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Yarkovsky effect: Delivery of Asteroids to near earth orbits

Rafa A. Mohamed* **and Awad S. Alhasi**

Department of Physics, Faculty of Science, University of Benghazi, Benghazi, Libya

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* Corresponding author:
E-mail address: rafzg.mohamed@uob.edu.ly
R.A. Mohamed

ABSTRACT

Significant advances have been made in recent years and extensive studies are going for assisting the asteroids' destiny. From these studies, we hope to obtain a much better understanding of the influence of the non-gravitational forces on the asteroids, and the overall history of the solar system. At the same time, Yarkovsky effect is important in terms of impact hazard. Both the pure scientific concerns, and the impact hazardous point of view concentrated on the need of developing reliable plans of impact evidence, require a major struggle in order to improve the current knowledge of the size of the Yarkovsky affection on these objects. In this article, a brief description of Yarkovsky effect is presented, and the delivery of NEAs to near Earth orbits as well.

1. Introduction

According to some geological evidences, an asteroid around ten-kilometer in diameter collided with the Earth and destroyed most of semblance of life on its surface, including dinosaurs. Recently, on February 15, 2013 a much smaller asteroid shattered in the atmosphere over the city of Chelyabinsk, in Russia, and as a sequence, this asteroid damaged buildings and injured many people. In spite of the destruction took place by such asteroids, most asteroids are not dangerous at all. In fact, out of all NEAs, less than 2% are labeled as "potentially hazardous". Nevertheless, we are not sure if some of these potentially hazardous asteroids will hit the Earth. There are two mechanisms that make these asteroids hazardous; first is the collision and second is the effect of tiny force of the ordinary sun light on asteroids, through a process known as Yarkovsky effect, named after the Russian civil engineer Ivan Osipovich Yarkovsky (Öpic 1951). Yarkovsky effect involves diurnal and seasonal variants. Diurnal variant depends on the body's spin rate and longitudinal temperature distribution, while seasonal variant depends on the body's mean motion around the Sun and its latitudinal temperature distribution.

Throughout the last two decades, the Yarkovsky effect has been used to explore ambiguities and potentially resolve unsolved mysteries in planetary science and particularly those related to small bodies. In spite of the effect of Jupiter on the main belt population, collision between asteroids can place ejecta into the main resonances. However, it appears that the recently rediscovered thermal force (Yarkovsky effect) helps to explain more unanswered points. The Yarkovsky force is due to thermal inertia and is most effective on rocky objects with diameters of 0.5 to 10 m; however, over a long timescale it may be effective on objects as large as 10 – 15 km. This force gradually transfers material toward the Sun. Accordingly, in addition to ejecta placed into resonances, ejecta within the asteroid belt slowly transferred toward resonances by means of the Yarkovsky effect (Bottle et al. 2005). These ejecta may reach near Earth orbits and consequently may collide with Earth. This explains why we need to study Yarkovsky effect and how it works and the possible outcomes as well (Vokrouhlický, 2015).

2. Diurnal component

Generally, the motion of the celestial bodies is controlled by gravity; therefore, the collision and gravitational forces were considered as the primary mechanisms governing the evolution of asteroids and their fragments. Nevertheless, Yarkovsky effect (non-gravitational forces) demonstrated that ordinary sunlight could exert a force on an asteroid (Neiman et al. (1965) and (Beekman 2006)). This is because light rays are made of photons and carries away momentum when it leave the surface according to the relation $p = E / c$, where p is the photon's momentum and c is the speed of light. When the photons reach the asteroid (Fig.1a), they can be reflected by the surface, or absorbed warming up that surface.

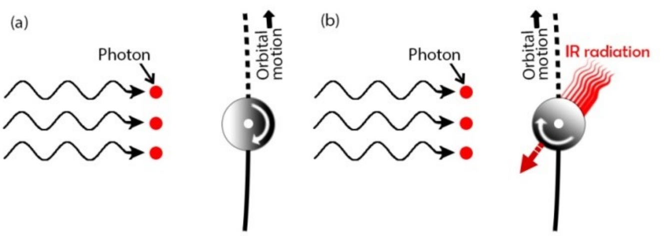

Fig. 1. *a*- Photons are incident on an asteroid spinning in prograde sense of rotation with spin axis perpendicular to the orbital plane. *b*- Radiation is emitted typically in the infrared part (IR) of the spectrum, unless the meteoroid is very close to the Sun. A case of asteroid slowing down.

Just like the Earth, asteroids are rotating around the Sun (orbital motion) and spinning around their axis of rotation as they orbit the Sun, so they have a season, day and night cycle too. Because of this rotation, the warmest part of an asteroid is not in the sunward side; it is slightly to the side. If the photons are absorbed by the asteroid surface, and after a short period of rotation of asteroid around its axis of rotation, the surface will reradiate more IR radiation into space in the form of heat. This process gives the asteroid a little kick analogous to the recoil force on firing cannon, see Fig.1b. This recoil thermal force can slow an asteroid down, or speed it up. Consequently, these thermal forces can change an asteroid's semi major axis over time.

If the asteroid is spinning such that the warmest part is slightly in front, the recoil thermal force will be backwards in a direction away from the hotter part (clockwise direction or prograde sense of rotation), the asteroid will slow down a bit (Fig.1b). However, if the asteroid is spinning the other way (counterclockwise direction or retrograde sense of rotation), the warmest part will be slightly behind, and the recoil thermal force will give the asteroid a push forward in its orbit speeding it up (Fig. 2b).

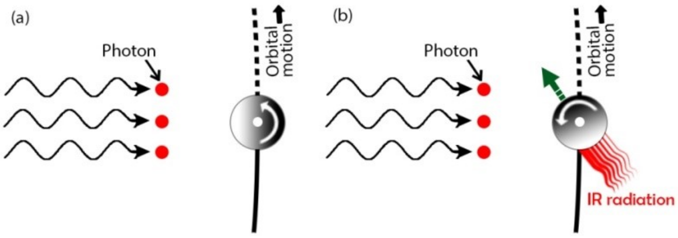

Fig. 2. *a*- Photons are incident on an asteroid spinning in retrograde sense of rotation with spin axis perpendicular to the orbital plane. *b*- Radiation is emitted typically in the infrared part of the spectrum, unless the meteoroid is very close to the Sun. A case of asteroid speeding up.

These tiny forces can change the asteroid's orbit. In order to explain how this happen let us consider an asteroid that has a spherical shape and rotates in a circular orbit about the sun. For simplicity, we consider that the spin axis is taken to be normal to the orbital plane, see Fig 3.

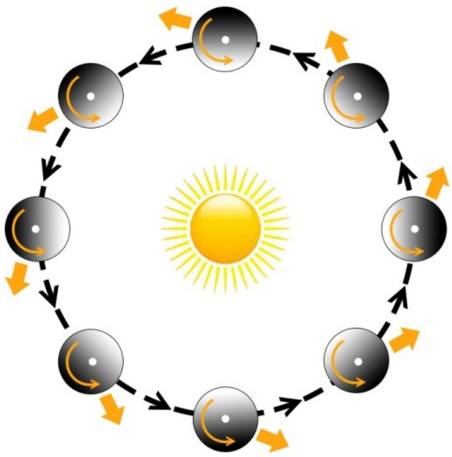

Fig. 3. Diurnal Yarkovsky effect, with the asteroid's spin axis normal to the orbital plane. The along-track component causes the asteroid to spiral outward. Retrograde rotation causes the asteroid to spiral inward.

The asteroids will be treated as indicated in Figs. 1 and 2. If the asteroid has no thermal inertia, the distribution of temperature will be symmetrical about the subsolar point. In this case, the asteroid will experience a force directed radially outward from the sun. If the asteroid is moving in a circular orbit around the Sun then the forces effecting the asteroid has two components; radially outward force from the Sun and the along track component. As explained above, if an asteroid has a prograde sense of rotation then the recoil thermal force (Yarkovsky force) causes a secular increase in the semimajor axis, which results in a smaller degree of eccentricity. This way, tiny Yarkovsky force can change the orbit of an asteroid and the sign of this effect depends on the sense of rotation. If the asteroid speeds up (retrograde sense of rotation), the orbit will expand. If it slows down (prograde sense of rotation), the orbit will shrink. In fact, the Yarkovsky effect is small, but during a long run of time, it gives asteroids sufficient time to change their orbits, possibly transporting them into or out of the Earth's way.

The Yarkovsky diurnal effect depends on the asteroid rotational period, proximity to sun and asteroid physical characteristics. The effect has a maximum value when the spin axis lie perpendicular to the orbital plane, and when inclining the asteroid gradually so that the spin axis lie parallel to the orbital plane, the Yarkovsky diurnal effect will consecutively vanishes. The diurnal variant is greatest when the spin axis is perpendicular to the orbital plane, and it causes the body to spiral outward for prograde rotations and inward for retrograde rotations.

3. Seasonal component

When Yarkovsky proposed his idea about the recoil force of thermal radiation, it was realized that there had to be a seasonal effect as well (Rubincam, 1990). For simplicity, we assume that the asteroid to be moving in a circular orbit around the Sun with the spin axis parallel to the orbital plane, and has a spherical shape. Unlike diurnal effect, the seasonal effect is produced by the force component situated along the spin axis.

When asteroids at position "A" (Fig.4) the Sun rays is incident strongly on the asteroid's northern hemisphere. Because of thermal inertia, the absorbed sunrays will be reradiated later (after some delay); this process makes the northern hemi sphere hottest at position "B". The same scenario is applied to the asteroid at positions C and D; light rays from sun is incident strongly at southern hemisphere at position C, and later the southern hemisphere will be hottest at position D. Fig. 4 shows that the incident sunrays on the asteroid surface is symmetrical. Nevertheless, the changing velocity vector indicates that the thermal force shrinks the asteroid orbit. The seasonal Yarkovsky depends on the orbital period, proximity to the Sun, and tilt of the spin axis with reference to the asteroid's orbit. It is important to note that Yarkovsky effect has a tendency to circularize the asteroid orbit in a similar way to the effect of atmospheric drag (Rubincam 1998, Vokrouhlický & Farinella 1998).

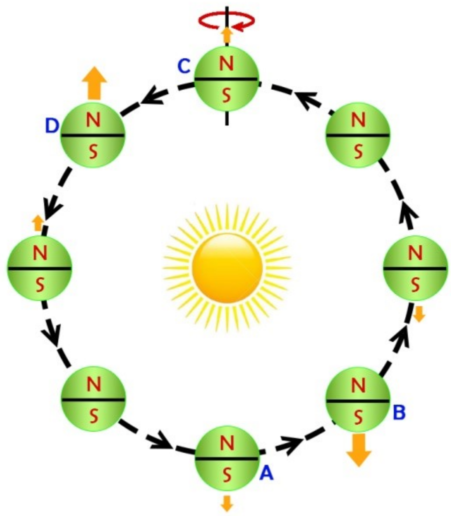

Fig.4. The seasonal, Yarkovsky effect is caused by the fact that the seasonal heating of northern and southern hemispheres of solar system bodies peaks at a point somewhat after the solstices. This seasonal Yarkovsky effect results the thermal force lying along the spin axis.

From one side, if the asteroid is very large (large diameter) then the photon's momentum is not able to create enough recoil thermal force, yielding no change in the velocity vector and accordingly neither diurnal nor seasonal effects is observed. These large objects have poor area to-mass ratio (e.g., the effect is negligible on a large body like Earth). From another side, if the asteroid is small in size it has a better area-to-mass ratio, nevertheless at some point the diameter becomes so small that the thermal waves penetrate all the way across the body, decreasing the temperature differences between the night and day sides and thus diminishing the effect. Low-density or ruble bile objects, slowly rotating dust particle or gaseous objects show weak and distorted Yarkovsky effect. The seasonal variant always causes the body to spiral inward, and it is maximized when the spin axis lies the orbital plane, and vice versa.

4. Computation of Yarkovsky effect

The computation of Yarkovsky force usually carried out in two steps; step one contains the calculation of surface temperature while step two determines recoil force of thermal radiation. Vokrouhlický (2001), recently, formulated the following method. Denoting usual symbols T as temperature, K as thermal conductivity, C_p as specific heat at constant pressure, ε as surface emissivity, ρ as material density, σ as Stefan Boltzmann constant and $\alpha = 1-A$, where A is Bond albedo, we have diffusion equations for energy flow inside the body given by:

$$\nabla \cdot (K\nabla T) = \rho C_p \frac{\partial T}{\partial t} \quad (1)$$

$$(K\nabla T \cdot \mathbf{n}_\perp) + \varepsilon\sigma T^4 = \alpha\mathcal{E} \quad (2)$$

In Eq. 2, $\mathcal{E}$ represents the flux of solar radiation and $\mathbf{n}_\perp$ denotes the unit vector normal to the surface. Above equations are solved numerically to determine the material parameters T, K and ρ, once ε is specified.

In order to reduce the number of parameters as small as possible, we have to reduce the size and time. It is achieved by decomposing the function $\mathcal{E}$ via Fourier term with frequency υ, which involves two parameters; thermal wave:

$$(l_\upsilon = \sqrt{K/\rho C_p \upsilon}) \quad (3)$$

and the penetration depth of thermal parameter

$$\Theta = \sqrt{K\rho C_p \upsilon/(\varepsilon\sigma T_*^3)} \quad (4)$$

The temperature appearing in last expression is sub solar temperature defined by $\varepsilon\sigma T_*^4 = \alpha\mathcal{E}_*$, where $\mathcal{E}_*$ denotes solar radiation flux at particular distance of a body. In fact, at a given frequency υ, the thermal parameter is a measure of relaxation between absorption and emission. If it becomes smaller then difference between absorption and emission becomes smaller as well.

Once the temperature T is solved, the computation of recoil force of thermal radiation is achieved by assuming isotropic (Lambert) emission where the corresponding force per unit mass is given by (Spitale & Greenberg 2001) and (Bottke et al. 2002a).

$$d\mathbf{f} = -\frac{2}{3}\frac{\varepsilon\sigma}{mc} T^4 \mathbf{n}_\perp dS(u,v), \qquad f = \int_S d\mathbf{f} \quad (5)$$

where m is mass and c is velocity of light. By assuming parametrized coordinates u and v, for example longitude and latitude for spherical bodies, the integration in above is carried out on whole body surface.

Coming now to Yarkovsky force, we assume the local coordinate system in which spin axis of the body is aligned in z-direction (acceleration in this direction is known as diurnal), whereas xy-axes in equatorial plane (accelerations in these directions are known as seasonal). Yarkovsky acceleration, basically, changes body's semi-major axis a. Assuming spherical body of radius R and averaging over one revolution, we write the diurnal and seasonal perturbation components as

$$\left(\frac{da}{dt}\right)_{diurnal} = -\frac{8\alpha}{9}\frac{\Phi}{n} F_\omega(R',\Theta) cos\gamma + O(e) \quad (6)$$

$$\left(\frac{da}{dt}\right)_{seasonal} = \frac{4\alpha}{9}\frac{\Phi}{n} F_n(R',\Theta) sin^2\gamma + O(e) \quad (7)$$

where $\Phi = \pi R^2 \mathcal{E}_0(m/c)$ is radiation pressure coefficient, γ is obliquity of spin axis and α is albedo factor. Obviously, the total rate is superposition of Eqs. 6 and 7. The function $R_\nu (R', \Theta)$ depends on scale radius of the body ($R' = R/l\upsilon$), and the thermal parameter Θv, both depending on frequency υ. The frequency ($\upsilon = \omega$) and ($\upsilon = n$) respectively, for diurnal and seasonal effects. Despite the difference in frequency, the function F remains same given by:

$$R_\upsilon(R',\Theta) = -\frac{\kappa_1(R')\Theta_\nu}{1 + 2\kappa_2(R')\Theta_\upsilon + \kappa_3(R')\Theta_\upsilon^2} \quad (8)$$

where κ_1, κ_2 and κ_3 are analytic functions of R'. The parameters differentiate between diurnal and seasonal effects. We discuss below the change in Yarkovsky perturbation due to different parameters.

4.1. Obliquity and rotation

Since F is negative, hence a decreases always. Physically this means thermal reemission always lags absorption. At $\gamma = 90°$ obliquity, the seasonal effect is maximum whereas diurnal effect is zero. At $\gamma = 0°$ (or 180°), it is just the opposite. Also for $\gamma < 90°$, the diurnal effect increases a, and for $\gamma > 90°$, it decreases a. Because the surface temperature variation smeared out along lines of constant latitude, it becomes negligible for infinitely fast rotation.

4.2. Size

There is no Yarkovsky effect for very large objects where $da/dt \approx \Theta l_\upsilon/R$ and for very small objects where $da/dt \approx \Theta R^2/l_\upsilon^2$. The maximum drift in a, occurs when $l_\upsilon \approx$ R, i.e. the penetration depth of thermal wave becomes approximately the same as the size of the object.

4.3. Surface conductivity

Thermal conductivity K is main parameter which modifies l_υ and Θ. For small K (≈0.001–1.0 $Wm^{-1}K^{-1}$), Θ is small, whereas R' is large as penetration length l_υ decays to zero. Thus $da/dt \approx \Theta$, which makes Yarkovsky effect disappear. For large K (≈ 40 $Wm^{-1}K^{-1}$), $da/dt \approx R'^2/\Theta$ there is a fast decay in Yarkovsky effect as body drives towards thermal equilibrium. da/dt becomes maximum at $R' = 1$ and $\Theta \approx 1$.

4.4. Solar distance

The diurnal effect yields $da/dt \approx \Phi/n\Theta$. Hence, as the distance of the object increases from the sun, the Yarkovsky effect decreases because Θ and $R'n$ are large. Using functional dependence of Φ, n and Θ, it is found that $da/dt \approx a^{-2}$ (Radzievskii 1952) and (Peterson 1976). In contrast to above, the seasonal effect is not so simple to analyze as it cannot be approximated to $\approx 1/\Theta$. The example of such situation occurs for 0.1 – 1 km icy bodies in Kuiper belt. For such case, the seasonal drift da/dt becomes much swallower as the distance from the sun increases (penetration depth increases to $l_n \approx 0.1$ km).

5. Delivery of asteroids to near Earth orbits

Due to Yarkovsky effects, main belt asteroids may migrate from main belt asteroids to near Earth populations, and end up crossing one of the orbital resonances, eventually becoming a planet-crosser. In asteroids' main belt, there are two effective regions in this concern: dynamical models have shown that the predominant source of NEAs is a narrow zone of the asteroid belt bound by the ν_6 secular resonance (Fig. 5), at around 2.15 AU (inner part of main belt), and the 3:1 Kirkwood gap resonance at 2.5 AU (Wisdom 1985), (Scholl & Froeschle 1991) and (Bottke et al., 2000).

Orbital resonances occur when two bodies have orbital periods that are a simple integer ratio of each other. Over time, such a gravitational resonance causes dramatic effects on the trajectories of specific objects and destabilization of some orbits, which intend to migrate into different orbits, particularly for small bodies. For example, the Yarkovsky effect has moved some 10 – km objects from stable main belt orbits into unstable resonance and turn into the near earth populations. Within the main belt, objects that have orbital periods in resonance with the orbital period of Jupiter are gradually ejected randomly into different orbits with a larger or smaller semi major axis. Any objects that have been ejected into the region of these resonances because of perturbing orbits or mutual collision will experience chaotic random increase of eccentricity. This process leads to the fact that after some time the orbits of these objects will cross the earth's orbit. A special attention will be drawn to the secular resonance ν_6, which is considered as the most effective mechanism to increase the eccentricity value to $e > 0.6$ in a short period around 10^6 years. Consequently, the secular resonance ν_6 is the main mechanism of injecting asteroids to inner planets area (Holman & Wisdom 1994).

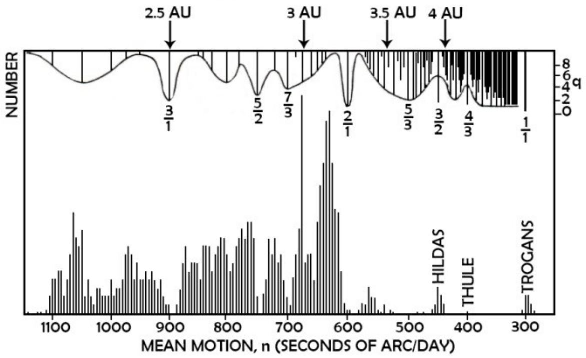

Fig. 5: Frequency distribution of the asteroids between the Sun and 1:1 resonance with Jupiter. Resonances are indicated at the top of the diagram as vertical solid lines of length inversely proportion to their order (Greenberg & Scholl, 1979).

If asteroid experiences the influence of the two resonances simultaneously so its eccentricity may reach unity ($e = 1$), which means that the asteroids surly ends up into the Sun. Fig. 7 shows the presence of other resonances (5/2, 2.82 AU), and more others which seems to be insignificant, but to some extent, they have some influence on the evolution of the asteroid's motion. The resonance mechanism involves two main processes: First is the ejection of objects to the resonance field in the main belt because of catastrophic collisions or ejecting fragments during the formation of craters. Second is the migration of fragments to the NEAs zone because of increasing eccentricity. The near Earth asteroid population is continuously depleted through collisions or ejecting fragments during formation of craters, and by ejection into the inner solar system while simultaneously being replenished by main belt asteroids that strayed into orbital resonances with Jupiter and Mars (Menichella et al. 1996) and (Bottke et al. 2002a). However, recent studies carried out by (Farinella and Vokrouhlický, 1999), (Zappala et al. 2002) and (Bottke et al. 2006) showed that the direct ejection of asteroid fragments into the NEAs region by resonance is ineffective. This implies that the resonance mechanism is not the only one process that governs the migration of bodies from the main belt to the region of NEAs. Therefore, it is believed that the Yarkovsky effect, mentioned above, is responsible.

The complete scenario of replenishment of near earth population by objects from the main belt region can be summarized by the following manner. Most of near earth population are outcomes of catastrophic disruption events of asteroid parent bodies; see for example (Granvik et al. 2016). The most traditional mechanism identified is injection into one of the major mean-motion or secular resonances that cross that main belt, analogous to forbidden values of the orbital elements (Cellino et al. 2002). Other remaining fragments will stay in their orbits in the main belt region unless they disintegrate because of collision. As explained in secs 1 & 2, the existence of the thermal physical mechanism (Yarkovsky effect) has been known long time ago (Neiman et al. 1965), but its real importance has been recognized recently (Rubincam ,1998; Vokrouhlický, 1999; Vokrouhlický & Farinella 1999; Spitale & Greenberg, 2002). This effect is intrinsically weak, but it acts steadily over long timescale. Therefore, objects from main belt are under influence of many possible factors and mainly collisions, gravitational forces, radiation forces, sum of any two forces or all at once.

6. Discussion and conclusion

With the help of radar observation, it was possible to get first cleared measurement of thermal conductivity of asteroid 6489 Golevka, K=0.01 $Wm^{-1}K^{-1}$ by Chesley et al. (2003). These objects experience non-gravitational acceleration coinciding with those values obtained theoretically for Yarkovsky effect at accepted value of density ($\rho = 2.7$ g/m^3) and thermal conductivity ($K = 0.01$ $Wm^{-1}K^{-1}$). Other methods of detection the Yarkovsky effect can be found in (Nesvorný & Bottke 2004 and Steven et al. 2015). Nesvorny & Bottke, 2004 who investigated main belt asteroid 832 Karin in order to estimate the Yarkovsky effect on the orbital distribution of Karin cluster, achieved the striking result.

As explained earlier, Yarkovsky effect depends on the orientation of the spin axis, and this means that the effect can be increased or reduced by spin axis reorientations owing to collisional processes. In other words, when asteroid has a retrograde sense of rotation the semimajor axis of asteroid's orbit should decrease, i.e. retrograde rotation causes the asteroid to spiral inward (Bottke et al. 2006). La Spina et al. (2004) have studied the distribution of NEAs according to spin of rotation. They found that 71% of 21 NEAs have retrograde sense of rotation, which is significant abundance of retrograde sense of rotation in comparison to random distribution. This result turned out to be unexpected, and clear prove of transporting objects from main belt region to near earth orbits. Using numerical model of NEA population Bottke et al. (2002b) evaluated that 37±3% of NEAs having a diameter of a km are supplied by secular resonance ν_6. So far as this resonance is dominant in inner belt region it can be reached only by objects that have orbits evolving inward to the direction of Sun. Owing the change in the orbit semi major axis ($da\ /\ dt$) because of the influence of the Yarkovsky effect these objects must have retrograde sense of rotation. Objects evolving both inward and outward from Sun (objects with prograde and retrograde sense of rotation) can reach all other resonances in the main belt region. Although that above context is based on numerical model, but if 37% of a km-objects which supplied by the secular resonance ν_6 have prograde sense of rotation, and other remaining objects have equal probability of prograde and retrograde sense of rotation, so this leads to the fact that NEAs having retrograde sense of rotation equals 69%. This result coincides with the result obtained by La spina et al. (2004), i.e. (71%).

Bottke et al. (2006) noted, to some extent, that the constant speed of crater formation on Moon point to the steady state of NEAs population. This, of course, means that the mechanism of transporting this family to near earth orbits most probably associated with a process of constant effect, and over typical long timescale of millions of years.

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