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On the optical properties and mineralogy of the surfaces of Near-Earth Asteroids

Rafa A. Mohamed

University of Benghazi, Faculty of Science, Department of Physics, Benghazi
E-mail address: rafzg.mohamed@uob.edu.ly

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ABSTRACT

In this article, we review the literature for constraints on physical properties and mineral composition of near-Earth asteroids. We discuss spectroscopic and microscopic studies of optical and physical effects and the surface structure of NEAs. This topic is of great importance to guess the nature and origin of these objects, and may help understanding investigation of extra-terrestrial bodies and providing indirect valuations of hazard on Earth via cosmic-ray bombardment, meteoroid, asteroid and comet impacts.

1. Introduction

Asteroids are small, airless rocky bodies rotating around the Sun, sometimes called minor planets, and most of them lie in a huge region between the orbits of Mars and Jupiter. In general, asteroids are classified according to two criteria; first criterion is their orbit (dynamical classification) and the second criterion is their surface composition (spectral classification). Most asteroids have similar surface composition and this similarity makes it difficult to distinguish them. However, dynamically, asteroids can be classified into one of many groups and subgroups: Near-Earth asteroids (Amors, Apollos and Atens); Near-Mars asteroids (Hungarias, Mars-crossers and Phocaeas); Mid solar system (Hildas, Jupiter Trojans and Main belt,); Outer solar system (Centaurs, Kuiper Belt, Plutinos, trans Neptunian objects (TNOs) and Scattered Disk). Near-Earth asteroids (NEAs) have special interest in many aspects, because the Earth is under constant bombardment from a rain of extra-terrestrial materials mostly from asteroids. This collision, if happens, possess a finite hazard to humanity. This fact has led to enormous new discoveries and a substantial increase in research on the nature and origin of these asteroids. NEAs may have very elongated and unstable orbits and can approach Earth or crosses Earth's orbit. These objects were supposed to be distinguished according to their orbits (Shoemaker et al. 1979), see Table 1 for more details.

Amors' closest approach to Earth's orbit is at perihelion and can never cross Earth's orbit, while Apollos can approach Earth's orbit and some of them enter inside the Earth's orbit. Atens approach Earth's orbit at Aphelion and some of them crosses Earth's orbit. Although that the above classification is still used effectively today, recently, Michel et al. (2000) distinguished new group whose orbits are contained completely with the Earth's orbit, which called Inner-Earth Asteroids (IEAs). It is very difficult to discover these minor planets optically because the ground-based observations are restricted to whole-disk observations.

These objects lie mostly with the Sun side (day sky), and may be observed only at the morning and evening times at longitudes from the Sun $\approx 90°$. The IEAs is considered as "potentially hazardous" (PHAs), because of their possible sudden appearance near Earth due to the perturbation of their orbits. According to Michel et al. (2000) members of IEAs together with Atens make up around 20% of the Earth crossing asteroids and around 2% of the whole NEAs, see Bottke et al. (2002).

Table 1
Orbital classifications of NEAs

Group	Description	Definition	Named after
NEAs	Near-Earth Asteroids	q<1.3 AU	
Atiras	NEAs whose orbits are contained completely with the Earth's orbit.	a<1.0 AU, Q<0.983 AU	163693 Atira
Atens	Earth-crossing NEAs with semi-major axes smaller than Earth's orbit.	a<1.0 AU, Q>0.983 AU	2062 Aten
Apollos	Earth-crossing NEAs with semi-major axes larger than Earth's orbit.	a>1.0 AU, q<1.017 AU	1862 Apollo
Amors	Earth-approaching NEAs with orbits exterior to Earth's but interior to Mars' orbit.	a>1.0 AU, 1.017<q<1.3 AU	1221 Amor

For the time being, the total discovered and catalogued NEAs are more than 10000 objects. In the last two decades NEAs began to have special interest from the point of view of fundamental and applied science as well, and many discoveries were achieved. These discoveries can help understanding investigation of extra-terrestrial bodies and providing indirect valuations of hazard on Earth (Gehrels, 1994).

From one side, these asteroids are scientifically interesting because they carry records of the origin and evolution of planetesimals such as those that accreted to form the planets. For this reason, understanding the source and mechanism of their production is one of the fundamental scientific goals for NEAs studies. Why these asteroids left the main belt region and have a very elongated and/or unstable orbit? What about the orbital evolution and their lifecycle on these orbits? All these concerns are very important to solve the cosmic problems of the asteroid belt and solar system as whole. On the other side, the rapid growth of the number of these asteroids near the Earth's orbit alarms with the risk of asteroid collision and related hazard. Moreover, asteroids are a source of metals and a potential rich of variety of raw materials.

The NEAs approach the Earth in the limits 0.01 – 0.02 A.U., which enable us to observe and study individual objects of the solar system with very small, sizes (≈ 5 m). Some NEAs are primary substance, which preserve information about the earlier times of the solar system. Most of others are considered as fragments of larger main belt asteroids (MBAs) which give an opportunity to study the nuclei of the parent bodies of these asteroids. When approaching Earth, these asteroids become accessible targets to observe in a wide range of geometrical illumination that never be reached for MBAs, and hence receive information on some MBAs that have similar compositional types.

2. Physical properties

The main difference between MBAs and NEAs is that the later have relatively small sizes. Table 2 shows size sample of some known NEAs and their diameters. The two largest NEAs are members of Amors and do not represent serious collision, because they can approach Earth but do not cross Earth's orbit.

Table 2
Size of some known NEAs

NEAs		Diameter
1036	Ganymed	38.5 km
433	Eros	16.5 km
1866	Sisyphus	8.9 km
2000	WL107	38 m
2003	SQ222	10 m
2008	TC3	4 m

The smallest discovered NEA is about 4 m in diameter. Stuart (2003) proposed the distribution of NEAs according to the following function:

$$N\,(>D\text{ km}) = k\,D^{-b}$$

where $b = 1.95$ and $k = 1090$. This means that there are 1090 NEAs with diameter ≥ 1 km. Taking into account the approximation errors, Stuart and Binzel (2004) evaluated the number of NEAs with diameter ≥ 1 km to be 1090 ± 180 which agrees to some limit with the evaluation of Bottke et al. (2002) 960 ± 120. Table 3 indicates the density values of some NEAs and their compositional type (more exact values of the density of 433 Eros can be found in Yeomans et al. (2000). The discovery of binary asteroids is an additional possibility for mass and density determination. However, the accuracy of mass and density values depends on how the binary asteroids' parameters are determined, see Table 3.

Table 3
Some known density values

NEAs		Density (g/cm³)	Type
6489	Golevka	2.67 ± 0.03	Q
433	Eros	2.67 ± 0.20	S
1999	KW4	2.0 ± 0.2	S
25143	Itakawa	1.95 ± 0.14	S, Q
1996	FG3	1.4 ± 0.3	C

Q: Metallic; S: Siliceous; C: Carbonaceous.

The analysis of photometric, polarimetric, spectral, radiometric, charge-coupled device (CCD) and other data show that the surface optical properties of NEAs are similar to those of MBAs (Lupishko et al. 2007). NEAs have values of albedo ranges from 0.03 to 0.60, exactly as MBAs. Shapes, spin characteristic and rotation periods of NEAs are also similar to those of MBAs. This clearly indicates that NEAs and MBAs populations have the same mineralogy of the surfaces. Moreover, the similarity of photometric and polarization parameters, phase coefficient (α), polarimetric slope (h), the depth of the negative branch of the asteroid polarization phase curve ($P_{\min}$) give an idea about the similarity of the surface structure of these populations at submicron scale.

Fig. (1a) and (1b) display the distribution of the rotation rates of NEAs and small MBAs respectively. These figures show that the NEAs are relatively different in comparison with the rotation rates of MBAs. It also shows the noticeable extremes of slow and fast rotators (Lupishko et al. 2007). Most likely, MBAs obey the normal Gaussian distribution, while NEAs does not. This phenomenon can be explained by the difference in asteroid diameter distributions, influence of the radiation pressure torques (YORP-effect), and the influence of the rotational parameters of binaries (Lupishko and Pozhalova, 2010). The whole interval of NEA rotation periods ranges from 500-600 hrs to 1.3 min. It is clear that these small and super-fast rotating asteroids are beyond the rotational breakup limit for aggregates like "rubble-piles" and they are monolithic fragments.

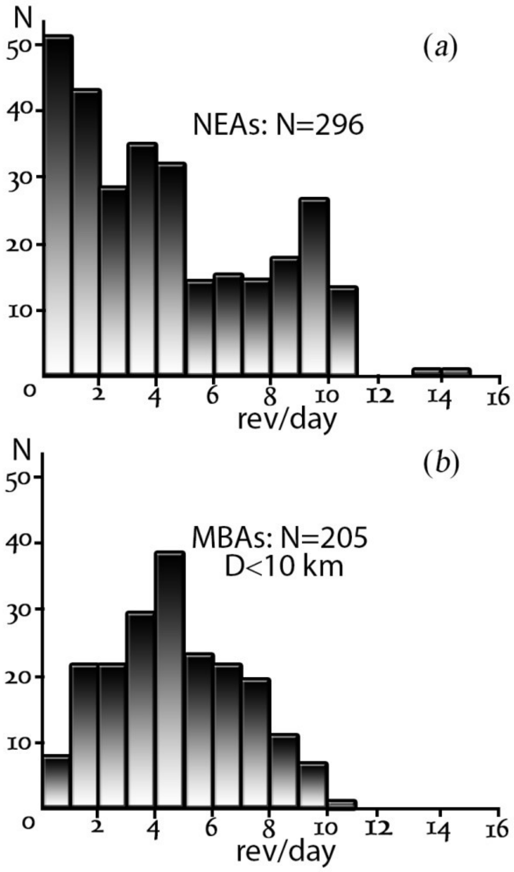

Fig. 1. Distribution of rotational rates as a function of speed of rotation: *a*- rotation rates of 296 NEAs; *b*- rotation rates of 205 MBAs with D < 10 km

In NEAs population, some objects with very problematic rotation were discovered. Another property of some very slowly spinning NEAs which should be mentioned is nonprincipal axis rotation, or "tumbling". It is clear that these asteroids rotate slowly and show lightcurves with two maxima. Classical period of rotation for such NEAs is asteroid 4179 Toutatis. In contrast to other asteroids, Toutatis rotates with period of rotation of 129.8 hr around major axis a ($a > b > c$), meanwhile the axis has a period of precession of 176.4 hr (Hudson and Ostro, 1995; Spencer et al. 1995).

NEAs have diversity of shapes wobble between very elongated ellipsoidal to spherical shapes. Nevertheless, both NEAs and MBAs have the same elongated shapes. For example, asteroids 1943 Anteros and 2102 Tantalus have spherical shapes, while asteroids 1620 Geographos and 1865 Cerberus have very roughly elongated ellipsoidal shapes. Asteroid 1865 Cerberus have a diameter of 1.2 km and $a{:}b$ = 3:2, where a- is semi major axis and b-is semi minor axis. More detailed information about physical properties of NEAs can be found in Lupishko and Di Martino (1998), Binzel et al. (2002), Lupishko et al. (2007) and Lupishko et al. (2000).

3. Mineralogy composition

Any specific NEAs can be characterized by its size and taxonomic class. The taxonomic class points to the mineralogy of a given asteroid. The spectroscopic evidence suggests that the compositional type of MBAs have similarities to the composition types of NEAs, though with some differences in the details, including low albedo types (C, P and D), which are associated to outer part of the main belt. Results of spectroscopic investigations of NEAs by Lazzarin et al. (2008) and Stuart & Binzel (2004) are summarized in Table 4.

Table 4
Abundance of asteroid types (%)

Type	L	SB
S+Q	62%	36%
C and other types	12%	-
C and low albedo types	-	27%
Other types*	26%	-

* – Bus, 1990, L – Lazzarin *et al* 2008, SB – Stuart & Binzel 2004.

By observing more small sized S-type asteroids Michel et al. (2000) discovered a continuous transition in the visible and near-infrared spectral properties between the solid lines depicting typical S-type asteroids and ordinary chondrite meteorites (Q-type asteroids), see Fig. 2. This S- to Q-class transition within the NEA population was shown by Binzel et al. (2001) based on spectral properties measured over visible wavelengths. At the same time, data showed that small sized objects (Q-Asteroids) have unexpectedly high albedos and according brighter surfaces if compared to S-objects, which indicates that their surfaces are young. Since asteroid surfaces become darker with time due to exposure to solar radiation, the presence of brighter surfaces for Q-objects may indicate that they are comparatively young. This fact is considered as an evidence for the continuing evolution of NEAs population.

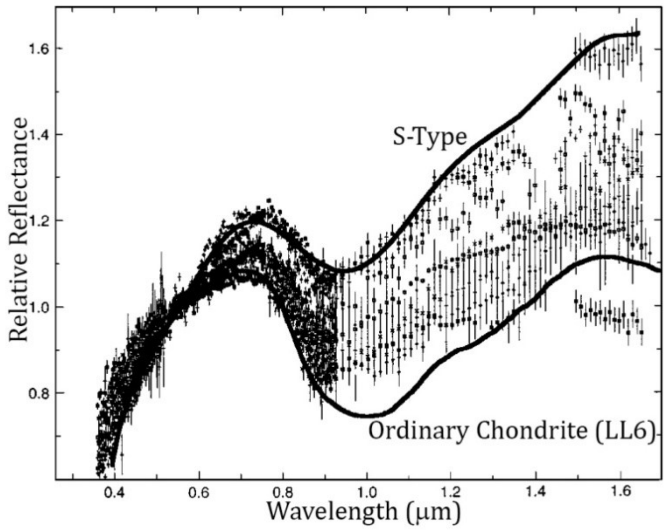

Fig. 2. S- to Q-class transition within the NEAs population. Fig. 2 adopted from Binzel et al. (2001).

The scale shown in Fig. 2 is explained by the influence of two factors: space weathering (deformation that occurs to the surface of any airless body exposed to the harsh environment of outer space) which affects the interpretation of all spectroscopic (compositional) observations of asteroids; the collisions with the surfaces of Q-type asteroids as well as surfaces of S-type asteroids. For more details, see Binzel et al. (2004). They also found statistical valid linear increase of spectral slope with increase of asteroid exposure (i.e., amount of Sun's radiation that a body receives along its orbit) which supports the idea of space weathering (Lupishko and Pozhalova, 2010). According to Fevig and Fink (2007) there is a significant statistical orbit-dependent trend in their spectrophotometric data. S-type NEAs are found in Amors, Apollos and Atens orbits, which do not cross the asteroid main belt, while most of Q-type asteroids reside in highly eccentric Apollo orbits crosses the asteroid main belt region. This scenario suggests that Q-type asteroids probably were injected into these orbits after some collision inside the main belt region.

The investigation of photometric, polarimetric and radiometric data on NEAs as well as direct imaging of 433 Eros and 25146 Itakawa shows that the surfaces of most NEAs are covered with thick (>10 cm) layers of particular material (regolith). Despite their low surface gravities, NEAs appear to retail some regolith or dust coating. Interestingly, formation conditions, accumulation and evolution of the regolith of NEAs surfaces differ completely than those of MBAs, because of the great difference in gravitation (The gravitation is more intensive in the MBAs region than in NEAs region) and to the difference in the solar radiation as well. As a result, the regolith of NEAs must be coarser in comparison to the regolith of MBAs (Lupishko and Pozhalova, 2010).

The recent studies of thermal IR emission of NEAs shows the average thermal inertia of km-size NEAs is 200 ± 40 $Jm^{-2}s^{-0.5}K^{-1}$, that is about four times that of the Moon (Delbo 2004). This clearly indicates that the regolith of NEAs is coarser than the regolith of MBAs, which are still more coarsely than the lunar regolith. Images direct from 433 Eros and 25146 Itakawa show a complete variety of characteristics ranging from rocks or stones to smooth ponds of fine-grained materials (Ebihara et al. 2015, Bhatt et al. 2015, Sears et al. 2015). These different types of NEAs reflect the diversity in their mineralogy and complete analogy to MBAs. Taking into account their small sizes one can conclude that these bodies are fragments of larger differentiated bodies. Radar data gives evidences that NEAs surfaces are coarser in comparison to MBAs in the scale of decimeters and meters, while micro porosity and macro porosity constitute from 20% to 40%, which coincides with the porosity of lunar regolith. If the estimated values of porosity are correct it implies that, they have no coherent tensile strength. This means that they appear to be piles of rubble weakly held together by their own mutual gravity.

4. Conclusion

Studying the physics, dynamics and origin of NEAs is of great importance. From one side, these objects preserve evidence about the earliest times in the solar system. On the other hand, NEAs provide a link between the macro planetary scale studies of small bodies and micro planetary scale of meteorites. Moreover, NEAs are considered as one of the sources of raw materials that can be used for humanity needs and carry a rich bounty of scientific information.

The asteroid hazard is one of the most dangerous problems that face the Earth civilization, see for example Włodarczyk (2014). Hence, there is noticeable interest in NEAs in order to understand the danger they pose via impacts by Near-Earth objects (NEOs), and because of these facts, thousands of NEAs will be discovered in the next few years. Therefore, the studies of the optical and physical properties of these objects remain one of the most oriented fields in solar system research.

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