Contrib. Astron. Obs. Skalnaté Pleso **53/2**, 61 – 70, (2023)
https://doi.org/10.31577/caosp.2023.53.2.61

Temporary capture of a small body into a geocentric orbit

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Received: August 22, 2023; Accepted: December 6, 2023

Abstract. The radius of the Earths activity sphere relative to the Sun is more than 900,000 km. New asteroids whose orbits intersect this sphere have been discovered every year. It would appear reasonable that under certain conditions of an asteroids approach to the Earth, it can be captured into a geocentric orbit. Using the method for a numerical simulation of test point masses in the gravitational fields of the Sun and major planets, we determined some orbital elements of the asteroids, which are most likely to be temporarily captured into geocentric orbits.

We came to the conclusion that semi-major axes of these orbits take values close to 0.97 au and 1.03 au. Hence, the heliocentric speed during rapprochement with the Earth should be close to 30.2 km s^{-1} and 29.2 km s^{-1}, respectively.

We found that the most probable time for the existence of the asteroid in the Earth orbit is about 90-110 days; it can also be up to 180-200 days. But if an asteroid remains in the Earth orbit for more than 5 years, $\frac{3}{4}$ of such celestial bodies collide with the Earth.

Key words: Minor planets, asteroids: general – Methods: numerical

1. Introduction

The recorded passage of a small body over North America on 9 February 1913 initiated the study of the objects temporarily captured by the Earth-Moon system. A subsequent analysis of the orbit of the asteroid in the studies by Denning (1916) showed that the object was moving in a near-Earth orbit.

From the second half of the XX century onward, the problem of temporary capture of asteroids into geocentric orbits has been the subject of many studies, like Baker (1958), Cassidy et al. (1965) and Cline (1979). The authors investigated the origin of temporarily captured asteroids, their orbital evolution, the possibility of collisions with the Earth, and the dynamic characteristics, such as velocity, total energy, and angular momentum. It has been found that for the temporary capture, the relative speed and the relative position of the asteroid near the Earth in the Sun's gravitational field must satisfy certain conditions. Our numerical research is dedicated to studying these conditions. The discovery of asteroid 2006 RH120 on 14 February 2006 sustained claims of the existence of other Earths moons temporarily captured by the Earth-Moon system. According to the computed orbital elements at the instant of the asteroids capture, it was moving along the heliocentric trajectory close to the Earths orbit. Having approached the Earth, the asteroid went into a geocentric orbit and stayed there from September 2006 to June 2007 (Kwiatkowski et al., 2009). Being Earths second known temporary natural satellite, or minimoon, asteroid 2020 CD3 (Fedorets et al., 2020).

This study aims to estimate certain characteristics of a small bodys temporary capture into a near-Earth orbit, namely the geocentric velocity, momentum, total energy before and after the capture, distribution of orbital elements, and a typical lifetime of the captured body in the near-Earth orbit.

We propose to use the change of the asteroid's angular momentum relative to the Earth as a criterion for its transition into the Earth orbit.

2. Numerical model

In the course of this study we developed a numerical model of the motion of a small celestial body in the Solar System. This model accounts for the perturbations by the main planets, Pluto and Moon, as well as light pressure and perturbation due to the second zonal harmonic in geopotential on the motion of the investigated small body.

In accordance with IAU resolution[1], the Solar System has 8 major planets, satisfying the conditions: (a) is in an orbit around the Sun, (b) has a sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium shape, and (c) has cleared its neighborhood around its orbit.

We do not take into account the Yarkovsky effect, since the magnitude and direction of the jet moment depend on the speed and the physical properties of the test particle surface.

The differential equations of motion of a small body were solved in Cartesian coordinates with numerical integration by the Everhart 15^{th}-order method with an automatic step-size control (Everhart, 1974; Bazey & Kara, 2009):

[1] https://www.iau.org/static/resolutions/Resolution_GA26-5-6.pdf

$$\frac{d^2\overrightarrow{r_i}}{dt^2} + k^2(m_0 + m_i)\frac{\overrightarrow{r_i}}{r_i^3} = -k^2 \sum_{j=1}^{10} m_i \frac{\overrightarrow{r_i} - \overrightarrow{r_j}}{r_{ji}^3}$$
$$-k^2 \sum_{j=1}^{10} m_j \frac{\overrightarrow{r_j}}{r_{j0}^3} + \frac{\partial U}{\partial \overrightarrow{r}} + k^2 m_0 \beta \frac{\overrightarrow{r_i}}{r_i^3}, \quad i \neq j. \tag{1}$$

$$\begin{cases} \left.\frac{\partial U}{\partial \overrightarrow{r}}\right|_x = -\frac{3k^2 m_3 R_3^2}{2r^7} J_2 x(x^2 + y^2 - 4z^2), \\ \left.\frac{\partial U}{\partial \overrightarrow{r}}\right|_y = -\frac{3k^2 m_3 R_3^2}{2r^7} J_2 y(x^2 + y^2 - 4z^2), \\ \left.\frac{\partial U}{\partial \overrightarrow{r}}\right|_z = -\frac{3k^2 m_3 R_3^2}{2r^7} J_2 z(3(x^2 + y^2) - 2z^2). \end{cases} \tag{2}$$

Hereinafter, $\overrightarrow{r} = (x, y, z)$ is the position vector of the small body in the heliocentric system; t is time, k is the Gaussian gravitation constant, m_0 is the mass of the Sun, m_i - the mass of the perturbing body: the eight major planets, Pluto and the Moon, m_3 - the mass of the Earth, R_3 - Earth's radius. On the right hand side of the equation, $\frac{\partial U}{\partial \overrightarrow{r}}$ is a disturbing acceleration due to the Earth's compression, J_2 is a coefficient of the second zonal harmonic of the geopotential in the expansion (Troianskyi, 2015). The last term on the right hand side accounts for the pressure of sunlight: $\beta = \frac{\kappa \theta P_0}{a_{gr}}$ - photogravitational reduction of the mass of the Sun, κ - an optical coefficient of the small body surface, $P_0 = 0.0000045606\,\mathrm{N\,m^{-2}}$ - light pressure on the Earth's orbit; $\theta = \frac{A}{m_i} = \frac{3}{4R\rho}$ - a ballistic coefficient (windage)(Bazyey, 2014), A - the area of the middle section, R the radius of the small body, ρ - the density of the small body (Troianskyi & Bazyey, 2015). a_{gr} - the gravitational acceleration at the distance of 1 au from the Sun.

To account for the influence of the light pressure, the following parameters were assigned: $R = 100\,\mathrm{m}$, $m_i = 4.2{\times}10^9$ kg $= 2.1{\times}10^{-21}\, m_0$, $\rho = 1000\,\mathrm{kg\,m^{-3}}$, $\theta = 7.5{\times}10^{-6}\,\mathrm{m^2\,kg^{-1}}$, $a_{gr} = 5.9{\times}10^{-3}\,\mathrm{m\,s^{-2}}$, $\kappa = 1$ (Troianskyi & Bazyey, 2018; Troianskyi et al., 2023).

To minimize integration errors and optimize the computation speed, calculations of the positions of major planets, Pluto and Moon, were eliminated from the integration process. Their orbital position vectors were taken from the numerical theory DE405[2] and used in the differential equations of motion at each integration step. In fact, this method is equivalent to the decomposition process of integration into single steps, when in each step the position and velocity of all celestial bodies, except our test body, are assigned initial values from DE405 theory. In other words, it makes no sense to reintegrate the equations of motion of the major planets, Pluto and Moon, when this is done with high precision in numerical theory of the Solar System.

[2] https://ssd.jpl.nasa.gov/planets/eph_export.html

3. Initial conditions

The subject of this study was a family of orbits of test small bodies. Their heliocentric position vectors were generated in a random manner. To estimate the conditions of temporary captures of small bodies into near-Earth orbits we generated 1.5 million initial state vectors.

To integrate the trajectory of motion we selected only those state vectors which met a series of conditions, in particular:

– the semi-major axis of a test small body should lie in the range from 0.87 au to 1.5 au;

– the orbital eccentricity (e) ranges from 0.0 to 0.12;

– the orbital inclination to the ecliptic (i) ranges from 2.5° to 2.5° (or from 20.93° to 25.93° to the celestial equator);

– the epoch is within the time interval of 19 years (Fotheringham, 1924);

– the longitude of ascending node (Ω), argument of perihelion (ω) and mean anomaly at the epoch were evenly distributed over the interval 2π.

These initial conditions are selected on the basis of the study of Granvik et al. (2012). A 19-year period is used to eliminate the influence with rotation of the Lunar orbit.

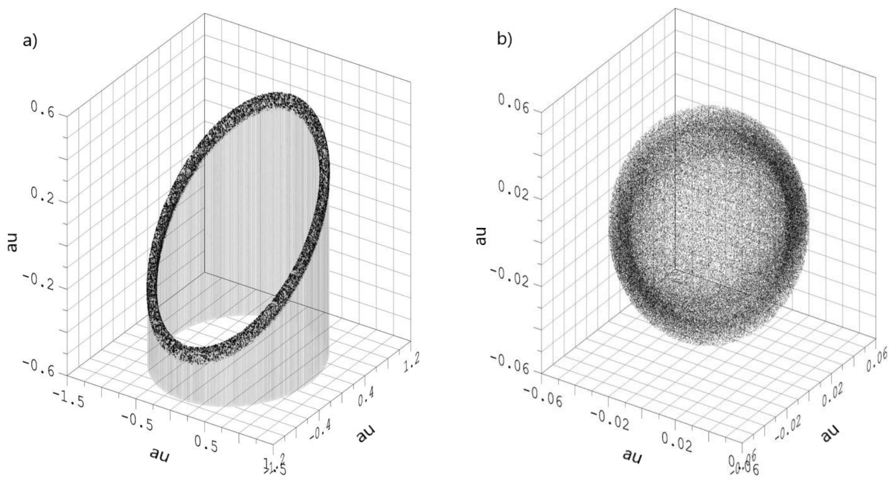

Figure 1. (a) Distribution of the initial conditions in the heliocentric system; (b) Distribution of the initial conditions in the geocentric system.

From the obtained range of small bodys initial conditions, the integration involved only those position vectors for which:

1) the geocentric distance at the start of integration was within the range of 0.04 au - 0.05 au;
2) the geocentric velocity of the object was smaller than its escape velocity at the same geocentric distance;
3) the angle between the geocentric direction and geocentric velocity vectors was smaller than 130° (Granvik et al., 2012).

The graphs for distribution of the initial conditions in the heliocentric and geocentric systems are presented below (see Fig. 1).

4. Definition of temporary capture

To determine whether a small body is the object captured into the Earth orbit or not, we used the following criteria:

1) the geocentric distance at the instant of the capture is smaller than three radii of the Hill sphere for the Earth (∼ 0.03 au; Kary & Dones (1996));
2) the number of full revolutions around the Earth is more than 1.

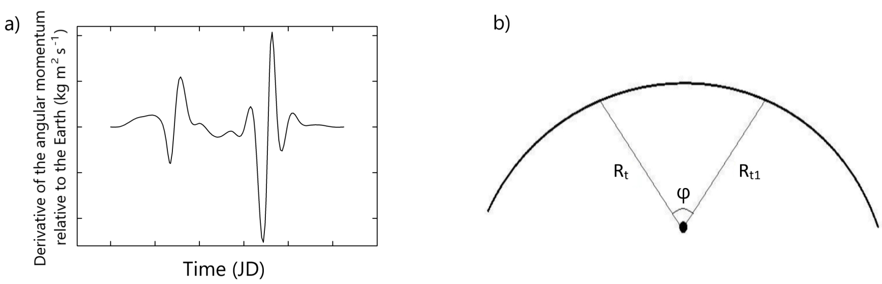

Figure 2. (a) A typical change in the angular momentum relative to the Earth of the small body temporarily captured into a geocentric orbit; (b) The angle between two position vectors of the small body in the geocentric orbit at the instants of time t and t_1.

To determine the instant of transition of a small body from the heliocentric orbit to the geocentric orbit, and then back, we used the derivative of the angular momentum of the small body relative to the Earth (Fig. 2, (a)). The ordinate axis shows this derivative, measured in (kg m^2 s^{-1}), without values. For each small body these values vary considerably, but there is always a very similar intermittent character of the curve (Fedorets et al., 2019).

We suggest interpreting such a stepwise change of this value as the transition of a small body from one orbit to another, that is, to define it as the instant of the capture of a small body by the Earth. Variation in the angular momentum of the small body can only be associated with the gravitational interaction with the Earth, such as the exchange of this value with the planet. As we know, this definition of transition into a geocentric orbit has not been previously introduced.

However, while such an exchange is not significant for the Earth because of a huge difference in the masses of celestial bodies, for a small body it means being temporarily captured into a near-Earth orbit.

The number of revolutions of a test small body around the Earth was determined by the angle between the position vector at the instant of capture (which corresponds to time t) and the position vector at the instant of the bodys return to the heliocentric orbit (which corresponds to time t_1), (Fig. 2,(b)).

5. Results

By substituting the obtained state vectors into the motion model, we observed the orbital evolution of test small bodies. The computation of the temporary capture parameters was started at the instant of their transition into geocentric orbits.

The instant of the integration end was not explicitly given. In case of a small bodys transition into a geocentric orbit, the instant of its return into the heliocentric orbit was reckoned as the instant of the integration end. Otherwise, the upper limit of the validity of the DE405 numerical model, the 20^{th} of February 2201, was taken as the end-time integration.

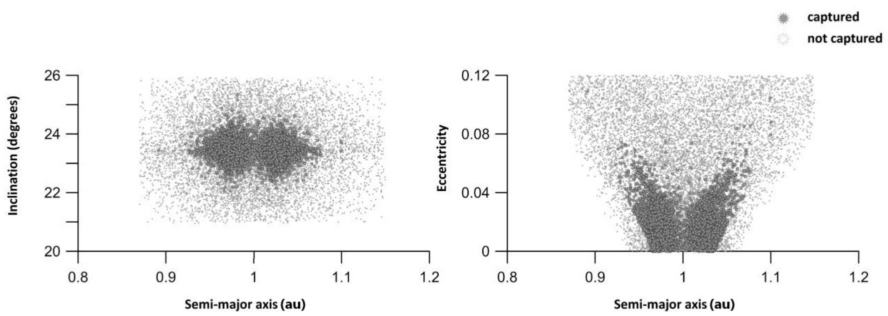

Figure 3. The interdependency between heliocentric orbital elements of the investigated small bodies.

Integrating the motion equations of the population of test small bodies resulted in the following: 14.4% of 1.5 million small bodies temporarily went into geocentric orbits, while 0.35% of them completed at least one revolution around the Earth. The small bodies which were also captured into geocentric orbits, but did not complete even one revolution around the Earth, were called transit ones.

The interdependencies between the orbital elements of captured and not-captured small bodies are presented below. The upper graph in Fig. 3 shows the orbital inclination toward the equator.

Based on the dependencies obtained, it is possible to unambiguously determine orbital elements for which the probability of a body being temporarily captured in a geocentric orbit is highest (Table 1).

Table 1. The limits of orbital elements for the captured small bodies. *Plane of the celestial equator.

	a, (au)	e	i^*, (deg)	ω, (deg)	Ω, (deg)
Min	0.89	0	21.75	0	0
Max	1.10	0.11	25.73	360	360

The heliocentric velocity is the next dynamic characteristic to be discussed.

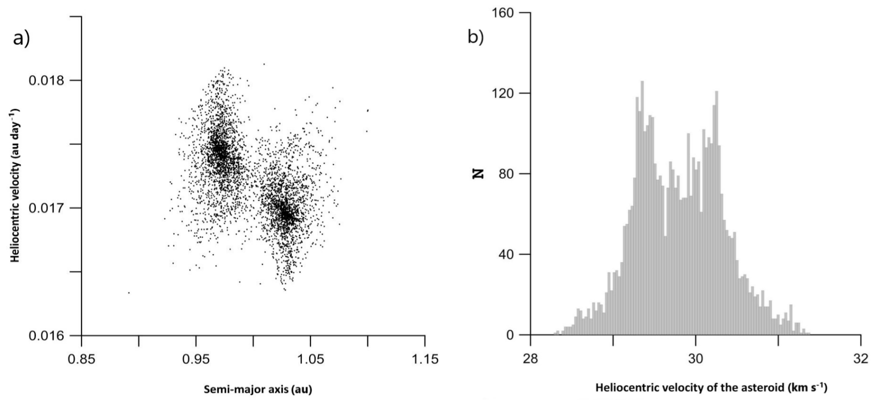

Figure 4. (a) The dependence of the heliocentric velocity of the captured particles on the semi-major axis of their orbit; (b) Distribution of heliocentric velocities of the captured particles.

As it follows from Figs. 4 (a), (b), the capture of a small body in the Earth's orbit is most likely when the heliocentric velocity lies between 29.2 km s^{-1} and 30.2 km s^{-1}, while it is least probable when the semi-major axis of the test body and its heliocentric velocity are close to those of the Earth or, in other words, for bodies in orbits similar to the Earths one. With regard to the Earth moving at an average speed of 29.8 km s^{-1}, the heliocentric velocity of such a small body does not exceed 0.6 km s^{-1}. A temporary capture is most likely to occur at such low speeds due to the insignificance of the mass of the Earth relative to the Sun mass. In the case of collision with the Earth, speed's possible values can vary significantly.

The next dynamic characteristic studied was the lifetime of a captured small body in a geocentric orbit.

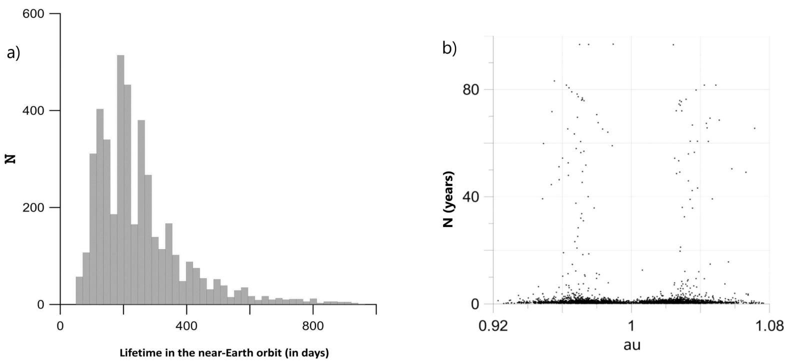

Figure 5. (a) Lifetime of a small body captured into a geocentric orbit; (b) Dependence of a small bodys lifetime on the semi-major axis of its orbit.

As it can be seen in Fig. 5 (a), the most probable lifetime in a geocentric orbit for small bodies that complete at least one revolution around the Earth is about 90-110 days. It can also be up to 180-200 days.

An equally interesting conclusion can be drawn upon considering the dependence of the semi-major axis of the captured small bodys orbit on its lifetime in that orbit.

As it follows from the graph, there are such values of the semi-major axes of the temporarily captured small bodies within the range of which the capture for an extended time span lasting for decades is possible. Such a capture is most likely to occur when the semi-major axis is close to 0.97 au and 1.03 au (see Fig. 5,(b)).

While simulating, we also obtained orbits of the small bodies which collide with the Earth. Among 1.5 million model orbits, we received 119 collisions.

It is interesting that 75% of the total number of captured long-lived objects (with the lifetime of a captured object in a geocentric orbit of 5-100 years) are accounted for by objects in collisional orbits.

6. Conclusions

The results of our simulation re-indicate the importance of the study of such objects as small bodies temporarily captured into geocentric orbits.

In the course of the numerical experiment, it was shown that small bodies moving along trajectories that are tangent to the Earth's orbit are most likely to be temporarily captured into near-Earth orbits. Most probable is the temporary capture of small bodies whose semi-major axis of the orbit is close to 0.97 au and 1.03 au. The probability of a small body being temporarily captured is least probable if the semi-major axis of its orbit is close to the semi-major axis of the Earths orbit.

Small bodies whose semi-major axes are close to 0.97 au and 1.03 au have the longest lifetime (up to 100 years) in the near-Earth trajectories.

It is necessary to take into account that an extended stay of a small body in a geocentric orbit increases the risk of its approaching to the orbits of artificial-Earth satellites, which may lead to their collisions.

The results obtained define the limits of the heliocentric orbital elements and the geocentric velocity for which a small bodys temporary capture into a near-Earth orbit is the most probable.

Thus we can suppose that for a temporary capture of an asteroid on the near-earth orbit, its heliocentric orbit must come liken the Earth orbits under for impact of different perturbations. Simple intersection and convergence of the orbits are not enough.

Perhaps this will determine among the known near-Earth asteroids, likely candidates for the temporary capture of the future, or to find asteroids that were captured in the past by the Earth.

Acknowledgements. VT was supported by the National Scholarship Programme of the Slovak Republic - academic year 2023/2024.

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