Near Earth Objects, our Celestial Neighbors: Opportunity and Risk
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Near-Earth objects as principal impactors of the Earth: Physical properties and sources of origin

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Abstract. Near-Earth objects (NEOs) are objects of a special interest from the point of view not only of cosmogonic problems of the Solar system, but of the applied problems as well (the problem of asteroid hazard, NEOs as the potential sources of raw materials, etc.). They are much smaller in sizes than main-belt asteroids (MBAs), very irregular in shape and covered with a great number of craters of different sizes. Most of NEOs are covered by regolith of low thermal inertia and different thickness. Objects with complex non-principal axis rotation (tumbling bodies) and with super-fast rotational periods have been detected among them. The new data, based on photometric and radar observations, evidence that about $15-20$ % of NEOs could be binary systems. Most of the classified NEOs fragments of differentiated assemblages of S- and Q-types. Analysis of physical properties of NEOs clearly indicates that the asteroid main-belt is the principal source of their origin and only about 10 % of NEOs have a cometary origin.

Keywords. transport of meteorites; asteroid, orbit; asteroid, shape; asteroid, spectra

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1. Introduction

Starting from Shoemaker *et al.* (1979), the objects belonging to the NEA population, which can approach and cross the Earth's orbit, are traditionally divided into three groups (the relative abundances have been estimated by Bottke *et al.* (2002) and refer to a modeled debiased population):

$$\text{Amor} \qquad a \geqslant 1.0 \text{ AU} \qquad 1.017 < q < 1.3 \text{ AU} \qquad (32 \pm 1\%)$$

$$\text{Apollo} \qquad a \geqslant 1.0 \text{ AU} \qquad q < 1.017 \text{ AU} \qquad (62 \pm 1\%)$$

$$\text{Aten} \qquad a < 1.0 \text{ AU} \qquad Q > 0.983 \text{ AU} \qquad (6 \pm 1\%)$$

There is also an additional group of rather dangerous asteroids whose orbits reside entirely inside that of the Earth ($Q < 0.983$ AU). These objects can become Earth-crossers without having been previously spotted, because they are usually difficult for observations. According to Bottke *et al.* (2002), objects of this inner-Earth asteroid (IEA) group can constitute about 2% of the total NEO population.

Milani *et al.* (1989) proposed a new classification of the NEOs. On the basis of orbital evolution analysis, they named 6 dynamical classes after the most representative object in each class, i.e. Geographos class, Toro class, Alinda class, Kozai class, Oljato class and Eros class.

Table 1. Bulk density estimates currently available for NEOs. *) radar data.

Asteroid	Density, g/cm^{-3}	Type	Reference
433 Eros	2.67 ± 0.03	S	Yeomans *et al.* (2000)
6489 Golevka*	$2.7(+0.4, -0.6)$	Q	Chesley *et al.* (2003)
25143 Itokawa	1.95 ± 0.14	S,Q	Abe *et al.* (2006)
1999 KW4	1.97 ± 0.24 (primary)	S	Ostro *et al.* (2006)
	$2.81(+0.82, -0.63)$ (secondary)		Ostro *et al.* (2006)
2100 Ra-Shalom*	$1.1 - 3.3$	C	Shepard *et al.* (2000)
1996 FG3	1.4 ± 0.3	C	Mottola & Lahulla (2000)
2000 DP107	$1.6(+1.2, -0.9)$	–	Hilton (2002)
2000 UG11	$1.5(+0.6, -1.3)$	–	Hilton (2002)

More than $4,000$ NEOs have been discovered so far. They are the objects of special interest from the point of view not only of basic science but applied science as well (the problem of asteroid hazard, NEOs as the potential sources of raw materials in the nearest to the Earth, etc.). NEOs are the principal cosmic bodies which strike our planet occasionally and therefore they are a real threat to the humankind.

2. Sizes and Densities

The principal distinctions between NEOs and MBAs are in their orbits and sizes. NEOs are much smaller in size in comparison with MBAs. Amor asteroid (1036) Ganymed, with a diameter of 38.5 km, is the largest among NEOs. Two objects, 433 Eros and (3552) Don Quixote, are about 20 km in diameter and all others are smaller than 10 km. Fortunately, the three largest NEOs belong to the Amor group, that is, they are not dangerous bodies (at least now) because they can only approach the Earth but not cross its orbit. Among Earth-crossers, (1866) Sisyphus is the largest object with a diameter of about 9 km. The smallest known NEOs are about 10 m across (2003 SQ_{222}).

The size distribution of NEO population can be approximated by a power law

$$N(> D) = kD^{-b}$$

with an exponent $b = 1.65 - 2.0$ (Morbidelli & Vokrouhlický (2003); Stuart & Binzel (2004)) and is similar, and only slightly steeper, than that of the MBAs.

Unfortunately, the data on densities are available only for a few NEOs and the most accurate bulk density (see Table 1) was obtained for (433) Eros from the successful NEAR-Shoemaker mission. Similar values were obtained for other S- or Q-type objects (silicate types). Comparing their bulk densities with a density of S-asteroid meteorite analogues (ordinary chondrites) we have to suppose about 30% for the NEO porosity. Approximately the same situation is with low-albedo C-type objects. It means that some NEOs are not monolithic bodies but "rubble-pile" structures, which have no coherent tensile strength and are weakly held together by their own mutual gravity. One example of a "rubble-pile" body is the Apollo-object (25143) Itokawa (Fujiwara *et al.* (2006)).

For the largest Apollo-object 1866 Sisyphus (S-type, $D = 9$ km), considering a density of 2.67 g/cm^{-3}, the mass is 10^{12} tons. The collision of it with the Earth at a velocity of 20 km/s would release an energy of about 5×10^7 MT, that is, about 106 times the Tunguska explosion. However, the frequency of such event is about 10^{-7} - 10^{-8} $year^{-1}$.

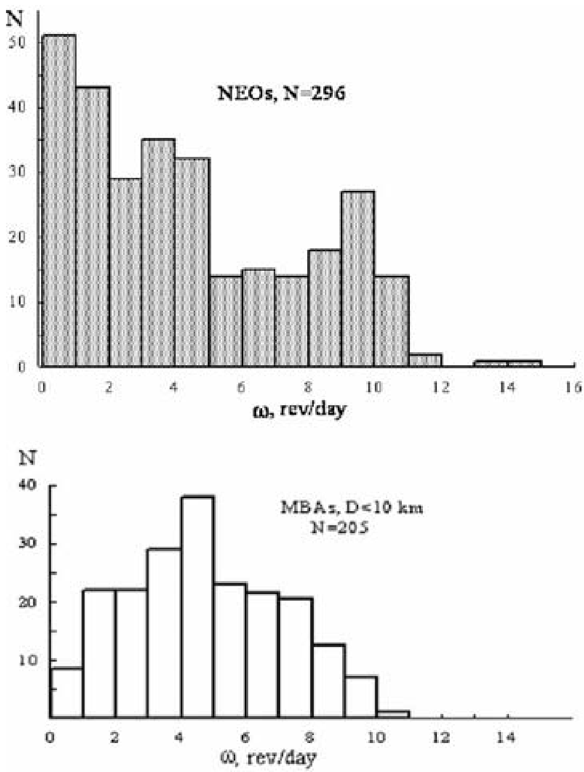

Figure 1. Distribution of the rotation rates of NEOs and small ($D \leqslant 10$ km) MBAs.

3. Shapes and Axis Rotation

Table 2 contains the average measured amplitudes (corrected to zero phase angle) of asteroid lightcurves, which characterize the shape elongation of the body. It is important to know that corrected amplitudes of the NEOs and MBAs are the same. Thus, NEOs on the average are elongated to the same extent as those of MBAs of corresponding sizes. But observations showed a striking diversity of NEOs shapes from nearly spherical (1943 Anteros, 2102 Tantalus) to very elongated (1620 Geographos, 1865 Cerberus) and to bifurcated (4179 Toutatis) and contact-binary ones (4769 Castalia, 2005 CR_{37}). The most elongated asteroid among observed NEOs is 1865 Cerberus ($D = 1.2$ km), the axis ratio $a : b$ of its figure is estimated to be equal to 3.2. The opinion that NEOs have more exotic shapes than MBAs may belong only to the large MBAs, because apart from lightcurves we know practically nothing about the real shapes of km-sized main-belt objects.

Figure 1 shows the histograms of distribution of the rotation rates (ω) of NEOs in comparison with that for small MBAs in the same intervals of ω. As one can see, they are quite different. It is an observational result which needs to be explained. But it is rather complex task, because there exist several reasons for that difference, among them the influence of the rotational parameters of binaries, the difference in asteroid diameter distributions within these two asteroid populations, possible influence the radiation pressure torques (YORP-effect), imperfect data statistics and maybe some selection effects. However, the whole interval of NEO rotation periods ranges over four orders of magnitudes from 500-600 hrs ((96590) 1998 XB and 1997 AE_{12}) to 1.3 min (2000 DO_8).

Table 2. Mean values of asteroid lightcurve amplitudes.

Population	Amplitude measured mag	Amplitude corrected mag	$a:b$	N
NEOs	0.53 ± 0.03	0.27	1.3	292
MBAs, $D < 10$ km	0.32 ± 0.02	0.26	1.3	205
MBAs, $D > 130$ km	0.22 ± 0.01	0.19	1.2	100

Among the km-sized NEOs the fastest rotators have rotation periods about $1-2$ hrs, for example,

(1566) Icarus - 2.273 hrs

2000 EB_{14} - 1.79 hrs

(23714) 1998 EC_3 - 1.2 hrs

but the slowest ones rotate with the periods equal to $1-2$ hundred hrs and even more (up to $500-600$ hrs):

(4179) Toutatis - 129.8 hrs

(3102) Krok - 147.8 hrs

(1998) QR_{52} - 235 hrs

There exist two peculiarities of NEO rotation, which are not discovered elsewhere among MBAs. The first: recently among the small NEOs the objects with superfast rotation were discovered, among them

2000 PH5 - 0.203 hrs (D∼100 m)

2000 AG6 - 0.077 hrs (D∼30 m)

2000 DO8 - 0.022 hrs (D∼40 m)

which have rotation periods within $2-20$ min Harris & Pravec (2006). It is clear that such fast-spinning bodies are beyond the rotational breakup limit for aggregates like "rubble piles" and they are monolithic fragments.

The second peculiarity is that among this population there are objects with very complex and non-principal axis rotation (so-called "tumbling" asteroids). They are usually slowly spinning objects. An example is the Apollo object (4179) Toutatis ($D \sim 3$ km), which rotates around the longest axis with a period 129.8 hrs, and has a long axis precession with a period of 176.4 hrs (Spencer *et al.* (1995); Hudson & Ostro (1995)). Other examples include 3288 Seleucus, (4486) Mithra, 2002 TD_{60}, and other NEOs that show two or more harmonic frequencies in their lightcurves. Among them there is only one MBA, (253) Mathilde, which is suspected to be tumbling (Pravec *et al.* (2005)). Tumbling objects may have experienced a recent collision and their internal stresses try to re-align the rotation axis with the principal axis to restore a non-tumbling state of the body.

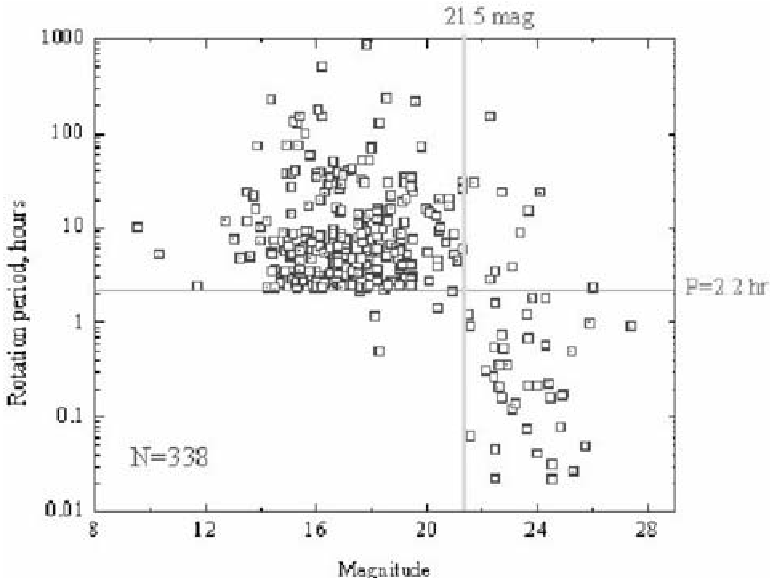

Figure 2. Rotation periods versus absolute magnitude for NEOs (from Krugly (2003)).

Figure 2 shows the rotation periods of NEOs versus their absolute magnitudes similar to the Figure 3 in Harris & Pravec (2006) for MBAs, NEOs and comets, but instead D (km) H (mag) is used. This diagram indicates the critical limit magnitude $H = 21.5$ which (at the bias-corrected mean albedo for the NEOs $pv = 0.14 \pm 0.02$, Stuart & Binzel (2004)) corresponds to the boundary diameter equal to 180 m. Objects below 180 m appear to be capable of fast rotation, indicating they must have an internal tensile strength (monolithic bodies). There is also the rotation "speed limit", corresponding 2.2 hours (as pointed out by Harris & Pravec (2006) as the "rubble pile spin barrier"). Thus, the region in rotation-diameter space where "rubble piles" can exist is limited by rotation period $P \geqslant 2.2$ hrs and $D \geqslant 180$ m. One can note that knowledge of the rotation period and size sometimes can provide important initial information on the nature and internal strength of a NEO.

4. Taxonomy and Mineralogy

Practically all Tholen's taxonomic classes of MBAs are represented among classified NEOs (Figure 3), including the low-albedo P- and D-types most commonly found in the outer asteroid belt among the Hilda and Trojan groups. Binzel *et al.* (2004) in their spectroscopic survey of 252 NEOs and Mars-crossers noted that 25 of 26 Bus' taxonomic classes of main belt are represented among the NEO population. Once more the principal question of the NEO taxonomy is the relative abundance of the two most numerous super-classes: C (carbon) and other low-albedo classes and S-Q (silicate) classes. About 70 % of the classified NEOs belong to S- and Q-classes, and the observed number of these objects exceeds the number of low-albedo ones (C and others) by as much as a factor $4-5$. Stuart & Binzel (2004) modeled the bias-corrected distribution of taxonomic classes and obtained that C and other low-albedo classes consist of 27% while S+Q classes consist of 36% of the NEO population. At the same time, Bus & Binzel (2002) obtained the bias-corrected distribution of asteroids ($D \geqslant 20$ km) of taxonomic complexes S an C in main belt ($2.25-3.25$ AU). Their data show that the ratio of asteroid number of C-complex to

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that of S-complex is about 1.8 (see Figure 19 in their paper). It means that the relative number of low-albedo objects among near-Earth population is 2.4 times less than in the main asteroid belt. It is very important result of NEO taxonomy and the most immediate explanation could be that NEOs are coming preferentially from the inner regions of main belt (Bottke *et al.* (2002)), where the relative abundance of low-albedo asteroids is small.

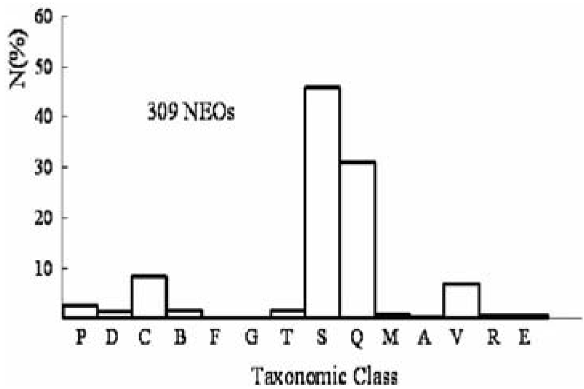

Figure 3. Distribution of taxonomic classes among NEOs.

Both taxonomy and mineralogic interpretation of spectra show evidence of genetic relationship between NEOs and MBAs. Many of the NEOs represent differentiated matter. Among them, there are objects with monomineral silicate composition and purely metallic ones. For example, small asteroid (1915) Quetzalcoatl does not contain olivine, thus diogenitic meteorites (Mg-pyroxenes) are the best analogs for it. A contrary example is (3199) Nefertity, which has no pyroxene and its composition corresponds to that of stony-iron meteorites - pallasites, that is, olivine and iron. There is a representation of unusual types such as R-types, which contain an olivine-pyroxene mixture. Three NEOs belong to the M-class, one of them, 6178 1986 DA, has a radar albedo (0.58) clearly indicating metallic composition for this asteroid. (3103) Eger with very high albedo (0.53) corresponds to assemblages of iron-free silicate minerals, such as enstatite. 22 NEOs classified as V-class, have spectra identical to those of main-belt asteroid (4) Vesta, which is known to be a differentiated body and is covered by basaltic (pyroxene-rich) material. About 30 % of classified NEOs belong to the Q-class which are the ordinary chondrite-like objects. So, the problem of finding parent bodies for the most common class of meteorites, the ordinary chondrites, now does not exist. Observing smaller and smaller S-objects Binzel *et al.* (1996, 2001) showed a continuous range of NEO spectra from those of S-types to ordinary chondrites (Figure 4). That is, there is a continuous transition (some continuum) from spectra of S-types to those of Q-types. At the same time Q-objects are smaller in size and brighter than S-objects, that is, their surfaces are "younger and fresher". Therefore, this continuum is interpreted as a result of a space weathering process, that is, a process of alterating the young surface of Q-asteroid to look more and more like an S-type surface. Figure 5 gives the spectral slope versus diameter for Q and S-asteroids. A running box mean shows that the spectral slope of Q-asteroids increases with diameter and at $D = 5$ km it becomes equal to the slope of S-types. That is, 5 km may represent a critical size in the evolution from an ordinary chondrite-like surface (Q-type) to an S-type surface. This means that objects of this size and larger have sufficient age for complete space weathering of their surface. Independently, Cheng (2004) found that $D = 5$ km may mark the boundary between primordial survivors and multi-generation fragments among the asteroids.

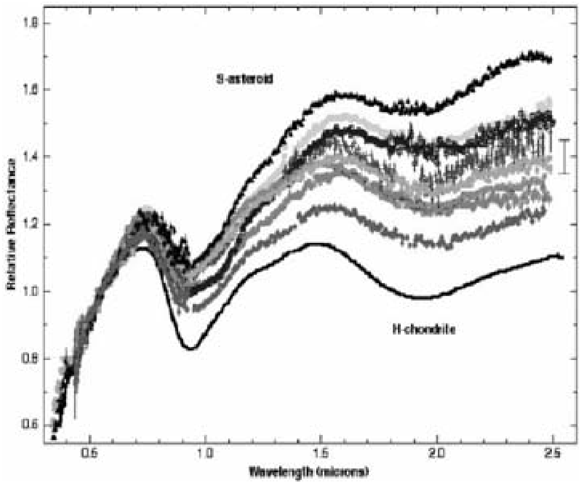

Figure 4. Continuum of spectral properties between S-type asteroids and ordinary chondrite meteorites.

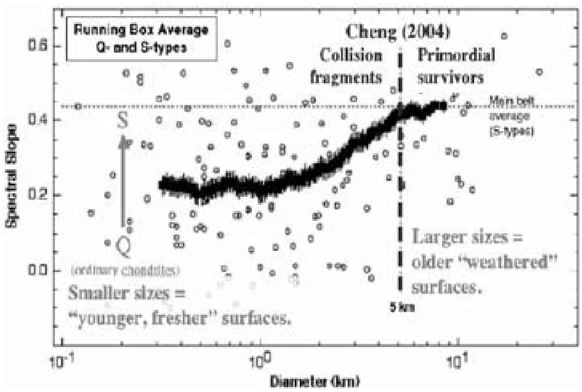

Figure 5. Spectral slope versus diameter for Q- and S-asteroids. A running box mean shows that spectral slope of Q-objects increases with diameter and at $D = 5$ km it become equal to slope of S-types.

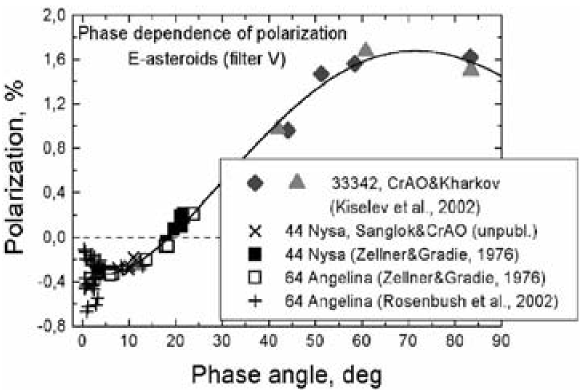

Figure 6. Polarization-phase angle dependence of Aten object 33342 (1998 WT_{24}) at large phase angles let us to obtain the complete phase dependence of polarization for E-type asteroids (Kiselev *et al.* (2002)).

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Table 3. Mean optical parameters of S-type asteroids in V-band (Binzel *et al.* (2002)).

Parameter	NEAs	N	MBAs ($D > 100km$)	N
Albedo polarim.	$0,183 \pm 0,011$	9	$0,177 \pm 0,004$	28
Albedo radiom.	$0,190 \pm 0,014$	23	$0,166 \pm 0,006$	27
U-B (mag)	$0,445 \pm 0,013$	30	$0,453 \pm 0,008$	28
B-V (mag)	$0,856 \pm 0,013$	31	$0,859 \pm 0,006$	28
β (mag/deg)	$0,029 \pm 0,002$	9	$0,030 \pm 0,006$	18
P_{min} (%)	$0,77 \pm 0,04$	3	$0,75 \pm 0,02$	28
h (% /deg)	$0,098 \pm 0,006$	9	$0,105 \pm 0,003$	23
α_{inv} (deg)	$20,7 \pm 0,2$	6	$20,3 \pm 0,2$	18

5. Optical Properties and Surface Structure

Analysis of photometric, polarimetric, radiometric and other observational data clearly demonstrates that the surfaces of NEOs display in general the same optical properties as the surfaces of MBAs (see Table 3). The whole range of NEO albedos (from 0.05 to about 0.50) is basically the same as that of MBAs and it corresponds to the same in general mineralogy within these two populations. But the strict similarity of the other photometric and polarimetric parameters (such as phase coefficient, polarization slope and others, which are related to surface structure) gives evidence of the similar surface structures at a submicron scale.

Having similar optical properties, NEOs help us to some extent to study the MBAs, since, approaching the Earth, they let us to observe objects in a wide range of geometries of illumination and observation. For example, polarimetry of the high-albedo Aten object 33342 (1998 WT_{24}) at large phase angles (see Figure 6) allows us to obtain the complete phase dependence of polarization for E-type asteroids (Kiselev *et al.* (2002)). It was quite unexpected to obtain the maximum positive polarization $P_{max} = 1.7$ % at a phase angle $a_{max} \approx 76$ deg, whereas for S-asteroids $P_{max} = 8.5 - 10$ % and $a_{max} = 100 - 110$ deg.

The data of radiometry, polarimetry and direct imaging of 433 Eros and 25143 Itokawa, obtained by the NEAR-Shoemaker and Hayabusa missions, show that most observed NEOs are covered with regolith. But the conditions of formation, accumulation and evolution of regolith on NEOs are different from those on MBAs because of the much smaller gravity NEOs, the higher flux of impactors in the main belt than in the near-Earth region ($1-3$ orders of magnitude), and the difference in intensity of solar wind. As a result, the regolith of NEOs tends to be more coarse-grained than that of MBAs and still more coarse-grained than the lunar one. The recent studies of NEO thermal IR emission showed that the thermal inertia of the observed NEOs is 550 ± 100 $\mathrm{Jm^{-2}s^{-0.5}K^{-1}}$, that is about 11 times that of the Moon (Delbò (2004)). It means that regolith of the NEOs is really coarser than the lunar one and, it is very likely, than that of MBAs.

Finally, radar data reveal that NEO surfaces are rougher than surfaces of large MBAs at the scale length of decimeters and meters and the porosity of NEO surface matter is about $30 - 50$ %, corresponding to a porosity of the top 5 to 10 cm of lunar regolith. The images of one of the largest NEOs, (433) Eros, and the rather small NEO (25143) Itokawa showed surfaces with variety of characteristics ranging from craters and boulders to perfectly smooth "ponds" of fine-grained dust. Ground-based radar observations also showed that even the relatively small NEO 4179 Toutatis and 1999 JM_8 ($D \sim 3$ km both) are cratered at about the same extent as MBAs (951) Gaspra and (243) Ida.

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6. On the Origin of NEOs

The short typical lifetime of NEOs $\sim 10^6 - 10^7$ years implies that the currently present population must be continually supplied. The study of physical and mineralogical properties of NEOs clearly indicate that the main asteroid belt is the principal source of their origin. It means that most of the NEOs are the fragments of main-belt asteroids ejected into their current orbits by processes of collisions and chaotic dynamics (Farinella *et al.* (1993)). On the other hand, the identification of a few objects with extinct or dormant comets (118401, 133P/Elst-Pizarro, P/2005 U1) does not exclude the cometary origin of some of them. Hence, the problem is the determination of the relative contributions of both sources.

The candidates for comet origin should be low-albedo objects of D, P and C-types, with lower rotation and more elongated shapes as compared with asteroids of corresponding sizes; they should also have atypical for asteroids orbits (comet-like, with $Q \geqslant 4.5$ AU) and association with meteor streams.

The most recent estimates of the contributions of the cometary origin of NEO are:

Lupishko & Lupishko (2001): $\leqslant 10\%$ of NEOs
Fernandez *et al.* (2001): "at least 9 % of NEOs are cometary nuclei"
Whiteley (2001): "$\sim$ 5 % rather than 50 % of the cometary origin".
Bottke *et al.* (2002): $\sim$ 6 % of the NEO comes from the Jupiter-family comet region
Binzel *et al.* (2004)): $\sim$ 15 % of the NEO may be extinct comets.

Apparent difference between the two last quantities (6% and 15%) is due to the estimate in Bottke *et al.* (2002) is given for a H-limited sample, while in Binzel *et al.* (2004) for a size-limited sample. When the correction for albedo is done, the two fractions are actually the same.

Thus, the recent estimates give the contribution of cometary origin of the NEO population to be on average about 10 %. This conclusion does not contradict the results of dynamical considerations (Menichella *et al.* (1996); Bottke *et al.* (2002)), according to which the main asteroid belt can supply a few hundred km-sized NEAs per 1 Myr, a rate sufficient to sustain the current NEO population.

7. Summary

The discovery rate of NEOs has increasd greatly over the last few years due to new observational programs. It is a very positive result but a new problem arises: the rate of physical studies of the NEOs remains behind of the rate of their discovery. Therefore our knowledge with respect to the discovered NEO population are becoming more and more scanty. That is why the study of the nature and physical properties of NEOs remains one of the priority directions of Solar system investigations which is necessary for addressing both fundamental scientific problems and applied problems of the humanity survival.

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