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SINEO: Spectroscopic Investigation of Near Earth Objects

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

Dipartimento di Astronomia – Vicolo dell'Osservatorio 3, I-35122 Padova, Italy
e-mail: monica.lazzarin@unipd.it

Abstract.
In this paper we present the results obtained until now from our spectroscopic survey in the visible and Near Infrared Region (NIR) of Near Earth Objects (NEO), named **SINEO**, started in 2000. Up to now we have obtained a data set of about 150 spectra, most of them in the visible range (0.40-0.95 μm) and about half of them in the whole region 0.40-2.5 μm. The observations have been performed with the NTT of ESO (Chile) and the Telescopio Nazionale Galileo (TNG) at the Canary Islands. We present the taxonomic classification of the objects, their linkage with meteorites and the influence of space weathering.

Key words. Asteroids: spectroscopy – Near Earth Objects: mineralogy – Near Earth Objects: taxonomy

1. Introduction

Near-Earth Objects (NEOs) represent one of the most peculiar population of Solar System minor bodies. Their origin and their link with the other minor bodies of the Solar System are till now not completely understood: NEOs seem to be the principal parent bodies of meteorites, while main belt asteroids and cometary nuclei are both indicated as NEOs sources (Harris & Bailey 1998; Weissman et al. 2002). The detailed comprehension of the mechanisms of the resupply of the NEO population is one of the principal aims of NEO investigations.

The population appears heterogeneous in all the aspects of its physical properties, so their investigation is necessary for understanding their origin and evolution. The different nature of these bodies is particularly evident from their taxonomy. In fact 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. The most common taxonomic class among NEOs is however the S-type. Besides a possible selection effect (being this class dominated by high albedo objects), this could indicate that asteroidal NEOs derive mostly by the inner MB, via the ν_6 resonance, where S-types are the most common asteroids. However, other sources have been proposed like the the 3:1 resonance (see for example Morbidelli et al. (2002)), which is surrounded by C- and S-type asteroids in almost equal quantity.

Another possible source of NEOs is represented by dead or dormant comets that is devolatilised cometary nuclei and/or comets

Send offprint requests to: M. Lazzarin whose icy surface is covered by a subtle non volatile crust which inhibits possible gas emissions. The spectra of these objects show a behaviour typical of cometary nuclei (featureless and flat to reddish spectrum).

Spectroscopic investigation of NEOs is fundamental to investigate most of the issues indicated above (mineralogy, taxonomic classification, origin, relationships with comets, MB asteroids and meteorites). With our survey **SINEO** (**S**pectroscopic **I**nvestigation of **N**ear-**E**arth **O**bjects, see http://www.astro.unipd.it/planets/sineo.html) we presently represent the first European data set existent for number and spectral extension and the second in the world. In this paper we present the results obtained so far from our spectroscopic investigation.

2. Observations and data reduction

The observations, both in the visible and in the near infrared spectral range, have been performed with the ESO-NTT in Chile (5 runs) and the Telescopio Nazionale Galileo (TNG) at the Canary Islands (7 runs).

2.1. TNG

57 spectra have been recorded with the TNG in the course of seven runs performed in December 2002, July 2003 and May 2004, June 2005, July 2006, November 2006, June 2007 for a total of 18 nights observed (23 assigned), 9 in the visible and 9 in the NIR.

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″ in order to minimize effects due to atmosphere differential refraction. For the same reason for all objects the slit was oriented along the parallactic angle.

In the near-infrared (NIR) we used NICS (Near Infrared Camera Spectrometer) equipped with the AMICI prism, which provides a resolving power of about 50 almost constant through out the range 0.8-2.5 μm. In the NIR we used a 2″ slit width. As the influence of the differential refraction is less relevant in the NIR, we oriented the slit along the direction of the motion of every asteroid and along the parallactic angle for solar analogues.

For both visible and NIR, to minimize the possibility of losing the objects, we decided to check the position of each moving target on the slit every 15-20 minutes, depending on the velocity of the asteroid. Longer exposures, needed on fainter objects, have been split in shorter ones, repeated as many times as needed to reach the required S/N ratio.

In every shorter LRS exposure we decided to shift the position of the object along the slit of 10-15 arcsecs, to minimize the noise due to a fringing effect present in the red part of the spectrum with LRS, longward ~ 0.8 μm.

2.2. NTT

80 spectra have been recorded with the ESO-NTT during five runs in October 2000, November 2001, May 2003, December 2004 and December 2006 for a total of 18 nights, 9 in the visible and 9 in the NIR.

For the visible observations the NTT was equipped with EMMI (ESO Multi–Mode Instrument) in low resolution spectroscopy mode. The disperser element was the Grism #1 which gives a dispersion of 0.59 nm/pix, and the spectra obtained are in the range 0.38–1.0 μm with a resolution of 270 (for a slit of 1″). As for TNG+LRS we used a slit aperture of 5″. We oriented the slit along the parallactic angle for all objects.

In the NIR we used NTT equipped with SOFI (Son OF Isaac) in the low resolution mode with two different dispersers: the Grism Blue that in the range 0.95–1.64 μm gives a resolution of 1000 with a slit of 0.6″; the Grism Red for the range 1.53–2.52 μm, with the same resolution. As for TNG+NICS we used a 2″ slit width for all objects. We oriented the slit along the direction of the motion for every asteroid observed and along the parallactic angle for solar analogues.

The reduction was carried out with usual reduction techniques, and for details we refer, for instance, to Lazzarin et al. (2004) and Licandro et al. (2002). To obtain the relative reflectance, several Landolt G stars (Landolt

1973) and Hyades 64 were observed during the nights at different airmasses. All these stars showed negligible differences. They were also observed in previous runs together with the solar analogue star P330E (Colina & Bohlin 2000) and they present similar spectra in the infrared region, so we used them as solar analogues for both visible and NIR.

3. Data analysis

In this section we describe the analysis we have performed with the main aim to obtain the taxonomic types and to study 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.

3.1. Taxonomic classification

One of the principal aims of this spectroscopic investigation is the taxonomic classification of the observed NEOs. This has been obtained by performing a best fit between our data and the mean spectra of each spectral class proposed by Bus (1999) on SMASSII data. Since Bus taxonomy was restricted to visible data, we applied this analysis only to NEOs for which visible measurements were available (the range considered was 0.52-0.92 μm). The "best" solution of the fitting was chosen as the "right" taxonomic class.

Afterwards, we applied the Principal Component Analysis (PCA) technique to the data. Fig. 1 shows a plot of the first two components (*slope* and $PC2'$), in the 0.52–0.92 μm range, computed on a set that includes all the SMASSII main belt data, all TNG NEOs and all the ESO-NTT NEOs visible spectra obtained so far. The Bus' mean types locate in different zones on the $(slope, PC2')$ plot. It clearly results that we can distinguish between the C-,X- complexes and the S-complex. Moreover all S subclasses are well separated. As a result, we found an excellent compatibility between the taxonomic classification obtained by the best fitting with Bus' mean types described above and the location of the NEOs

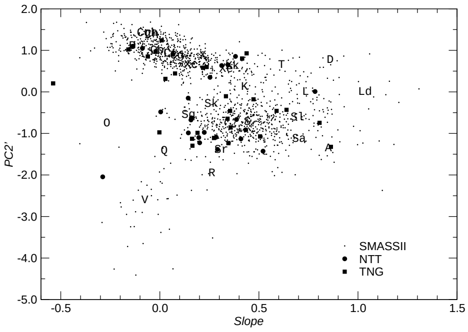

Fig. 1. PCA of SMASSII main belt asteroids spectra and NEOs spectra obtained in SINEO project.

in the $(slope, PC2')$ plane, as obtained 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.

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.

So, the distribution among the several taxonomic complexes obtained so far can be summarised as in the following: 62% belongs to S-complex, 20% to X-complex, 12% to C-complex and 6% to other classes.

3.2. Link with meteorites

The investigation of NEOs can give important information on the origin of meteorites, NEOs being the bodies closest to the Earth.

We compared the visible plus near infrared spectra of our NEOs with those of meteorites. For this task, we developed a code which is able to automatically perform a least square fit between our NEOs spectra and the vast me-

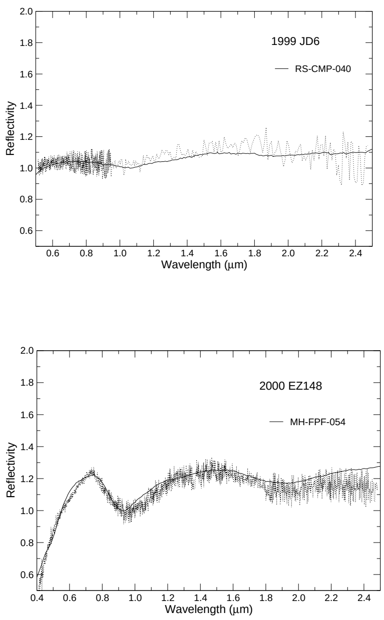

Fig. 2. Some examples of NEOs spectra with the "best fitting" meteorites. The spectra are normalized at 1 around 0.55 μm. Meteorites names refer to the RELAB Catalogue nomenclature.

teorite spectral database available on RELAB (http://www.planetary.brown.edu/relab/). We used all the public spectra cataloged as 'XT' (namely extraterrestrial), for a total of 847 spectra. For each NEO of which we had NIR measurements we selected 20 meteorites in order of descending fit quality. The best fitting was chosen through visual inspection, to avoid possible mistakes, especially in the case of too noisy NEOs spectra, and to check if there was a real acceptable solution or not: in some cases we did not find a good meteorite analog in the database. 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. 2 we report some NEOs for which a good fitting has been achieved.

In most cases we obtained a good match providing also new information about the relationships between ordinary chondrites meteorites, aubrites and carbonaceous chondrites with NEOs.

For several 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, like slight compositional variations and/or grain size effects, just to mention some.

3.3. Space weathering effects

For part of the S-type objects the fit was really bad, indicating that for these objects we are dealing either with big compositional differences having no analogues among meteorites, or we are in presence of big 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. 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, like 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 MBOs and for a large sample of OCs. NEOs spectra are a merging of SINEO, SMASS (Binzel et al. 2004a,b; Rivkin et al. 2004) and 52COLOR (Bell et al. 1985) data; MBOs spectra are a merging of SMASS (Xu 1994; Bus 1999; Burbine and Binzel 2002) and 52COLOR. The results are reported in Fig. 3.

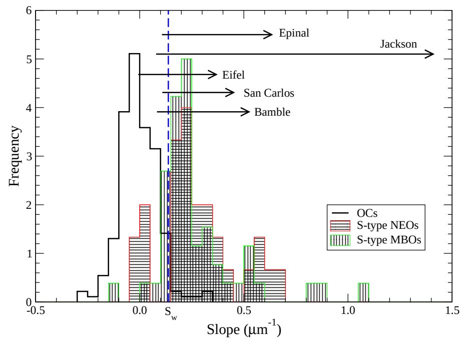

Fig. 3. Spectral slope distributions of OCs, NEOs, and MBAs. Each distribution has been normalized (area= 1). The vertical dashed line marks the 95% OCs limit (corresponding to a slope of S_w = 0.138 μm^{-1}). Horizontal arrows mark the reddening measured for irradiated Epinal, Jackson (Strazzulla et al. 2005; Brunetto & Strazzulla 2005), Eifel, San Carlos, and Bamble (Marchi et al. 2005).

As expected, the vast majority of OCs has small slopes, although some OCs exhibit a red spectrum. 95% of OCs are below a slope S_w = 0.138 μm^{-1}. So, in this analysis we assumed this value of slope S_w as indicator for the space weathering process in asteroids. OCs distribution (representative of pristine materials) peaks at slope = 0, and is by far bluer than the NEOs and MBAs distributions. On the contrary, the two latter distributions are basically indistinguishable. The striking feature is that we find that 83% of the NEOs and 94% of the MBAs are redder than S_w. Thus only the 17% of NEOs and 6% of MBAs are compatible with OCs spectra. Although these percentages can be affected by low numbers statistic, NEO population seems to contain a higher percentage of OC-like objects. We suggest that this can also be due to the fact that in the NEO space we can detect and study smaller objects than in the MBO space: smaller asteroids usually mean younger bodies (if we infer their age from the collisional age), that have been exposed to the space weathering for a shorter time, not able to increase the spectral slope significantly.

We also underline that, in spite of the wide size range involved, NEOs and MBAs span over a similar interval of slopes, and that the asteroid slope distributions have a broader FWHM with respect to that of OCs.

In Fig. 3 we also report the results for ion irradiation experiments (Strazzulla et al. 2005; Brunetto & Strazzulla 2005; Marchi et al. 2005) to simulate solar wind and cosmic ion irradiation. Epinal shows the trend for a typical OC, while Jackson is representative of the maximum reddening attained in laboratory experiments, which largely overcome asteroid slopes. Therefore the shift between OCs and asteroids distributions can be explained by ion irradiation experiments (see Marchi et al. (2005) for further details).

However it is not yet possible to say whether we are in presence of space weathering or not and a final discernment between these two different possibilities can only be obtained with the help of more data of NEOs, and also of their albedoes.

3.4. A general approach to SW

A complete analysis of SW would require the knowledge of all the relevant parameters. The most important one is the age of the body, owing to the “progressive” nature of SW. Other parameters follow from the properties of the physical processes (micrometeorites impact, ion bombardment, sputtering etc). Some of these processes depend on the distance from the Sun, which may be an important parameter of SW whenever the related processes are important.

About the age T of an asteroid we can consider separately Main Belt asteroids and NEAs: for the first ones the age T_{MB} can be expressed as dependent on collisional age t_{coll} and hence on the asteroid diameter D; for NEAs the age is dependent on t_{coll} and t_{yark} the “Yarkovsky time”, both dependent (in different ways) on the diameter D (we refer to Marchi et al. (2006a)).

In order to estimate the amount of radiation from the Sun that a body receives along its orbit (i.e. what we call *exposure*) we have

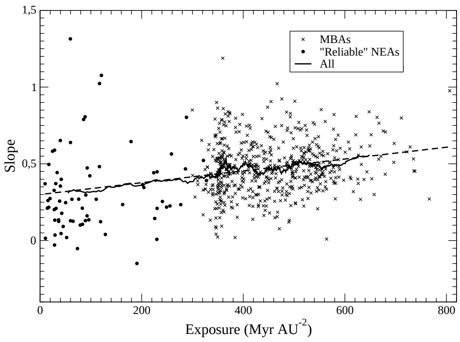

Fig. 4. A general slope–exposure relationship for "reliable" NEAs and MBAs. Only NEAs having a total probability of origin from the Main Belt exceeding 75% have been considered as "reliably" distance–assessed. The solid curve corresponds to a running box average (50 points) of the data, putting together NEAs and MBAs. The curve can be approximately fitted with a line (dashed line). P of the linear fit is less then 0.1%, supporting a full statistical significance.

to take into account of a correction factor due especially to the distance from the Sun and, in general, to the orbit shape. The *exposure* can thus be expressed as:

$$\text{Exposure} \propto \frac{1}{a^2\sqrt{1-e^2}} \cdot T \qquad (1)$$

where a is the semi–major axis and e is the eccentricity of the orbit and the T is the age of the MB asteroid or NEA, T_{MB} or T_{NEA} respectively, as explained before.

We select only NEAs having a total probability of origin from ν_6, Pho, 3:1 and Outer Belt exceeding 75% as "reliably" distance–assessed objects (only in this case the estimate of the orbital correction to the exposure can be considered as enough accurate).

Finally, we can plot this *exposure* versus the spectral slope (Figure 4), finding a unique (holding for NEAs and MBAs), approximately linear fit, with an angular coefficient of $3.8543 \cdot 10^{-4}$ MyrAU^{-2}. The P of the linear fit is less then 0.1%, supporting a full statistical significance.

Afterwards (Paolicchi et al. 2007) we deepen the study of this relation by adding unweathered Ordinary Chondrites (OCs) and Mars Crossers (MCs) spectra to the data set, by correcting family members asteroids age (we consider the age of the family as an upper limit to the age of its members) and by considering orbital proper elements instead of osculating ones.

Even with some minor open problems the existence of a unique space-weathering scenario including meteorites as well as Near Earth, Mars Crossers and Main Belt asteroids can be suggested. However, the SW timescales that we obtain from our observational sample are systematically larger than one might expect, on the basis of laboratory experiments

3.5. Resurfacing on planet crossing asteroids?

We are studying the existence of a spectral slope vs. perihelion distance correlation, which may represent the first evidence for the occurrence of the tidal stripping as a rejuvenating process (see Marchi et al. (2006b)).

In order to undergo close encounters, the orbits of the asteroid must cross the orbits of at least one of the inner planets. Thus the NEO perihelion distances determine the "strength" of coupling for each object to the terrestrial planets: orbits with $0.72 < q < 1au$ are Earth-crossing, orbits with $0.466 < q < 0.72au$ are both Venus-crossing and Earth-crossing, and orbits with $q < 0.466au$ are Mercury, Venus and Earth-crossing (this is because all the NEOs in our sample have $Q > 1au$). Moreover, many NEOs also have aphelion $Q > 1.38au$, thus they can also have close encounters with Mars. As for MCs, by definition they can attain only close encounters with Mars.

There is probably a statistically significant relation between the perihelion distance and the spectral properties of NEOs and MCs. This trend seems to be real and not affected by the history of individual bodies, and its significance is also indirectly confirmed by the distribution of the relative number of Q–types with respect to S–types (see fig. 5).

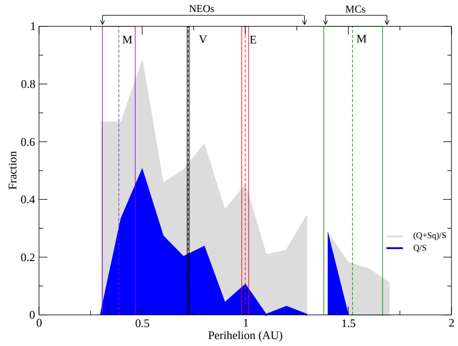

Fig. 5. Histogram of the fraction of Q-type and (Q+Sq)-type NEO and MC bodies as functions of perihelion distance. Vertical lines indicate the perihelion, semimajor axis and aphelion distances for terrestrial planets, i.e. the region where close encounters can happen. Notice that the gap of asteroids for $1.3 < q < 1.4$ AU is not real, but rather due to a lack of observed bodies within this range.

The obtained relation seems to entail a sort of "surface reset" due to close encounters with the inner planets. This process, if confirmed, could be regarded as a sort of "dynamical" reverse space weathering.

4. Discussion and conclusion

In this work we presented the observational program of a survey of NEOs started in 2000 by our group and named **SINEO**. In particular we discussed the spectral properties of about 150 NEOs observed so far with the NTT Telescope of ESO-La Silla and the TNG telescope at La Palma (Lazzarin et al. 2004, 2005). 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 Bus' taxonomy (Bus 1999). From this analysis, it has been possible to taxonomically classify the observed NEOs, obtaining 62% of S-complex, 20% X-complex, 12% C-complex and 6% other classes.

The NIR part of the spectrum indicated that in some cases the classification performed using only the visible part could be sometimes uncertain.

We observed also 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 providing also information about the relationships between chondrites meteorites and NEOs.

For 15 S-type objects, no fit with meteorites has been achieved and this could be due to space weathering.

We started to deepen the space weathering effects, by studying relations between the spectral slope and others physical and dynamical properties of the asteroids (NEOs, MCs and MBOs) as well as by comparing asteroids spectral slopes with meteorites ones.

First of all we found (Marchi et al. 2005) that the the shift between OCs and asteroid spectral slope distributions can be explained by ion irradiation experiments, able to simulate space weathering effects due to solar wind and cosmic ion irradiation.

Then, in spite of a few simplified assumptions and of their intrinsic uncertainties we have found (Marchi et al. 2006a) a significant relation between the asteroid spectral slopes and their past evolution (and thus their cumulated SW), providing a unique and general slope–exposure plot, valid for the whole S–complex. Most noticeably, the use of both NEAs and MBAs, has allowed us to obtain a general description of the SW in the range 10 Myr–3.7 Gyr. Moreover, by using NEAs we were able to link their reddening with their past evolution into the Main Belt. Doing so, we find important constraints on several physical processes, like the efficiency of the NEAs Yarkovsky delivery and the dominance of Sun–related effects among SW processes. Indirectly, our results support also the existing reconstructions of the past dynamical evolution of NEAs.

More recently (Paolicchi et al. 2007) we obtained a by far more refined and reliable slope-exposure relation, capable to include in a unique scenario the ordinary chondrite meteorites, NEOs, Mars Crossers and Main Belt asteroids. We suggest that, on the basis of spectroscopic properties, Mars Crossers should be, on the average, significantly younger than Main Belt asteroids of the same size. We also argued that the solar ion flux is the most relevant source of the asteroidal space weathering.

Moreover we found a statistically significant relation between the perihelion distance and the spectral properties of NEOs and MCs (Marchi et al. 2006b). We found that the orbital distribution of Q-type planet-crossing asteroids is correlated with the perihelion distance (that means with the increasing probability of encounters and close encounters with an inner planet). These results may represent the first direct evidence for the effects of close encounters on the optical properties of asteroid surfaces. In particular, close encounters seem to act as an efficient rejuvenating process, probably due to tidal stripping and/or mixing of the upper layers of asteroid surfaces.

Last, with a view to future spatial missions to NEOs, our survey could constitute an useful reservoirs for possible targets.

Other data reduction and analysis are in progress (Lazzarin et al. 2008) and an observational run will be performed at TNG in July 2008.

References

Bell J. F., Hawke B. R., Owensby P. D.,Gaffey M. J. 1985, BAAS 17, 729.

Binzel, R.P., Birlan M., Bus S.J., Harris A.W., Rivkin A.S., Fornasier S. 2004, Planet. Space Sci., 52, 291.

Binzel R.P., Rivkin A.S., Stuart J.S., Harris A.W., Bus S.J., Burbine T.H. 2004, Icarus, 170, 259.

Brunetto, R., & Strazzulla, G. 2005, Icarus, 179, 265.

Burbine T.H., McCoy T.J., Nittler L.R., Benedix G.K., Cloutis E.A., Dickinson T.L. 2002, M&PS, 37, 1233

Burbine T.H., Binzel R.P. 2002, Icarus, 159, 468.

Bus S.J. 1999, PhD Thesis, MIT.

Colina, L., Bohlin, R. 1997, AJ, 113, 1138

Harris N.W., Bailey M.E. 1998, MNRAS, 297, 1227

Hiroi T., Sasaki S. 2001, M& PS, 36, 1587

Landolt A.U. 1973, AJ, 78, 959

Lazzarin M., Marchi S., Barucci M.A., Di Martino M., Barbieri C. 2004, Icarus, 169, 373

Lazzarin M., Marchi S., Magrin S., Licandro J. 2005, MNRAS, 359, 1575.

Lazzarin M. et al 2008, in preparation.

Licandro J., Guerra J.C., Campins H., Di Martino M., Lara L., Gil-Hutton R., Tozzi G.P. 2002, EM&P, 90, 495

Marchi S., Brunetto R., Magrin S., Lazzarin M., & Gandolfi D. 2005, A&A, 443, 769.

Marchi S., Paolicchi P., Lazzarin M., Magrin S. 2006, AJ, 131, 1138

Marchi S., Magrin S., Nesvorný D., Paolicchi P., Lazzarin M. 2006, MNRAS, 368, L39.

Morbidelli A., Bottke W. F. Jr., Froeschlè Ch., Michel P. 2002, in Asteroids III, Bottke W. F. Jr., Cellino A., Paolicchi P., and Binzel R. P. (eds), University of Arizona Press, Tucson, 409

Paolicchi P., Marchi S., Nesvorný D., Magrin S., & Lazzarin M. 2007, A&A, 464, 1139.

Pieters C.M., Taylor L.A., Noble S.K., Keller L.P., Hapke B., Morris R.V., Allen C.C., McKay D.S., Wentworth S. 2000, M&PS 35, 1101

Rivkin A.S., Binzel R.P., Sunshine J., Bus S.J., Burbine T.H., Saxena A. 2004, Icarus, 172, 408.

Strazzulla G., Dotto E., Binzel R., et al. 2005, Icarus, 174, 31.

Ueda Y., Hiroi T., Pieters C.M., Miyamoto M. 2002, LPSC XXXIII, abstract no.1950

Weissman P.R., Bottke W.F. Jr., Levison H.F. 2002, in Asteroids III, Bottke W.F. Jr., Cellino A., Paolicchi P., and Binzel R.P. (eds), University of Arizona Press, Tucson, 669

Xu, S. 1994, PhD thesis, MIT.