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The Near Earth Objects: possible impactors of the Earth/Les astéroïdes geocroiseurs: impacteurs potentiels de la Terre

Surface compositions of NEOs

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Abstract

The physical characterization of the surfaces of Near Earth Objects (NEOs) is crucial to analyse the relationships among NEOs and the other populations of minor bodies of the Solar System (main-belt asteroids, comets and meteorites) and to investigate NEO origin and evolution. Reflectance spectroscopy provides a powerful tool for determining several aspects of the surface composition of atmosphereless bodies. In particular, photometry and spectroscopy in a large wavelength interval (from visible to far-infrared) allow us to characterize the materials present on the surfaces of NEOs and to classify them, depending on the albedo values and the observed spectral behaviour. ***To cite this article: E. Dotto et al., C. R. Physique 6 (2005).***

Résumé

La caractérisation physique de la surface des astéroïdes proches de la Terre (Near Earth Objets, NEOs) est cruciale pour analyser les relations entre la population des NEOs et les autres populations de petits corps du Système Solaire (astéroïdes de la ceinture principale, comètes et météorites) et pour étudier l'origine des NEOs et leur évolution. La spectroscopie de reflectance nous donne un excellent outil pour déterminer plusieurs aspects de la composition de la surface des objets sans atmosphère. En particulier la photométrie et la spectroscopie dans un grand intervalle de longueurs d'onde (du visible a l'infrarouge) nous permettent de caractériser les matériaux présents sur la surface des NEOs et de classifier ces objets, en fonction de l'albédo et des caractéristiques du spectre observé. ***Pour citer cet article : E. Dotto et al., C. R. Physique 6 (2005).***

Keywords: Near Earth objects; Reflectance spectroscopy; Albedo

Mots-clés : Astéroïdes proches de la Terre ; Spectroscopie de reflectance ; Albédo

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1. Introduction

The importance of studying NEOs has been recognized worldwide, considering also that these objects constitute a potential hazard for Earth. Both ground based observations and spacecraft missions are being applied to their study. Scientists have developed international cooperative efforts to increase the available information about the physical and dynamical characteristics

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of these potentially dangerous bodies. The necessity of these observations has been underlined by the Resolution of the Council of Europe of January 1996 in favour of the development of world-wide programs for the search and physical characterization of NEOs. This need has been highlighted also during the international workshop IMPACT held in Torino (Italy) in June 1999 and sponsored by IAU, NASA and ESA. A recommendation for the necessity of physical and chemical characterization of NEOs has been issued and addressed to the world governments and the international agencies and organizations involved in space and astronomical research. In the last years, several NASA space programs, such as NEAR-Shoemaker and Deep Space 1, have targeted NEOs and the Japanese mission MUSES-C (now called Hayabusa) is designed to return a sample from a near-Earth asteroid. ESA commissioned in 2002 six assessment studies of space missions devoted to the investigation of NEOs. Such in situ investigations provide very detailed information about most of the physical, dynamical and geological characteristics of each target body. Size, mass, bulk density, mineralogical and chemical composition, rotational state, to name just a few, are among the parameters which can be determined with a high degree of accuracy by space missions. However, space probes can visit and can give us a very detailed view of a very limited number of objects. If we want a picture of the whole population we need to observe NEOs from ground-based observatories. Earth-based observations allow us to extend the results from space missions to all the known NEOs, to study the global properties of the whole population and its heterogeneity.

The NEO population seems to be very diverse in nature. Available data show that among NEOs there exist objects with unusual shapes, including very elongated or bifurcated shapes [1]. Radar observations and optical photometry suggest that a substantial fraction of NEOs could be binary systems [1]. Lightcurve studies show that some of these objects have a complex, non-principal axis rotation state (*tumbling* asteroids) while some others display very long rotational periods [2], which are not easily explained by the current dynamical and collisional models.

In this scenario photometric and spectroscopic data are of fundamental importance to study the physical properties of NEOs, in order to retrieve information about the region where these bodies formed and to investigate the thermal and dynamical evolution they suffered.

More generally, the knowledge of the surface composition of NEOs allows us to define some constraints: (i) on the nature and composition of this population of small bodies of the solar system; (ii) on the processes that governed their formation and physical and thermal evolution; and (iii) on the relationship that NEOs have with main-belt asteroids, comets and meteorites.

2. V and NIR spectroscopy: taxonomic classification

To define the surface composition of asteroids, and consequently to assess their origin and thermal evolution, it is fundamental to characterize them through spectroscopic analysis. Spectroscopy is the most exploited technique to derive the surface mineralogy of atmosphereless bodies and to classify them taxonomically. On the basis of the visible spectra of the whole asteroid population, several taxonomies have been obtained [3–6]. All these classifications group asteroids which have similar spectral properties and thus must have similar surface compositions having experienced a similar evolution.

The most part of information available about the NEO surface composition comes from the analysis of the visible and near-infrared spectra. This wavelength range is in fact useful to look for spectral features of silicates (e.g. olivine and pyroxenes). In particular the analysis of the wavelength position of the spectral band at 1 micron, allows us to investigate the mineral diversity (namely different olivine-orthopyroxene mixtures) among silicatic objects. Moreover, the visible spectral range contains features due to the presence on the surface of oxidized or aqueous altered materials. These materials constitute evident signatures that aqueous alteration processes occurred and are important indicators of the temperature reached and the thermal history suffered by each body.

Unfortunately, little spectral information has been gathered about NEOs. The data available are referred to a sample of 389 objects ([7–9] and references therein), among the approximately 3000 known NEOs.

We considered the whole sample of 389 NEOs so far classified and we placed each of them in one of the major groups, called complexes, defined in the Bus taxonomic system [6]. Table 1 reports the asteroid complexes with likely mineralogy and possible meteorite analogues. This Table does not report the X and U complexes: X-types are spectrally similar to E, M, and P-type objects and when their albedo is measured are classified into one of these classes, while the U type groups objects which have unusual spectra and are far from the cluster centers [6]. Fig. 1 shows the NEO distribution across all the taxonomic ‘complexes’, grouped as in Stuart and Binzel [10].

The most obvious property is the variety of spectral features, physical characteristics, and compositions: the NEOs population includes all the taxonomic classes present in the main belt, with the exception of the class Cgh (by Bus [6]) which is typical among the outer main-belt asteroids (beyond 2.7 AU). In our sample, the ‘bright’ asteroids are more numerous than the ‘dark’ ones. In particular, the S complex contains the greatest number of NEOs (149 objects), while the dominating group within the main belt itself is the C-class (which contains about 75% of the population of known main belt asteroids). This characteristic was already noticed and discussed by several authors. Luu and Jewitt [11] investigate the possible source of the abundance of S among NEOs and found, as possible biases, albedo and phase-angle effects. The discovery of S-type NEOs could take advan-

Table 1
Taxonomic types, minerals and possible meteorite analogous

Tax. type	Minerals	Possible meteorite analogous
A	Olivine ± FeNi metal	Olivine Achondrites Pallasites Olivine-metal partial melt residues
V	Pyroxene ± Feldspar	Eucrites, Howardites, Diogenites
E	Enstatite	Enstatite achondrites (aubrites) Iron-bearing Enstatites Fe-bearing Aubrites
M	Metal ± Enstatite Hydrates Silicates + Organics?	Iron Meteorites Enstatite Chondrites
S	Metal ± Olivine ± Pyroxene	Pallasites with accessory py. Olivine-dominated Stony-Iron Urelites and primitive achondrites CV/CO chondrites Ordinary Chondrites
O	Olivine + Pyroxene	L6-LL6 Ordinary chondrites
Q	Olivine + Pyroxene (+ metal)	Ordinary Chondrites
R	Olivine + Orthoyroxene	Olivine-pyroxene cumulates Olivine-pyroxene partial melt residues
C	Iron-bearing hydrated Silicates	CI1 and CM2 Chondrites Dehydrated CI1 and CM2 assemblages
P	Anhydrous silicates + organics	Olivine-organic cosmic dust particles
D	Organics + Amhydrous silicates	Organic-olivine cosmic dust particles

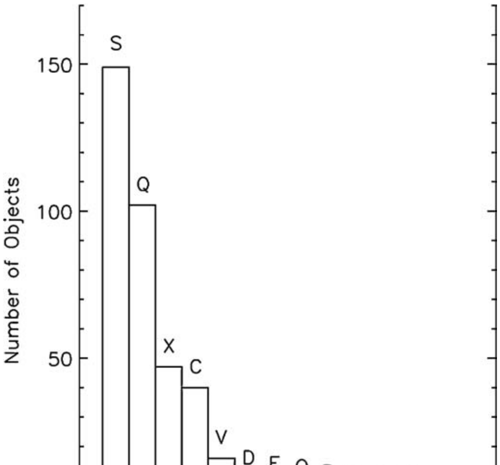

Fig. 1. Taxonomic complexes among NEOs (from [7–10] and references therein).

tage of the fact the NEOs are usually discovered at a large phase angle and the apparent magnitude of S-type objects decreases less rapidly than it does for C-type asteroids. Moreover C-type asteroids have albedo values lower than S-type asteroids and this may bias their discovery and observations. Lupishko and Di Martino [12] suggested that the dominance of S-type NEOs could be due to a dominant contribution from the inner asteroid belt where S-type asteroids are dominant. Binzel et al. [7] carried out a wide analysis of the source regions of NEOs and concluded that the ν_6 secular resonance is the most important source for observed NEOs belonging to all the taxonomic classes. Moreover, they showed that C-type NEOs have an origin signature from the mid to outer belt, P-type objects from the outer belt, D-type NEOs from the Jupiter-family comets and S, V, and Q types have similar signatures of source region contributions (close to the average) and probably have similar main belt region origin.

Among all the 389 NEOs so far analysed only few objects (e.g. 2099 Opik, 5585 Parks, 1995 WQ5, 2002 DH2) have visible spectral behaviours which can be related to the presence of aqueous altered materials on their surfaces [7]. This is a very low percentage in comparison with main-belt asteroids, where more than 60% of the C-type asteroids, at heliocentric distances between 2.5 and 3.5 AU, have been claimed to have undergone some kind of aqueous alteration process [13]. Aqueous alteration is a low temperature chemical alteration of materials by liquid water which acts as a solvent and produces materials such as phyllosilicates, sulfates, oxides, carbonates and hydroxides. Spectral characteristics at 0.43, 0.5, 0.55, 0.6–0.65, 0.7, 0.8–0.9 micron are related to transfer transition which are usually forbidden and possible only in presence of liquid water on the surface of the object. These spectral features, found in the visible spectra of several low-albedo main-belt asteroids and outer belt asteroids, indicate that liquid water was present on their surface during some previous epoch. Several possible explanations can justify the lack of spectral features due to aqueous alteration processes on the surface of NEOs. Howell et al. [14] analysed main-belt asteroids and found a relation between the presence of aqueous alteration processes and diameters. They did not find any aqueous alteration feature within the spectra of asteroids smaller than 50 km and interpreted this as probably due to the fact that below a given dimension aqueous alteration processes cannot occur. Nevertheless, since small asteroids can be fragments of hydrated larger bodies, the present sample of visible spectra of small objects is too limited to draw any final conclusion. Other possible explanations for the absence of aqueous alteration features within NEO spectra have to be taken into account and discussed: (i) the observed lack could be just an observational bias; (ii) it could indicate that the amount of water on NEO surfaces was not sufficient to produce such abundant hydrated silicates to survive a collisional evolution and for this reason these minerals are not still detectable; (iii) it could be due to the fact that the likely source region of aqueous altered NEOs, from the outer belt, is a minor contributor; and (iv) the meteorites containing aqueous altered materials probably arrived on Earth millions of years ago, and the NEO parent body has long since disappeared.

3. Albedo values

The albedo – the percentage of incoming solar light reflected by the surface of the object – is a fundamental physical parameter in determining the size distribution, nature, and the composition of the NEO population. Albedo information is useful to interpret the observed spectra and to infer the surface composition of small bodies. It is very well known that the classifications of E, M, P-types objects, displaying relatively featureless spectra, can be ambiguous. Albedo information allows the taxonomic designation to be resolved.

The albedo distribution and its correlation with the taxonomic types and the orbital elements is the key to investigating the nature of NEOs and to obtaining a reliable size distribution for this population of objects. The knowledge of the albedo distribution allows the convertion of the NEO absolute magnitude distribution, which is now well constrained, into a size distribution. Stuart and Binzel [10] apply currently known albedo information to debias the discovery statistics of the NEO population. They find the NEO population consists of 1090 ± 180 objects with diameters larger than 1 km, a value in good agreement with a theoretical model of the population developed by Morbidelli et al. [15]. Unfortunately albedo information cannot be derived from visible wavelength photometry or spectroscopy: the absolute brightness of an asteroid is proportional to the product of $D^2\times$ albedo, where D is the object's effective diameter (i.e. the diameter of a sphere with the same projected area). Colour information obtained with visible wavelength measurements (UBVRI-photometry or spectroscopy) can be used to classify asteroids into broad compositional types, restricting the albedo uncertainty to within the ranges of 0.03–0.09 for C-type objects and 0.10–0.22 for S-type asteroids. Those albedo ranges which are too broad for any reliable diameter determination are based on measurements obtained for main-belt asteroids, whose sizes are in general larger than 50 km of diameter. It is worth to point out here that main-belt asteroids are fifty times the sizes and five orders of magnitude more massive than a typical 1 km NEO.

NEO albedos are measured with a number of different techniques (see Levasseur-Regourd et al. this issue). Recent long-term observational programs devoted to the study of thermal infrared emission have incremented the number of NEOs with measured sizes and albedos by 54% [16,17]. Fig. 2 shows the total number of near-Earth asteroids with measured size and albedo as a function of their diameter. On the basis of this new large database of radiometric diameters and albedos it has been found that the observed NEOs have significantly higher albedos than main-belt asteroids belonging to the same taxonomic types. Such a discrepancy between the albedo properties of large and small asteroids may imply some fundamental differences in surface characteristics. This may also explain the trend of increasing albedo with decreasing size for observed S-type NEOs shown in Fig. 3. According to Delbó et al. [16] this trend may be indicative of recently exposed, relatively unweathered surfaces: smaller/younger objects should have younger/less weathered surfaces with higher albedo values (see Section 5). This result is also consistent with a general trend for smaller NEOs to exhibit reflectance spectra more similar to those of ordinary chondrite meteorites [18]. Also a selection effect in favour of the discovery of brighter NEOs in a magnitude-limited survey may explain such a trend. A simulation of the NEO discovery process and of the possible selection effect, involved in the choice of the objects to be observed in the thermal infrared, is an important future work that can clarify this issue.

Radiometrically derived albedos (and size) strongly depend on the applied thermal model. In fact, in the interpretation of radiometric data some physical assumptions on the surface temperature distribution and infrared emissivity are needed. Compli-

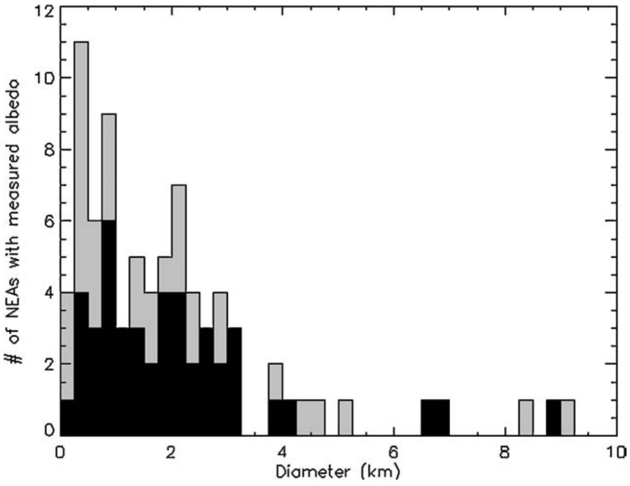

Fig. 2. The number of NEOs with measured size and albedo as a function of their diameter: in black are shown the values given by Binzel et al. [18]; in grey are shown new and refined diameters and albedos obtained by Delbó [17].

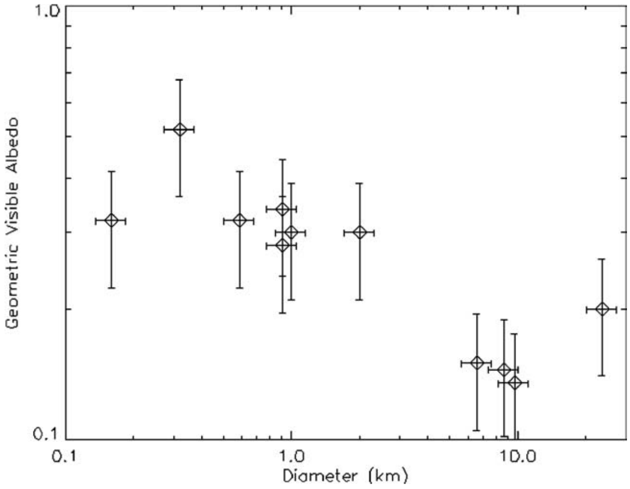

Fig. 3. Plot of the geometric visible albedo versus diameter derived by NEATM (the near-Earth asteroids thermal model, see Harris [19]) for S-type NEOs. The plot suggests a significant trend of increasing albedo with decreasing size. The trend may be due to a bias in favour of the discovery and characterization of high albedo objects.

cations arise due to the fact that important physical properties, like shape and mainly thermal inertia which are usually unknown, strongly affect the actual temperature distributions and the expected infrared fluxes. These effects become increasingly important when observations are carried out at large phase angles (e.g. $\alpha > 40^\circ$). In several known cases, measurements carried out at large α have led to grossly inaccurate sizes and albedos, incompatible with radar derived diameters and/or taxonomic classification [20–22]. A quantitative assessment of the accuracy of thermal models and a correction function for the nominal results at large phase angle would be an important project to be pursued in the near future.

4. Relationship with main-belt asteroids comets and meteorites

Increasingly over the past decade, the small body population has become better understood as being a continuum of left over planetesimals whose principal differences arise according to the region were they formed and evolved. As an example, it has been recognized that the compositional differences among outer main-belt asteroids, Jupiter Trojans and short period comets is subtle, as well as the distinction among near-Earth asteroids, and comets. In this new scenario NEOs play a fundamental role as they represent a very interesting link among main-belt asteroids, cometary nuclei, and meteorites. Examples include the

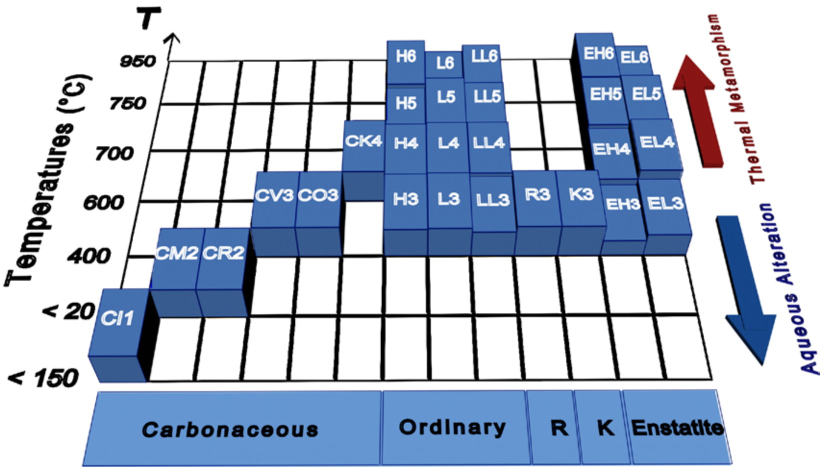

Fig. 4. The chondrite classification as a function of the estimated temperature required for producing the petrographic types. R and K on the bottom indicate Rumuruti and Kakangari, respectively. Arrows on the right indicate the degree of aqueous alteration or thermal metamorphism. The level of each box in the third dimension gives the relative proportions of the various petrologic types for each chondrite group: few chondrites are not affected by secondary processes.

identification of the asteroid (4015) 1979 VA with comet Wilson–Harrington, and the discovery of 3200 Phaethon as the parent body of the Geminids' meteor stream.

Two other NEOs, 2201 Oljato and 1566 Icarus, due to their very elongated orbits, have been proposed as good candidates to be extinct comets although their spectral properties suggest an S-type composition which is not apparently compatible with cometary origin.

An important point is to understand the number of NEOs which are surely extinct comets. In a classic analysis, Fernandez et al. [23] found a dependence between albedos and the Tisserand parameter T. Inner and outer Solar System objects with $T \leqslant 3$ have distinctively low albedo and are candidate to be cometary nuclei. For NEOs the value of the Tisserand parameter is not so strictly meaningful, since after interaction with planets and non-gravitational forces, NEOs can have changed the Tisserand parameter. Binzel et al. [7], on the basis of their taxonomic statistics found that 10–18% (in a diameter limited sample) of NEOs with both $T > 3$ and $T < 3$ may be extinct comets. This extinct comet population estimate is also consistent with the theoretical model of Morbidelli et al. [15].

Meteorite analogues have been assessed for the different asteroid taxonomic classes and several NEOs have been indicated to be the sources of meteorites delivered to the Earth. Lazzarin et al. [8] found good spectral matches among some NEOs and meteorite types. Nevertheless the link between NEOs and meteorite types is not completely understood. It has been noticed that there is a significantly greater apparent mineralogical diversity among asteroids than among meteorites. This seems to suggest that meteorites would be an incomplete sample of the mineralogy present among asteroids. Also the study of the cosmic ray exposure ages of meteorites indicates the presence of discrete groups at different ages (Perron and Zanda this issue). This seems to suggest that the delivery of meteorites is not a continuous flux. It should be due to few events and would be drawn by some selection effects e.g. the proximity of the parent body to a chaotic zone in the asteroid main belt and/or the structure and nature of the parent body itself.

Fig. 4 shows the chondrite classification as a function of both the compositional and petrographic type. As an example the compositional type H is classified in several petrologic grades, depicted for example by H3, H4, H5 and H6. The figure reports also the estimated temperature needed to produce the different petrographic types and the corresponding level of thermal metamorphism or alternatively aqueous alteration. Meteorites belonging to the same compositional group would come from the same parent body or several similar parent bodies. Different thermal histories (metamorphism or aqueous alteration) are supposed to have produced the different petrological types. Since for each taxonomic class there has been found a meteoritic analogy, we can infer that Q-type asteroids (similar to ordinary chondrites), have undergone modest thermal evolution over the age of the Solar System, while carbonaceous chondrites (similar to C-type asteroids) are inferred to be more primitive. Asteroids similar to the CO3 meteorites may have supported some initial stage of metamorphism, while objects more similar to CI meteorites are less thermally evolved bodies.

In some cases it has been possible to find a strong relation between a group of meteorites and a specific NEO candidate to be the parent body. This is the case of 6 Hebe: from dynamical and spectroscopic constraints it has been suggested that Hebe may be the source of a significant fraction of the ordinary chondrite meteorites [24,25]. Another interesting example is 3103 Eger, an E-type NEO probably coming from the Hungaria region of the asteroid belt [26]. It has been suggested to be the parent body of the aubrites, a type of achondrite enstatite meteorites. More recently, several authors have noted the presence of V-type NEOs, similar to the howardite-eucrite-diogenite meteorites and to the main-belt asteroid 4 Vesta. These objects are supposed to come from the Vesta family and to be the result of the collisional activity of 4 Vesta which produces family in the main belt and displaced some fragments in the NEO region.

A problem known as the ordinary chondrites conundrum has persisted for nearly two decades, but now appears to be coming toward some resolution. Stated briefly, the conundrum is that 80% of all meteorites that fall to Earth are ordinary chondrites, while a much smaller fraction of the NEO population has spectral characteristics matching these meteorites. The NEOs in the Q-class are most analogous to ordinary chondrite meteorites. The most commonly offered explanation is that a spectral alteration mechanism (space weathering) modifies the appearance of the regolith of ordinary chondritic asteroids and effectively makes them look different from meteorites. Another proposed explanation is that the parent asteroids of the ordinary chondrites are fragmented by collisional evolution down to sizes that are not thoroughly sampled in our observing programs.

Binzel et al. [27] suggested a possible solution of this conundrum. They showed that NEOs have spectral features which span the range between the domains of ordinary chondrite meteorites and the most common S-type main-belt asteroids. They concluded that this range could arise through a diversity of mineralogies and regolith particle sizes, as well as though a time-dependent surface weathering process. In this last case, asteroids most closely resembling ordinary chondrite meteorites would be those with the youngest surfaces. As the available data on small NEOs (most likely to have young surfaces) have increased, Binzel et al. [7] show that 65% (40 and 25%, respectively) of the observed NEO population falls in the S- and Q-classes, perhaps closing the gap with the fall frequency (80%) enough to begin to consider their material strength and atmospheric entry survival as part of the answer to the conundrum.

5. Space weathering processes

Solar radiation, cosmic rays, and microimpacts are inferred to alter the surface of atmosphereless bodies and progressively to change their reflectance spectra. The effects are different according to the solar distances of the bodies and their surface composition. In the inner part of the Solar System, silicate surfaces grow darker in time, while their reflectance becomes redder than the spectra of their constituting rocks. In the outer Solar System cosmic rays should lead to the selective loss of hydrogen in surface materials, and promote the formation of chemically complex polymers, many of which are dark in colour and spectrally red, due to their high carbon abundance. Space weathering was first studied on lunar soil [28] and was invoked to explain the surface variations of the main-belt asteroid 243 Ida seen in the images obtained by the Galileo space mission [29]. After that, time-related space weathering processes have been often been invoked to interpret spectral diversities among objects belonging to the same population: e.g. main-belt asteroids members of dynamical families, trans-neptunian objects and Centaurs.

In the case of NEOs, Binzel et al. [7] invoked space weathering processes to explain the trend of the spectral slopes studied as a function of size. These authors noticed that the visible spectral slope of NEOs have a high dispersion for the smallest objects, and are less dispersed for larger sizes. A possible cause of that could be the effect of space weathering processes. Smaller NEOs have shorter collisional lifetime than larger ones, thus larger asteroids can be expected to be usually older than smaller ones. Since collisions are a stochastic process not all the small asteroids can be supposed to be young. Nevertheless, we can estimate that a lot of small asteroids have rejuvenated, fresh and less reddened surfaces. In this scenario the dispersion of spectral slopes among small NEOs can be expected to be higher than among larger NEOs. Binzel et al. [7] also find a size dependent trend, where S-type NEOs smaller than 5 km are increasingly similar to ordinary chondrite meteorites. Above 5 km, S-type NEOs increasingly resemble their larger relatives in the main belt. These authors suggest that this size dependent trend is related to average surface age, if small asteroids are typically ‘younger’ than larger ones. They find that 5 km may be a transition size where either the surface has become ‘old enough’ for a regolith to become space weathered, or gravity becomes sufficient to retain a regolith that may be affected by space weathering processes. Independently, Cheng [30] presents a new collision model for asteroids and finds that 5 km may be a transition between long-term collisional survivors and younger fresher fragments – the same size at which S-type NEOs appear to make their transition in spectral characteristics with respect to ordinary chondrites.

5.1. Laboratory experiments

The importance of simulating one or more of the ageing processes (solar radiation, cosmic rays, and micro-impacts) has been pointed out by several authors. Nevertheless laboratory experiments to simulate the effects of these space weathering processes on silicatic and organic materials are, so far, very limited.

Shkuratov et al. [31] widely discussed the effect of reduced iron on the spectra of mafic materials: the spectral slope increases and the depth of the 1 micron band decreases. Sputtering of iron from iron-bearing silicates and the deposition of nanophase neutral Fe on adjacent grains seem to be the principal factor in producing spectral changes [32]. Pieters et al. [33] found that nanophase reduced iron (npFe^0), produced in the space environment by the reduction of FeO in minerals, causes a space

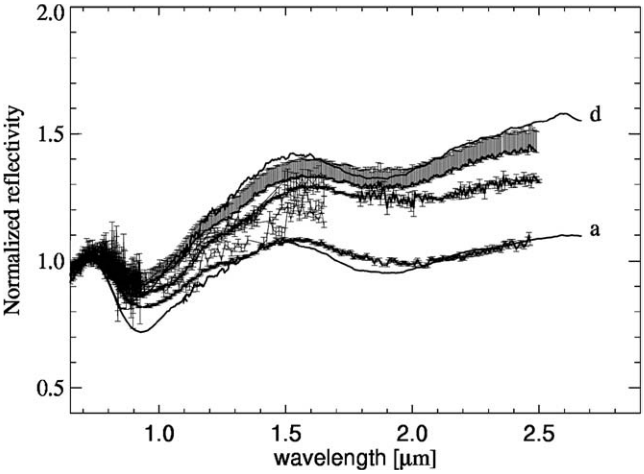

Fig. 5. The reflectance spectrum of Epinal before the ion irradition (spectrum a) and after 1.7×10^{16} Ar^{++}/cm^2 (spectrum d) compared with the spectra of near earth asteroids. The spectra are normalized to 1 at 0.7 micron.

weathering effect on lunar soil: the surface becomes darker, with redder spectral continuum and weaker absorption features. Binzel et al. [34] modeled the spectral reddening of the S-type asteroid 25143 Itokawa (1998 SF36), target of the Japanese space mission Hayabusa, with the spectrum of $npFe^0$. They found that only 0.05% of $npFe^0$ is enough to model this space weathering process. After the 'de-reddening' the asteroid spectrum is consistent with the range of spectral properties of LL ordinary chondrite meteorites.

Sasaki et al. [35] carried out laboratory experiments of laser irradiation on olivine samples to simulate micrometeorite bombardment. Their results showed reddening of the spectrum and decreasing of the depth of the 1 micron band. Spectral changes were not found by Dukes et al. [36] who tried to simulate the effect of the solar irradiation by irradiating olivine sample with H^+ and He^+ ions. They interpreted the lack of spectral changing as due to the re-oxidation of iron removed from the vacuum chamber. Yamada et al. [37] performed nanosecond and pulse laser irradiation and high energy (MeV) proton implantation, producing small changing in the spectra. Clark et al. [38] simulated micrometeorite bombardment by heating and grinding samples of ordinary chondrite meteorites and obtained changing in the reflectance spectra. Hiroi and Sasaki [39] modeled the surface composition of two main-belt asteroids with a mix of altered and unaltered silicates whose spectra fit the observed visible and near-infrared asteroid spectra.

Further laboratory experiments of ion irradiation of organics and silicates have been recently carried out [40,41].

Strazzulla et al. [40] irradiated a sample of the ordinary chondrite meteorite Epinal with 60 keV Ar^{++} ions. The bidirectional reflectance spectra of the meteorite sample, obtained in the range between 0.3 and 2.67 micron after different ion fluences, exhibit a progressive reddening. The range of variation of the spectral reddening obtained for the Epinal spectra before and after irradiation well reproduces the spectral spread observed for S-type NEOs. Fig. 5 shows the initial spectrum of Epinal, the spectrum obtained after the highest ion fluence and, as a comparison, the observed spectra of S-type NEOs. Taking into account the flux and the energy of Ar^{++} and heavy ions present in the solar wind, the time-scales needed to induce in space the same effects obtained in these laboratory experiments are estimated to be on the order of 10^4–10^6 yr. This quite short time scale implies that either the objects showing the least reddened spectra have been recently injected in their near Earth orbits or their surfaces have been recently rejuvenated.

In order to simulate the ageing effect of TNOs and Centaurs, Moroz et al. [41] also carried out laboratory irradiation of natural dark spectrally red organic materials (complex hydrocarbons asphaltite and kerite). Bulk and dust samples were irradiated by 15–400 keV H^+, N^+ and Ar^{++} ions and diffuse reflectance spectra between 0.3 and 2.5 micron were measured after increasing the ion fluences.

The results indicate that in all cases the initially 'red' spectra progressively flatten with increasing ion fluences. Near infrared spectra of the bulk sample of asphaltite before and after irradiation with 60 keV Ar^{++} ions are shown in Figs. 6. Ion irradiation of the sample causes an increase in brightness in the visible range and a decrease of spectral slope at longer wavelengths, the total effect being the flattening of the spectra. The optical changes have been interpreted as due to progressive carbonization of the material. In addition, the shape of the spectrum changes from concave – typical of solid oil bitumens and other organic solids such as tholins – to straight and convex.

Further laboratory experiments are already scheduled to simulate the space weathering effect of ion and proton bombardment on ices and icy mixtures of silicates and organics.

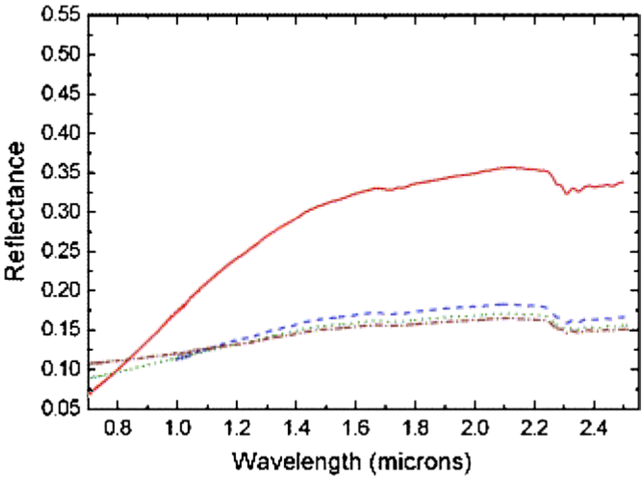

Fig. 6. Near infrared reflectance spectra of asphaltite before irradiation (continuous line) and after fast bombardment with Ar^{++} at 60 keV at increasing fluences (1.1×10^{14} Ar^{++}/cm^2 dashed line, 10.2×10^{14} Ar^{++}/cm^2 dotted line and 3.0×10^{15} Ar^{++}/cm^2 dashed-dotted line). These spectra were acquired 'in situ'.

6. Conclusions and future work

On the basis of all the results discussed above, it is evident that NEOs constitute a heterogeneous population based on both physical and dynamical properties.

NEO physical diversity is mainly reflected by the different taxonomic types present in the population: even if little is still known on the surface composition, the population appears heterogeneous in all the aspects of its physical characteristics. Also from the dynamical point of view we can recognize objects coming from the asteroid main belt, as well as objects having cometary origin. Although the cometary contribution is still uncertain, a possible percentage of comet nuclei among NEOs has been established. A better definition of the cometary contribution to the NEO population and, more in general, a better understanding of the NEO origin will be fundamental topics for future research.

Moreover, recent studies have shown that also the collisional history of NEOs could be more challenging than predicted: Binzel et al. [42] found a clustering of low inclination NEOs with aphelia slightly in excess of 3 AU. As for today the origin of this cluster is puzzling: it might have a purely dynamical origin, being possibly connected to the ν_6 secular resonance located close to that region, or alternatively it could be a dynamical family produced by the disruption of a parent body after a catastrophic collisional event. In this last case, it would be the first dynamical family discovered among NEOs. Although collisional families have been found so far only in the asteroidal main belt, the presence of young families cannot be excluded in the NEO population, even considering its short dynamical lifetimes. Also, in this case, a detailed study of the physical and dynamical properties of the cluster members will be necessary to assess their origin and provide the necessary observational clues on the existence (or not) of a family.

In the coming years space missions will give us important 'in situ' information on the composition and structure of a limited number of targets. Nevertheless, much work remains to be done for physical ground-based observations to have a global picture of the whole NEO population and to investigate its relationship with comets, main-belt asteroids and meteorites. Also the effect of space weathering processes on the alteration of NEO surfaces remains to be fully understood. For all these purposes the efforts to carry out major observational survey programs and further laboratory experiments must be continued in the future.

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