Steady State Scenario in Asteroids Orbital Simulation with Yarkovsky Effect Inclusion

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Abstract As one result in our orbital simulation of the 3372 samples of real NEAs (Near-Earth Asteroids) whose orbits were considered to be well-known, as many as 480 asteroids evolved out of the four major classes (Amor, Apollo, Aten and Atira) of NEAs at the end of the first 500,000 years period into Mars-Crossers asteroids in majority. To test the steady state hypothesis for NEAs population, these evolved asteroids had been used as a sample for further simulation to obtain the entrance flux from the Intermediate Sources/IS (in this case the Intermediate Mars-Crossers/IMC only) to NEAs region. The entrance flux from IMC → NEAs region is 71 ± 17 objects per million year for H< 18. Asteroids of this amount as a contribution from IMC (along with contributions from other sources in the Main Asteroid Belt) will be delivered to near-Earth space to replenish this region due to the decay of NEAs population into the Sinks (collide with the Sun/planets or being thrown to the outer Solar System). After 5 million years of simulation we found there were 1898 asteroids eliminated from further computational process with the majority ended their lives as Sun-grazer and ejected from the Solar System. The near-Earth space lost a total of 114 ± 17 objects per million year for H< 18. The median dynamical lifetime obtained directly from our NEAs sample decay is 3.7x106 years.

Keywords: near-Earth asteroids, orbital evolution, Yarkovsky effect.

1. Introduction
Near-Earth space is defined as an area that meets the inequality of perihelion distance q [= a(1 –e)] < 1.30 au(1 au is defined as Sun-Earth mean distance, which is equal 1.496x108 km) and aphelion distance Q [= a(1 + e)] > 0.98 au, which is inhabited by asteroid, comets and meteoroids or commonly known as Near-Earth Objects (NEOs). The asteroid is the largest population of NEOs, so we can be grouped this population as Near-Earth Asteroid (NEAs) which is our concern in this study. With the
rise of space survey programs that scan the near-Earth space since the 1980s, NEAs is increasingly found in various sizes [1]. For NEAs with diameter $D > 1$ km (corresponding to an absolute magnitude $H < 18$) of Amor class (semimajor axes $a > 1$ au and $1.017 < q < 1.3$ au) the survey completeness has already reached 66%, whereas for Apollo class ($a > 1.0$ au and $q < 1.02$ au) and Aten class ($a < 1.0$ au and $Q > 0.98$ au) the completeness are 33% and 45%, respectively [2]. Even the survey completeness of 100% has been achieved for NEAs with $D > 7$ km (corresponding to $H < 14$) [3]. The NEAs population is believed to be the source of projectiles that produce impact craters on terrestrial planets’ (and also on the Moon’s) surface.

The observations of craters formation on the surface of the Moon suggests that the rate of its formation nearly constant, which indicates that NEAs population is in a steady state within the last 3.7–3.8 billion years[4]. This means that the mechanism in the supply process of NEAs population is dominated by a continuous process rather than a sporadic. In the view of Classical Model (CM), supply process of NEAs populations is dominated by a catastrophic collision among asteroids in the Main Belt which often take place. Asteroids collide with a quite high speed, about 5 kms$^{-1}$[5], are able to produce impact craters and fragmentation that would affect the orbit, the shape, internal structure and the state of the rotation of asteroids involved. Even the devastating collision is able to destroy the asteroids into a cluster of fragments that each fragment has orbital parameters of $a$, eccentricity $e$ and inclination $i$ are similar to each other forming an asteroid family. A high ejection speed and correct direction from the impact site can make fragments enter the zone of strong resonance generated by gravitational perturbations of the planets. While stay in the zone of strong resonance, fragment can evolve into highly elliptical orbit so that it intersects the orbit of planet Mars or even reach the near-Earth region.

There are gaps between the CM predictions with observations. Therefore, factor other than collisions and gravity, is necessary to be included in the study of the dynamics of NEAs, which is known as the thermal effect (Yarkovsky). Yarkovsky effect is a non-gravitational phenomena related to non-isotropic thermal emissions which cause the system to lose heat and momentum. This effect is believed to have an effective influence on the rotating objects with small diameter $D$ (ranging from a few centimetres to several tens km) experiencing heating by solar radiation. Using the modified Swift integrator package [6], namely Swift_rmvs4y which has involved the Yarkovsky effect [7], as well as utilize the IS and NEAs steady state model exist, this work intend to demonstrate the validity of the NEAs steady state hypothesis. To the best of the authors' knowledge, direct proof through numerical simulation of steady-state NEAs population is not present yet in the literatures.

2. Method
With the help of Swift_rmvs4y integrator, the NEAs steady state hypothesis was tested. This means our method is numerical simulation. The numerical algorithm is an improvement of the one in [6] and including the thermal force (Yarkovsky effect). The main data were obtained from NASA JPL Small-Body Database Search Engine (http://ssd.jpl.nasa.gov/sbdb_query.cgi). Only four classes (Apollo, Amor, Aten and Atira) of asteroids with very well-known orbit (condition code = 0) were included. Using this filtering we obtained 3372 NEAs (as of 10th March 2016). Due to limitation of total number of bodies could be integrated, the computing process was executed by dividing the total samples into four batches (batch1 to batch3 consists of 1000 asteroids each and batch4 of 372 asteroids). The computations utilized Perseus cluster facilities and a PC of Intel (R) Core(TM) i7-2600K CPU (both are available at Astronomy Research Group of InstitutTeknologi Bandung) and other PC of Intel (R) Core(TM) i3-3240T CPU at Computational Physics Laboratory of Physics Education Department of UniversitasPendidikan Indonesia.

Computations were performed using a segmentation strategy, which meant we used multiples of 500,000 years on the three facilities available. Time step was set to be 1/1000 years (~9 hours) and the results were logged every 1000 years. The gravitational perturbations of all the planets except Pluto were taken into account in the simulations. The Moon was treated as separate body. The NEAs orbital evolution were followed until they either struck the Sun or a planet, travelled outside 100 au from the
Sun, or the final integration time was reached. We called the first two conditions as Sinks. The collision among asteroids and disruption events were not considered in this work.

3. Results
After the first 500,000 years, we found as many as 480 NEAs evolved out of the four classes of their origin (Amor, Apollo, Aten and Atira) as shown in one of the regions of 0.4 - T, fluxed MC tly. According to the steady state model of NEAs with stable value of \( T \) corresponding to the near-Earth region of 0.4 - T, ENAs are delivered from IMC region to near-Earth space, the entrance flux from IMC region to near-Earth space becomes \( F_{\text{IMC}} = 71 \) objects per million year for \( H < 18 \). This value is consistent with the number of asteroids delivered from IMC region to near-Earth space (65 ± 15 objects per million year \( H < 18 \) [2]) to keep NEAs population in steady state.

Figure 2 shows our remaining NEAs sample as the function of time (up to \( 5 \times 10^6 \) years) and calculated mean \( r_f \) curve. Within the time interval of \( 2.5 \times 10^6 - 5 \times 10^6 \) years (the interval with stable value of \( r_f \)) we obtained the absolute mean value of \( r_f = 0.1188 \pm 0.0016 \) per million years. According to the steady state model of NEAs, there are \( N_{\text{NEAs}} = 960 \pm 120 \) for \( H < 18 \) [2]. So we can calculate the NEAs entrance flux to the Sinks, that is \( F_{\text{NEAs}} = 114 \pm 14 \) per million year for \( H < 18 \). The decay of NEAs population due to asteroids evolution into the Sinks will be replenished by IS population, one of which is our IMC sample.

From the above, we can determine the median dynamical lifetime of our sample directly, that is \( 3.7 \times 10^6 \) years. This is the characteristic time at which the population is reduced to half its initial population. This new value is shorter than that obtained in [8], which is \( 1 \times 10^7 \) years. This indicates the different role played by resonances in the region of 0.4 au < \( a < 2 \) au [9] against NEAs.

Table 1. Subpopulation of asteroids out of the four NEAs class at the end of the first 500,000 years of evolution.

| \( \Sigma \) Particle | Orbit   | Remark                  |
|----------------------|---------|-------------------------|
| 384                  | 1.3 au < \( q < 1.58 \) au | Deep Mars-Crossers (DMC) |
| 34                   | 1.58 au < \( q < 1.67 \) au | Shallow Mars-Crossers (SMC) |
| 62                   | 1.8 au < \( a < 25 \) au   | -                       |
| 2 au < \( Q < 44 \) au |          | -                       |
sample used in [8] and in this work. Our result shows that the resonances in this region have made the asteroids evolved into Sinks rapidly.

![Figure 1](image)

**Figure 1.** The decay rate from IMC region to near-Earth region: (a) natural logarithm of the population left in the IMC region as a function of time; (b) absolute fractional decay rate into near-Earth region.

We also plot the residence time of our NEAs sample during $5 \times 10^6$ years of integration in figure 3. 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 an asteroid 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 asteroids and finally the cumulative time spent by all asteroids in each cell is normalized to the total time spent by all asteroids in all cells. This illustrates the steady-state distribution of objects in the $a < 4.2$ au region. These plots are constructed via a grid of $(a, e, i)$ cells covering $a < 4.2$ au, $e < 1.0$ and $i < 90^\circ$ with delta value of each orbital element is 0.05 au, 0.02 and $2^\circ$ respectively. These plots also tell us the mean residence time of our NEAs sample in different $(a, e, i)$ cells in the inner Solar System during their future evolution.
Figure 2. The decay rate from near-Earthspace to the Sinks: (a) natural logarithm of the NEAs population left as a function of time; (b) absolute fractional decay rate into the Sinks.

Figure 3. Mean residence time of our NEAs sample in different cells of the $(a,e)$ plane (a) and $(a,i)$ plane (b) during $5 \times 10^6$ years of evolution. The colour scale depicts the normalized average amount of time spent by asteroids in a particular cell. Red colour indicates where NEAs are most likely to spend their time (in contrast to black colour) and purely white regions are never visited.

4. Conclusion
Entrance flux of the IMC to the near-Earth space has been obtained from numerical simulation that includes Yarkovsky effect. The rate at which asteroids are delivered into near-Earth space is consistent
with the model. Therefore the steady state hypothesis of NEAs population can be demonstrated as valid through our numerical simulation. The shorter median dynamical lifetime of NEAs population obtained in this work have indicated the different role played by resonances in the 0.4 au <a< 2 au region which is affecting the dynamical lifetime of NEAs population.

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