NEOs.

References

Binzel, R.P., et al. 1996, Science 273, 946–948.
Binzel, R.P., et al. T.H. 2001, Icarus 151, 139–149.
Binzel, R.P.et al. 2002, In: Asteroids III, Univ. of Arizona Press.
Burbine, T.H., Binzel, R.P., Bus, S.J. & Clark, B.E. 2001, M&PS 36, 245–253.
Bus, S.J. 1999, PhD Thesis.
Bus, S.J. & Binzel, R.P. 2002a, Icarus 158, 106–145.
Bus, S.J. & Binzel, R.P. 2002b, Icarus 158, 146–177.
Di Martino, M., Manara, A. & Migliorini, F. 1995, A&A 302, p.609.
Fornasier, S. & Lazzarin, M. 2001, Icarus 152, p.127.
Gaffey, M.J. 1976, JGR 81, 905–920.
Harris, N.W. & Bailey, M.E. 1998, MNRAS 297, Issue 4, 1227–1236.
Lazzarin, M., Marchi, S., Barucci, M.A., Di Martino, M. & Barbieri, C. 2004, Icarus 169, 373–384.
Lazzarin, M., Di Martino, M., Barucci, M.A. & Doressoundiram, A. 1997, A&A 327, p.388.
Tholen, D.J. 1984, Ph.D. thesis, University of Arizona, Tucson.
Ueda, Y., Hiroi, T., Pieters, C. M. & Miyamoto, M. 2002, LPSC XXXIII, abstract no.1950.