WHAT PHYSICAL PROPERTIES OF NEAR–EARTH ASTEROIDS TELL US ABOUT SOURCES OF THEIR ORIGIN?

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It is generally recognized that main-belt asteroids (MBAs) and nuclei of extinct comets are two main sources for the near-Earth asteroids (NEAs) replenishment. Theoretical studies of NEA dynamics and numerical modelling of their orbital motions showed that so-called resonance mechanism for supplying NEAs is quite sufficient to sustain this population. The physical properties of NEAs and MBAs (and partly of comet nuclei) were compared to understand what the physical properties of NEAs can tell us about sources of their origin. The results of the comparison are given in this paper. The principal results of such a comparative analysis can be reduced to the following. All the NEAs have the small sizes, almost the same variety of their taxonomic classes and mineralogy, predominance of differentiated assemblages among them, approximately similar shape and rotation, optical properties and surface structure as compared to those of MBAs. All these conclusions clearly indicate that the main asteroid belt is the principal source of NEA, and comet nuclei contribution to the total NEA population does not exceed 10%. The NEAs 2100 Ra-Shalom, 2101 Adonis, 2201 Oljato, 2212 Hephaistos, 3200 Phaethon, 3552 Don Quixote and 4015 Wilson-Harrington are the most probable candidates for the cometary origin.

INTRODUCTION

According to available estimates a median lifetime of Aten-Apollo-Amor asteroids in unstable orbits, which approach or cross the Earth orbit, is relatively short and approximately equal to 10^6–10^7 years. As far as the population of Earth-approaching asteroids still exists it appears to be continuously supplied by new objects. It is generally recognized that there are two sources of near-Earth asteroids (NEAs) replenishment: main-belt asteroids (MBAs) and dormant or extinct cometary nuclei. Recent studies certainly suggest that the main asteroid belt is the dominant source of NEAs, *i.e.*, the near-Earth asteroids are the fragments of MBAs coming to the current orbits through collisional processes and chaotic dynamics. These results have been obtained mainly on the basis of theoretical studies of the NEA dynamics and numerical simulations of their orbital motions [3]–[6], [14].

In this study we tried to compare all the relevant physical properties of near-Earth and main-belt asteroidal populations and partly of cometary nuclei to extract the information on the sources of NEA origin.

TAXONOMY AND MINERALOGY

Almost all taxonomic classes of main-belt asteroids are presented among the classified NEAs except one or two low-albedo classes that are located in the outer part of the main belt. One of the important results of the NEA taxonomy is quite different relative abundance of two most numerous classes C and S. About a half of the classified near-Earth objects belongs to the S-class and the number of S-types exceeds that of low-albedo types by a factor of three, while among the MBAs the ratio is inverse, about 1:5 [20]. Taking into account the results of modelling of the selection effects in observations of both NEAs and MBAs [13] Lupishko and Di Martino [11] showed that the relative number of C and other low-albedo objects among the NEA population is approximately 2.5 times less than in the main asteroid belt. This could be an important constraint for the possible sources of NEA replenishment. The most immediate explanation could be that NEAs are coming preferentially from the inner regions of the main belt where the relative abundance of C and other low-albedo asteroids is much lower.

Most NEAs for which mineralogical information exists represent differentiated assemblages. Among them there are objects with monomineral silicate composition (1915 Quetzalcoatle, 3199 Nefertity) and purely metalic ones (6178 1986 DA). The variety of taxonomic classes among NEAs reflects the diversity of their surface mineralogy and an overall analogy with the MBAs. Taking into account their small sizes, one might infer that they are fragments of much larger differentiated bodies.

SIZE, SHAPE AND ROTATION

Size, shape as well as rotation of asteroid are the fundamental characteristics related to its origin and collisional history. There are size estimates for all discovered NEAs, but more or less exact determinations of their diameters have been obtained for less than 10% of those objects. Amor-asteroid 1036 Ganymed (D = 38.5 km) is the largest among NEAs, two other asteroids (433 Eros and 3552 Don Quixote) are of about 20 km in size, all others are of about or less than 10 km and approximately 3/4 of them are less than 3 km. The smallest known NEAs are of about 3–6 m across. The absence of NEA-objects larger than 40 km in diameter is usually interpreted as an evidence that near-Earth objects are not primordial, but they are collisional fragments of larger MBAs.

Table 1 contains the mean values of observed and corrected (reduced to 0° phase angle) asteroid amplitudes for NEAs and small-sized MBAs. Almost the same corrected mean amplitudes for both the NEAs and small-sized MBAs are an indication of the indentical shape elongations of these asteroid populations on the average. An irregular shape of an asteroid can be approximated by a three dimensional ellipsoid with an $a > b > c$ axial ratio. In this case, the mean light curve amplitude of 0.28–0.29 mag is characterized by an axial ratio $a : b = 1.3$. The data available show that comet axial ratios usually lie in the range from 1.6 to 2.5, that is, cometary nuclei have more elongated shapes than NEAs (see [7, 12]).

Table 1: Mean values of asteroid amplitudes and rotation rates

Population	$\bar{D}$, km	Observed amplitude, mag	N	Reduced amplitude, mag	Rotation rate, rev/day	N
NEAs	2.7 ± 0.4	0.53 ± 0.04	113	0.29	4.80 ± 0.29	119
MBAs ($D < 12$ km)	6.8 ± 0.3	0.35 ± 0.03	102	0.28	4.34 ± 0.23	100
MBAs ($D > 130$ km)	185.8 ± 0.9	0.22 ± 0.01	100	0.19	2.90 ± 0.12	100

The rotation rate distributions of the NEAs and comparable sized MBAs are characterized by close mean values of the rotation rates as well as their standard deviations (see Table 1). At the same time the mean rotation rate and reduced amplitude of large main-belt asteroids (Table 1, the last line) differ essentially. Thus, we can conclude that on the average NEAs as well as the comparable sized MBAs rotate in a similar manner. It should be added that according to the data available cometary nuclei rotate much slower than NEAs [1, 7]. Analyzing the rotation periods of 47 cometary nuclei Whipple [19] found out that the periods of only four comets lie in the range of 3.9 to 5.7 hrs, the rest of cometary nuclei rotate slower, thereby the mean value of comet rotation periods (15.0 hrs) more than two times exceeds the mean value for NEAs.

OPTICAL PROPERTIES AND SURFACE STRUCTURE

NEAs have relatively small sizes and, hence, relatively small masses and so the gravitational forces that determine compactness of the particles in the surface layer. Due to their location NEAs also differ from MBAs in terms of cratering rates and solar wind flux, both of which affect asteroid surfaces. Therefore, one may expect that if distinctions in optical properties and surface structure between two asteroid populations really exist they are even more prominent between NEAs and large MBAs.

Table 2 lists the mean values of optical parameters of NEAs and MBAs: the polarimetric and radiometric albedos, color indexes, phase coefficients β_V and polarimetric parameters such as the depth of negative polarization $P_{\min}$, the polarization slope h, and the inversion angle α_{inv}. As it can be seen the NEA polarimetric and radiometric albedos are somewhat higher than those of MBA, though the distinctions lie in the limits of accuracy. If these distinctions really exists, they may be caused by smaller contamination of S-type NEA surfaces by material of low-albedo asteroids, as compared with the situation in the main belt where relative abundance of low-albedo asteroids (as note above) is more than that among NEA population by a factor of 2.5. The difference between the mean radiometric albedos can be explained using the standard thermophysical model for some NEAs, which are the best fit for so-called “rotating” model as far as the standard (nonrotating) thermal model often overestimates albedos of “nonstandard” asteroids. In general, the whole range of NEA geometric albedos is in complete agreement with that of MBAs.

Table 2: Mean optical parameters of S-type asteroids (V-band)

Parameter	NEAs	N	MBAs ($D > 100$ km)	N
Albedo polarimetric	0.183 ± 0.011	9	0.177 ± 0.004	28
Albedo radiometric	0.190 ± 0.014	23	0.166 ± 0.006	27
U-B (mag)	0.445 ± 0.013	30	0.453 ± 0.008	28
B-V (mag)	0.856 ± 0.013	31	0.859 ± 0.006	28
β (mag/deg)	0.029 ± 0.002	9	0.030 ± 0.006	18
$P_{\min}$ (%)	0.77 ± 0.04	3	0.75 ± 0.02	28
h (%/deg)	0.098 ± 0.006	9	0.105 ± 0.003	23
$\alpha_{\rm inv}$ (deg)	20.7 ± 0.2	6	20.3 ± 0.2	18

The rest of the optical characteristics in Table 2 are basically the same for both asteroid samples. Since the near-Earth and main-belt asteroids have on the average the same albedos and similar surface composition, a strict similarity of their phase coefficients and polarimetric parameters suggests that at least majority of NEAs should have the same surface porosity and roughness at the scale length of submicrons [9].

Thus, it can be concluded that NEA surfaces display the same optical properties as those of MBAs, and it seems that they possibly have the same microstructure.

One of the characteristics of an asteroid reflecting surface is its radar albedo, which is related to a bulk density, that is, to the density and porosity of the surface material. The available data show that the mean radar albedos of small NEAs and large MBAs (S-type), in spite of the fact that they differ in sizes by a factor 25–30, are practically the same (0.161 ± 0.020 for NEAs and 0.147 ± 0.011 for MBAs). It can be explained by the similar composition (mineralogy) and the bulk density of surface materials of both asteroid populations.

CONCLUSIONS

The small sizes of NEAs, almost the same diversity of their taxonomic classes and reflectance spectra, the relative abundance of C and S objects, the same average shape and rotation, as compared to those of MBAs, clearly indicate that the main asteroid belt is the principal source of NEA population replenishment. On the other hand, the identification of some asteroids (and among them an Apollo asteroid 4015 Willson-Harrington) with extinct or dormant comets supports cometary origin for some of them. Thus, there is no doubt that some of NEAs may be extinct cometary nuclei, although the estimates of their abundance are controversial. Öpik [15] believed that most NEAs are extinct cometary nuclei. Levin and Simonenko [10] argued against cometary origin for most NEAs, because the latter are parent bodies of the meteorites which could not be formed in cometary nuclei. Wetherill [18] estimated that extinct comets could provide about 40% of NEAs, and Binzel *et al.* [1] constrained the fraction of cometary nuclei between 0 and 40% of total NEA population. Tedesco and Gradie [16] concluded that extinct cometary nuclei are rare among NEAs, if they exist at all.

The candidates for cometary origin, as a rule, should satisfy the following conditions: (a) they should be low-albedo objects of D, P and C-types [8]; (b) their rotational rates should be lower than the mean rates of NEAs [2, 7, 17]; (c) they should also be evolved on unstable orbits, and should be associated with meteor streams [17].

The data available (NEA taxonomy, shapes and rotation parameters, associations with meteors streams) show that less than 10% of known NEAs satisfy these conditions. Among the NEAs the most probable candidates for cometary origin are the following objects:

Asteroid	Type	Period of rotation (hrs)	D (km)	Comments
2100 Ra-Shalom	C	19.79	3.4	Meteor stream
2101 Adonis	?	?	?	Meteor stream, anomalous radar echo
2201 Oljato	S	24	2	Meteor stream, chaotic orbit
2212 Hephaistos	SG	> 20	5.7	Meteor stream, cometary orbit
3200 Phaethon	F	3.6	6.9	Geminid meteor stream
3552 Don Quixote	D	7.7	19	Comet orbit
4015 Willson-Harring	CF	6.1	2.0	Comet activity in the past

Thus, we can conclude that the main asteroid belt is the principal source of NEA replenishment and the fraction of NEAs of cometary origin does not exceed 10%. This conclusion does not contradict to the recent results of dynamic considerations, according to which the main asteroid belt can supply a few hundred km-sized NEAs per 1 Myr that is well enough to sustain the current NEA population [14].

REFERENCES

[1] *Binzel R. P., Xu S., Bus S. J., Bowell E.* Origin for the near-Earth asteroids // Science.–1992.–**257**.–P. 779–782.

[2] *Degewij J., Tedesco E. F.* Do comets evolve into asteroids? Evidence from physical studies // Comets / Ed. L. L. Wilkening.–Tucson: Univ. of Arizona Press, 1982.–P. 665–695.

[3] *Farinella P., Gonczi R., Froeschle Ch., Froeschle C.* The injection of asteroid fragments into resonances // Icarus.–1993.–**101**.–P. 174–187.

[4] *Froeschle Ch., Michel P., Froeschle C.* Dynamical transport mechanisms of planet-crossing bodies // Evolution and Source Regions of Asteroids and Comets: Proc. 173 Coll. IAU, Tatranska Lomnica, Slovak Republic, 1998 Aug. 24–28 / Eds J. Svoren, E. M. Pittich, H. Richman.–1999.–P. 87–96.

[5] *Froeschle Ch., Morbidelli A.* The secular resonances in the Solar system / Asteroids, Comets, Meteors 1993: Proc. 160 Symp. IAU, Belgirate Italy, 1993 June 14–18 / Eds A. Milani, M. Di Martino, A. Cellino.–1994.–P. 189–204.

[6] *Gladman B. J., Migliorini F., Morbidelli A., et al.* Dynamical lifetime of objects injected into asteroid belt resonances // Science.–1997.–**277**.–P. 197–201.

[7] *Hartmann W. K., Tholen D. J.* Comet nuclei and Trojan asteroids: a new link and a possible mechanism for comet splittings // Icarus.–1990.–**86**, N 2.–P. 448–454.

[8] *Hartmann W. K., Tholen D. J., Cruikshank D. P.* The relationship of active comets, "extinct" comets, and dark asteroids // Icarus.–1987.–**69**, N 1.–P. 33–50.

[9] *Helfenstein P., Veverka J.* Physical characterization of asteroid surfaces from photometric analysis // Asteroids II / Eds R. P. Binzel, T. Gehrels, M. S. Matthews.–Tucson: Univ. of Arizona Press, 1989.–P. 557–593.

[10] *Levin B. Yu., Simonenko A. N.* On the implausibility of a cometary origin for most Apollo-Amor asteroids // Icarus.–1981.–**47**.–P. 487–491.

[11] *Lupishko D. F., Di Martino M.* Physical properties of near-Earth asteroids // Planet. and Space Sci.–1998.–**46**.–P. 47–74.

[12] *Luu J.* Comets disguised as asteroids // Publs Astron. Soc. Pacif.–1994.–**106**, N 699.–P. 425–435.

[13] *Luu J., Jewitt D.* On the relative number of C types and S types among near-Earth asteroids // Astron. J.–1989.–**98**.–P. 1905–1911.

[14] *Menichella M., Paolicchi P., Farinella P.* The main belt as a source of near-Earth asteroids // Earth, Moon, and Planets.–1996.–**72**.–P. 133–149.

[15] *Öpik E. J.* The stray bodies in the solar system. Part I. Survival of cometary nuclei and the asteroids // Adv. Astron. and Astrophys.–1963.–**2**.–P. 219–262.

[16] *Tedesco E. F., Gradie J.* Discovery of M class objects among the near-Earth asteroid population // Astron. J.–1987.–**93**, N 3.–P. 738–745.

[17] *Weissman P. R., A'Hearn M. F., MacFadden L. A., Rickman H.* Evolution of comets into asteroids // Asteroids II / Eds R. P. Binzel, T. Gehrels, M. S. Matthews.–Tucson: Univ. of Arizona Press, 1989.–P. 880–920.

[18] *Wetherill G. W.* Where do Apollo objects come from? // Icarus.–1988.–**76**.–P. 1–18.

[19] *Whipple F. L.* The rotation of comet nuclei // Comets / Ed. L. L. Wilkening.–Tucson: Univ. of Arizona Press, 1982.–P. 227–250.

[20] *Zellner B.* Asteroid taxonomy and the distribution of the compositional types // Asteroids / Ed. T. Gehrels.–Tucson: Univ. of Arizona Press, 1979.–P. 783–806.