

THE ORBITAL EVOLUTION OF ASTEROID 367943 DUENDE (2012 DA14) UNDER YARKOVSKY EFFECT INFLUENCE AND ITS IMPLICATIONS FOR COLLISION WITH THE EARTH

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Abstract

Asteroid 367943 Duende (2012 DA14) holds the record as the one of Aten subpopulation with $H \leq 24$ that had experienced deep close encounter event to the Earth (0.09x Earth-Moon distance) as informed in NASA website. In this work, we studied the orbital evolution of 120 asteroid clones and the nominal up to 5 Megayears (Myr) in the future using *Swift* integrator package with and without the Yarkovsky effect inclusion. At the end of orbital integration with both integrators, we found as many as 17 asteroid clones end their lives as Earth impactor. The prediction of maximum semimajor axis drift for this subkilometer-sized asteroid from diurnal and seasonal variants of Yarkovsky effect was 9.0×10^{-3} AU/Myr and 2.6×10^{-4} AU/Myr, respectively. By using the MOID (Minimum Orbital Intersection Distance) data set calculated from our integrators of entire clones and nominal asteroids, we obtained the value of impact rate with the Earth of 2.35×10^{-7} per year (with Yarkovsky effect) and 2.37×10^{-7} per year (without Yarkovsky effect), which corresponds to a mean lifetime of 4.25 Myr and 4.22 Myr, respectively. The Wilcoxon Rank Sum test with a confidence level of 95% shows that the MOID data set from both integrators does not have a significant difference. This statistical test result shows that the influence of close encounters with planets in the inner Solar System on asteroid 2012 DA14 is more dominant than the Yarkovsky effect, which is consistent with asteroid short residence time for Yarkovsky force to grow up its small effect.

Keywords: Impact probability, Near-Earth asteroid, Orbital evolution, Yarkovsky effect.

1. Introduction

Currently, the population of the near-Earth asteroids (NEA, asteroids with the closest distance to the Sun $q < 1.3$ AU) is grouped into four main classes, i.e., Amor, Apollo, Aten and Atira. Amor subpopulation (the average distance to the Sun $a > 1$ AU and 1.017 AU $< q < 1.3$ AU) has an orbit that intersects the orbit of planet Mars. The subpopulation of Apollo ($a > 1$ AU and $q < 1.017$ AU) and Aten ($a < 1$ AU and the furthest distance to the Sun $Q > 0.983$ AU), both have orbits that intersect the Earth's orbit, while Atira subpopulation ($a < 1$ AU and $Q < 0.983$ AU) with an orbit entirely inside the Earth's. The subpopulation of Apollo has dominated the number of NEA discovered through various survey programs. As of 27th April 2017, the number of Amor, Apollo, Aten and Atira subpopulation is 6148, 8732, 1176 and 16 asteroids, respectively, as informed in NASA website [1].

NEA's orbit can be chaotic because of their close encounter events with Terrestrial planets. Significant changes in the value of a may occur that make asteroids undergo class changing as experienced by asteroid 367943 Duende (2012 DA14). Prior to February 15, 2013, this subkilometer-sized asteroid belongs to Apollo subpopulation. After its close encounter with the Earth on February 15, 2013 at less than geostationary satellite distance, this asteroid is now a member of Aten subpopulation. According to [2] the collision probability between Aten asteroids and the Earth is twice as high as that of Apollo asteroids. In addition to gravitational perturbation, orbital changes may also occur due to non-gravitational effects. One of the known non-gravitational effects is the Yarkovsky effect. The Yarkovsky effect is a non-gravitational phenomenon associated with non-isotropic thermal emissions that result in the system losing momentum in addition to heat loss. The effect of this thermal radiation works effectively on celestial objects with diameter ranging from a few centimetres to tens kilometres of rotating bodies and heated by solar radiation.

There two known variants of this effect, namely the diurnal effect (due to rotation) and the seasonal (due to revolution). Depending on NEA rotation, diurnal effect can make NEA's orbit larger (for prograde rotation) or smaller (for retrograde rotation). Unlike the diurnal, seasonal effect always make NEA experience drift in a into smaller orbit. The accumulation of non-gravitational acceleration vector of Yarkovsky effect in the time span of 106 to 109 years [3, 4] is the largest contrast with the other non-gravitational accelerations, such as radiation pressures and Poynting-Robertson drag [5]. The inclusion of this effect in the evolutionary studies and orbital dynamics of asteroids have been able to explain the gap between observations and predictions of classical model that rely on the influence of gravity only. A detail review of Yarkovsky effect can be found in [4].

NEA population has attracted researchers because of its short lifetime (~ tens of Megayears (Myr) [6-11] than the age of the Solar System. NEA population decays through the collision they experience with the Sun and the Terrestrial planets or ejected to the outer Solar System. Meanwhile, the observations of craters formation on the surface of the Moon suggest that the rate of its formation is nearly constant. This observational result indicates that NEA population is in a steady state within the last 3 Gigayears (Gyr) [12]. This means the mechanism in the supply process of NEA population is dominated by a continuous process instead of sporadic. The inclusion of Yarkovsky effect in NEA orbital dynamics

succeeds providing a mechanism for the sustainability of the asteroid supply from the Main Belt region to the near-Earth space via semimajor axis drift to the resonant regions [13]. Therefore, the purpose of this study is to investigate the presence of Yarkovsky effect in the orbital evolution of individual asteroid, namely 2012 DA14, and hence its implication for collision probability with our home planet. The orbit was propagated using *Swift_RMVS4* (gravitational effect only) and Modified *Swift_RMVS4* (gravitational and Yarkovsky effect included) to detect the presence of Yarkovsky effect on the future orbital evolution of asteroid 2012 DA14.

2. Method

The method employed in this work is numerical simulation using *Swift* integrator package [14] which has been modified to include the Yarkovsky effect besides the gravitational one in the asteroid orbital computation. This modified integrator makes possible to calculate the orbits more accurately, especially when close encounter between asteroid with massive objects (Sun and planets) occurs as well as for a long-time span ($> 10^5$ years). We adopted model of the Solar System including the Sun and the eight planets (Mercury to Neptune) as well as the Moon as a separated object. Positional vector and velocity data of all massive objects are generated through NASA HORIZONS web interface [15]. Meanwhile, the orbital elements (a , e , i , Ω , ω , dan M) data of asteroid 2012 DA14 and its uncertainty (within 1σ) according to epoch JD2457000,5 (December 9, 2014) are available at NASA Small-Body data base [1]. The asteroid orbital parameter values are presented in Table 1. Illustration of the orbit of the celestial object is shown in Fig. 1.

Due to strongly chaotic nature of the orbit of NEA implies that the results of our numerical integrations are not a deterministic prediction for the evolution of the real asteroid. The results can only be seen as a possible evolution which may occur to the real object. Therefore, we studied not only the 2012 DA14 nominal asteroid corresponding to the initial conditions, but also a sample of clones (virtual asteroids) obtained by slightly changing the initial orbital parameters shown in Table 1 one at a time. For each orbital element, we generated 20 clones. Totally we have 120 ($= 20 \times 6$) clones besides the nominal one. Computation was performed up to 5 Myr, when the accumulation of thermal radiation effect starts to be non-negligible [5]. By inclusion of the Yarkovsky effect, we need some information about asteroid physical and thermal quantities (bulk density, surface density, rotation period, spin state, thermal conductivity, thermal capacity, Bond albedo and emissivity). To estimate the values of some unknown asteroid's properties, we follow [16]. The computation time step was set 10-3 years (~ 9 hours) and the results were recorded every 103 years. The asteroids orbital evolution followed until they were eliminated due to collision with massive objects or ejected to the outer Solar System (when $a \geq 100$ AU; 1 AU is the mean distance of the Earth to the Sun which is equal to 1.496×10^8 km). As a comparison, computation using *Swift_RMVS4* integrator package has also been performed. Both *Swift_RMVS4* and Modified *Swift_RMVS4* are Fortran-based code. The Yarkovsky effect calculation in the Modified *Swift_RMVS4* are based on formulation in [17, 18]. Table 2 lists the value of asteroid physical and thermal parameters used in the computations.

Table 1. Orbital elements of nominal asteroid 2012 DA14.

Element	Value
a	0.91031593 AU ($1\sigma = 1.1534 \times 10^{-7}$)
e	0.0894277 ($1\sigma = 1.3761 \times 10^{-7}$)
i	$11^\circ.60909$ ($1\sigma = 8.491 \times 10^{-7}$)
Ω	$146^\circ.968375$ ($1\sigma = 1.27 \times 10^{-7}$)
ω	$195^\circ.58077$ ($1\sigma = 3.5598 \times 10^{-5}$)
M	$191^\circ.97808$ ($1\sigma = 1.639 \times 10^{-4}$)

Table 2. Physical and thermal parameters of asteroid 2012 DA14.

Parameter	Value
Radius [m]	22
Material	Regolith
Bulk Density [kg/m^3]	3500
Surface Density [kg/m^3]	1500
Thermal Conductivity [W/K/m]	0.005
Thermal Capacity [W/kg/K]	680
Bond Albedo	0.09
Emissivity	0.8
Rotation Period [Hour]	9.5
Spin State [Azimuth, Height]	[$234^\circ, -22^\circ$]

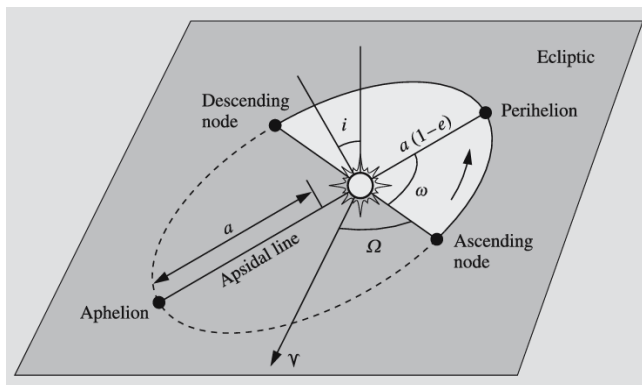


Fig. 1. Six integration constants are needed to describe celestial objects' orbit. The constants are the longitude of ascending node Ω , the argument of perihelion ω , the inclination i , the semimajor axis a , the eccentricity e and the time of perihelion passage $\tau [= (M \times P / 2\pi) + \tau_0$, where P is orbital period] [19].

3. Results and Discussion

Orbital computations using both integrator packages show the similarity of evolutionary path among the nominal asteroid and the 120 clones during the first 200 years of computation. For longer time span, the evolutionary path of asteroid is already different from each other, especially due to close encounter with planets. The evolutionary path of the nominal asteroid and clones throughout the integration time is shown in Fig. 2. Generally it appears that most of clones

mobility (wander in a) from both integrators is similar except for the three clones from non-Yarkovsky integrator that being ejected to the outer solar system.

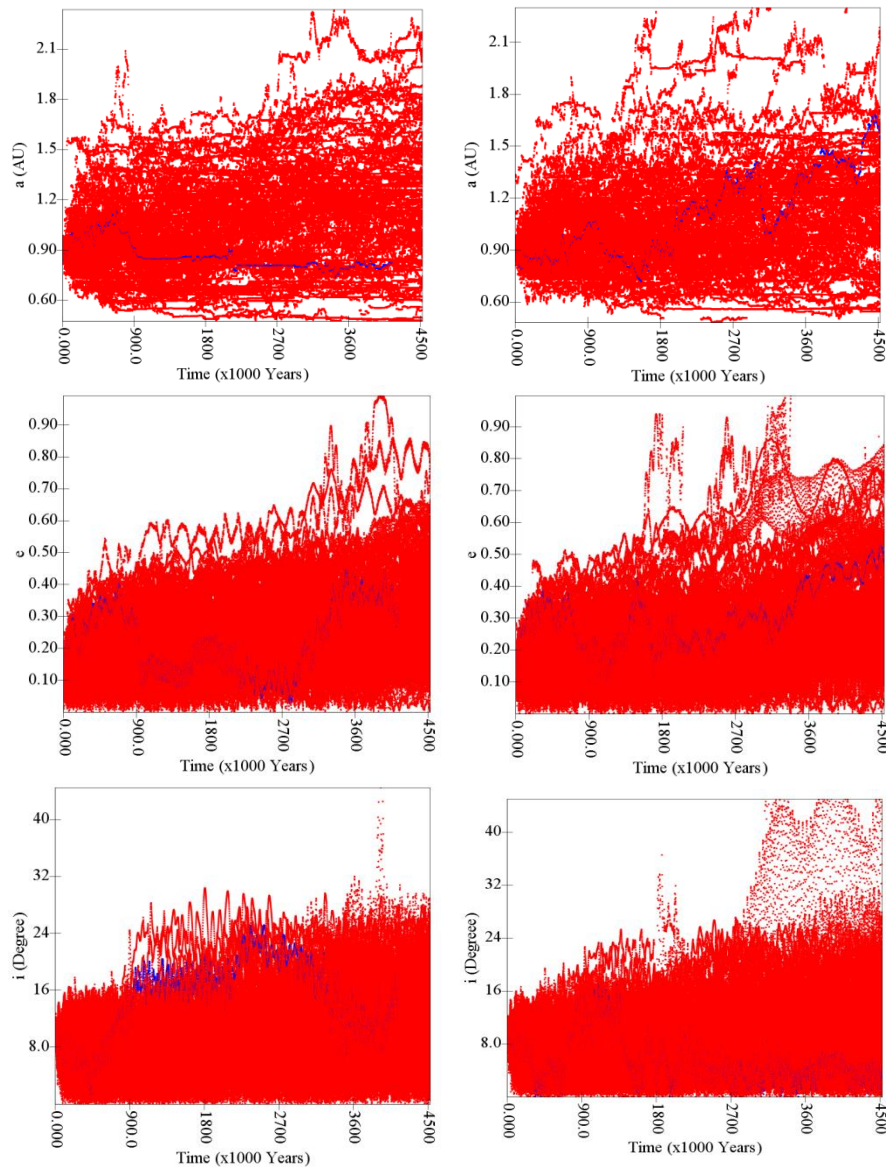
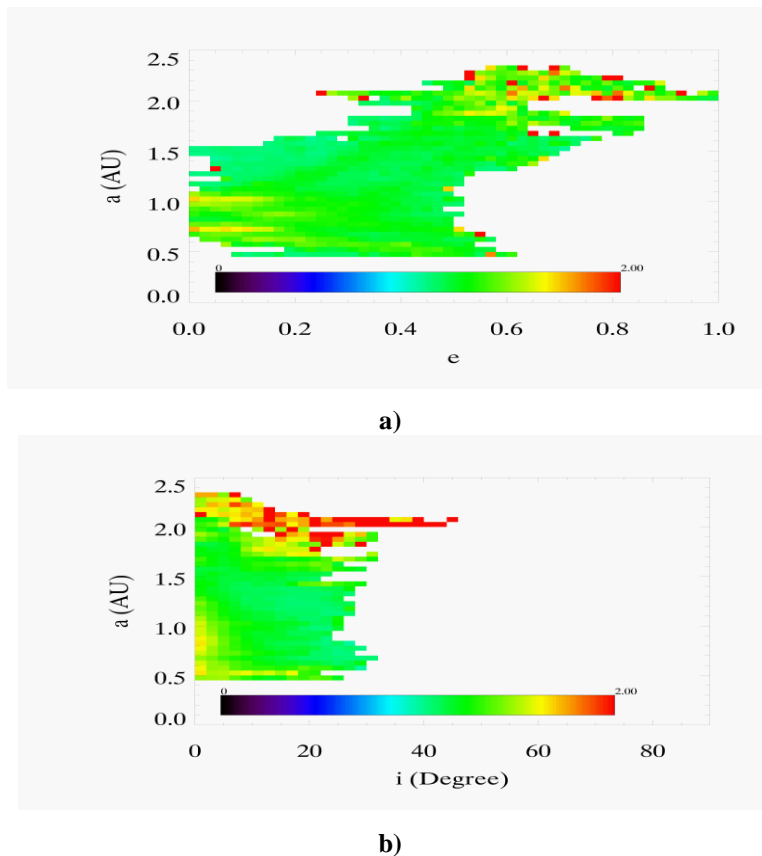


Fig. 2. Evolutionary path of asteroid 2012 DA14 orbital elements (a , e , i) (nominal and 120 clones) within 5 Myr of computation with Yarkovsky effect inclusion (left panel) and gravitational effect only (right panel). In all figures blue colour represents the nominal asteroid evolutionary path, while red colour represents all clones.

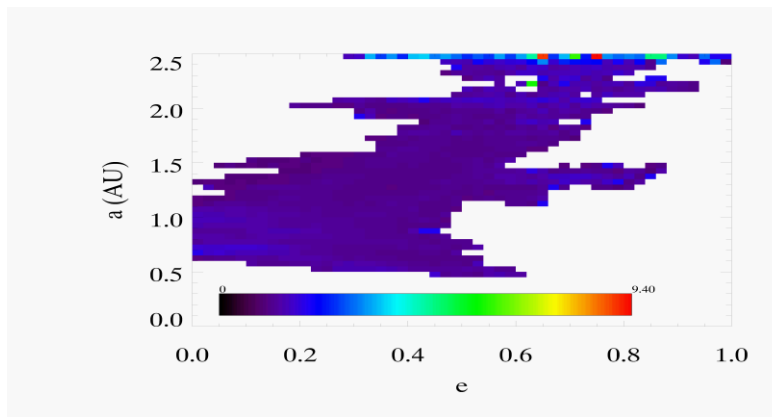
During the integration, the nominal asteroid and clones will wander in (a , e , i) space and become asteroid with particular orbital element values for a certain

time. This means the total time spent in a certain orbital state, or residence times, is a representation of probability to find an object in that state. Starting from the initial *epoch*, we have computed the time spent by all the asteroids in different (a , e , i) cells along the integration. For a clone in its initial location, we compute the time it spends in different cells of (a , e , i) over its whole evolution. We repeat this computation for all the clones and finally divide the total residence time by the total number of clones in each cell. Figures 3 and 4 show the mean residence time of asteroid 2012 DA14 in different regions during its future evolution with and without Yarkovsky effect inclusion, respectively. Following previous reference [20], Figures 3 and 4 are constructed using 0.05 AU, 0.02 and 2° cells covering the inner region of the Solar System with the limits of $a < 2.5$ AU, $e < 1$ and $i < 90^\circ$. It is generally seen that the asteroid residence time within a particular cell is longer for evolution not involving the Yarkovsky effect (up to 9,400 years).

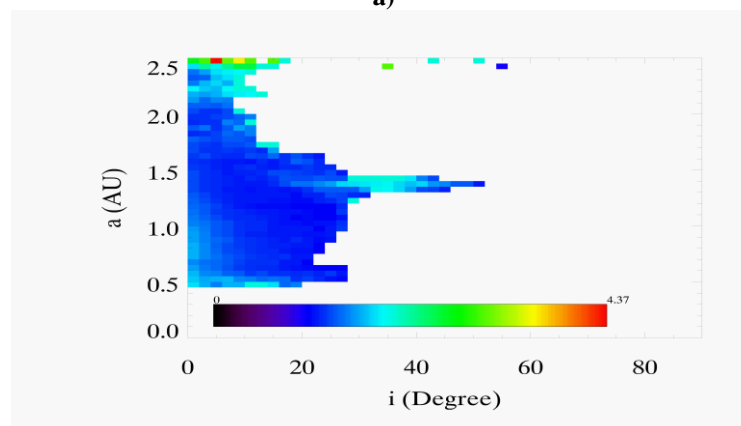


Note: Red color indicates where NEAs are most likely to spend their time and purely white regions are never visited.

Fig. 3. Mean residence time of asteroid 2012 DA14 and 120 clones in (a , e) plane (a) and in (a , i) plane (b) for evolution with Yarkovsky effect inclusion. The color scale depicts the average amount of time (in thousand years) spent by asteroids in a particular cell.



a)



b)

Fig. 4. Mean residence time of asteroid 2012 DA14 and 120 clones in (a, e) plane (a) and in (a, i) plane (b) for evolution without Yarkovsky effect inclusion.

At the end of 5 Myr integration using both integrators package, 17 asteroids (including nominal asteroid) were eliminated due to collision with Terrestrial planets. It is common that NEA often experience close encounter with planets which will modify their semimajor axis, eccentricity and inclination, so that suppress the contribution of Yarkovsky effect. As a consequence of high frequency of close encounter with planets is a wide orbital space can be visited and some clones eventually collide with the Earth. We found there were nine clones from Modified Swift_RMVS4 integrator (Yarkovsky effect included) which end their lives as an Earth impactor within timescales from 105 years to several Myr. As many as five clones among them collide with the Earth on a timescale less than 1 Myr; the fastest is within ~ 200 kiloyears (Kyr). The asteroids being eliminated from the two integrators are presented in Table 3.

Using analytic model of Yarkovsky effect [21], we have calculated the Yarkovsky force (per unit mass) contribution of diurnal and seasonal variants, as well as the predicted maximum value of semimajor axis drift (da/dt) averaged

over one revolution. The maximum force per unit mass of diurnal (seasonal) variant is 4.95×10^{-12} N/kg (1.41×10^{-13} N/kg), which corresponds to the maximum rate of da/dt 9.0×10^{-3} AU/Myr (2.6×10^{-4} AU/Myr). Positive value of da/dt indicate that the DA14 asteroid 2012 has a prograde orbit. This corresponds to the numerical fact that at the end of the orbital integration neither clones nor nominal asteroid has an inclination $i > 90^\circ$. The maximum force (per unit mass) of the diurnal variant and maximum drift obtained in this work have the same order as predicted by [22], i.e., 2.19×10^{-12} N/kg and 4×10^{-3} AU/Myr, respectively. There are small differences due to fact that in [22] and this work used different asteroid's thermal properties.

Table 3. Final fate of nominal and clones asteroid.

With Yarkovsky effect		Without Yarkovsky effect	
Final fate	Σ Asteroid	Final Fate	Σ Asteroid
Venus impactor	7	Solar impactor	2
Earth impactor	9	Venus impactor	15
Moon impactor	1	Earth impactor	8
		Ejected from Solar System	3

In order to estimate the impact rate of asteroid 2012 DA14 with the Earth, this work follows the procedure in [23]. Figure 5 shows the histogram of the cumulative number of MOID with the Earth that is fitted well by a parabola. This means the number of MOID is approximately proportional to the square of the chosen threshold distance. The orbital radius of geostationer satellite, 2.8×10^4 AU, was chosen as a MOID threshold. The MOID of each asteroid and target planet were computed from their orbital elements output employing new method in [24]. Extrapolation to the quadratic trend down to the Earth's capture radius (about 1.5 times Earth's effective radius due to gravitational focusing of impactor coming with typical speeds at infinity of about 10 km/s) was performed to obtain the asteroid impact rate. We then apply the relation in [25] to obtain the intrinsic collision probability with Yarkovsky effect inclusion (gravitational effect only), that is 2.57×10^{-15} km² year⁻¹ (2.59×10^{-15} km² year⁻¹), which corresponds to asteroid impact rate of about 2.35×10^{-7} year⁻¹ (2.37×10^{-7} year⁻¹). Mean lifetime or collisional lifetime is the timescale over which asteroid 2012 DA14 is expected to collide with the Earth, i.e. the inverse of impact rate, namely 4.25 Myr and 4.22 Myr as asteroid's mean lifetime under influence of (Yarkovsky + gravitational) and gravitational effect only, respectively. Further, we employ the Wilcoxon Rank Sum test with a confidence level of 95% to show that the MOID data generated from the output of both integrators do not have a significant difference indeed. We can infer that the presence of Yarkovsky effect on asteroid 2012 DA14 to contribute on modifying its orbit can be neglected contrast to the effect of the close encounter with planets which is dominant in the inner Solar System. This statistical test result is consistent with asteroid short residence time ($< 10^6$ year duration) in cells of (a, e, i) over its whole evolution.

Based on our actual records of Earth collisions in the integrations, makes asteroid 2012 DA14 one of candidate to be the next potential Earth impactor. Utilizing the presence of the Yarkovsky effect, [26] proposed a disaster mitigation technique for collision threat between hazardous asteroids and the Earth. Their

scenario relies on the dependence of Yarkovsky effect on Bond albedo. By using The Albedo Change System (ACS) a spacecraft sent to asteroid orbit will perform albedo modification by sprinkling fine powder onto the asteroid surface up to the required thickness. The altered albedo will change the Yarkovsky force acting on the asteroid and gradually change its orbit. The details can be found in [26] and references therein.

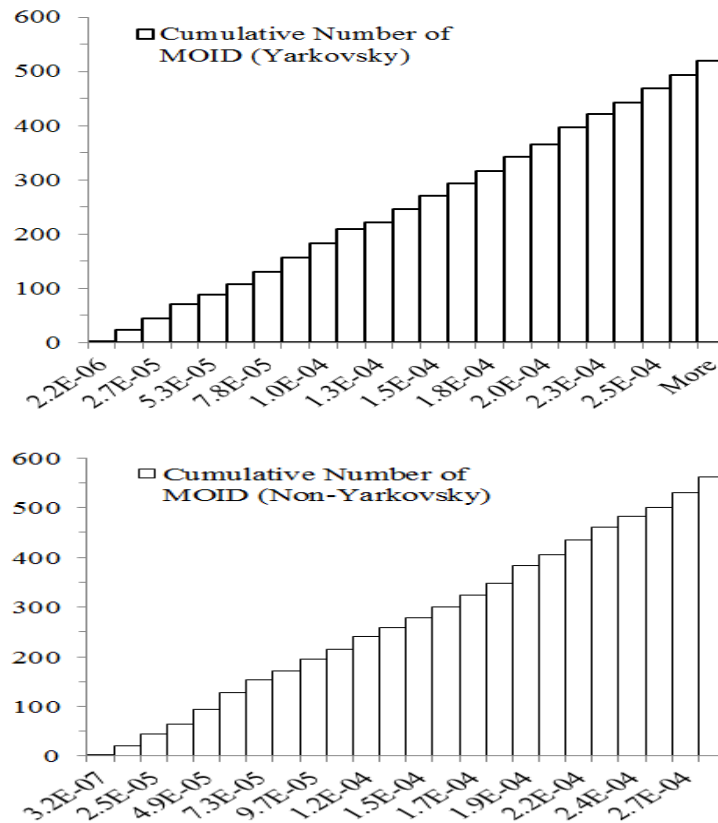


Fig. 5. Histogram of the cumulative number of MOID of asteroid 2012 DA14 to the Earth vs the value of MOID (in AU). All clones and the nominal asteroid are considered together to have the total time span during which MOID have been calculated is 605 Myr (= 121x5 Myr).

4. Conclusion

Numerical simulation of asteroid 2012 DA14 orbital evolution shows that mean residence time of clones on particular cell of (a, e) and (a, i) plane is longer for computation without Yarkovsky effect inclusion. Visually, the orbital wander of clones from both integrators is similar. Correct thermal properties are needed then to obtain the asteroid orbital path accurately under influence of Yarkovsky effect. Our prediction of maximum drift in asteroid semimajor axis caused by Yarkovsky effect is in agreement with other, besides we also obtain mean lifetime before a

collision with the Earth to occur; 4.25 Myr under influence of Yarkovsky effect and of 4.22 Myr without Yarkovsky effect. The negligible difference in asteroid mean lifetime from computation with and without Yarkovsky effect inclusion shows the dominant of planetary close encounters against this thermal effect in altering asteroid orbit during its future evolution.

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