The orbital dynamics of asteroid 469219 Kamo’oalewa

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Abstract. The study of orbital dynamics and evolution of Solar system small-bodies like asteroids has been conducted regularly with the latest data to ensure and update our understanding of the object’s motion, especially the ones located nearby the Earth. One of its examples is asteroid 469219 Kamo’oalewa, which currently known as an Earth Quasi-satellite (QS). In this article, we investigate the orbital dynamics of 469219 Kamo’oalewa by running an N-body numerical integration. It was calculated from its latest orbital solution at epoch JD 2458600.5 using Gauss-Radau scheme provided by IAS15 integrator, which available on REBOUND code package. We found that the co-orbital motion of the asteroid towards Earth happens during time interval (–19.7,19.5) thousand years, with QS–HS transition happening at that period. The current QS motion started 15 years ago and will be transitioning to HS at around 50 years from now. After losing its current state, it will orbit the Sun near the Earth as an Apollo asteroid. We also investigated the secular evolution of this asteroid and found the result that support its QS–HS transition nature. On some occasions like a long period of HS, we found several orbital characteristics that resemble Kozai–Lidov resonance, but it doesn’t hold long before the transition to QS resumes.

1. Introduction
The study of orbital dynamics and evolution of small-body in our Solar system such as asteroids has been regularly conducted by observation and numerical integration to obtain new analysis regarding its current and future trajectory. This study becomes especially significant to the near-Earth asteroid, whose existence may threaten (by a close approach or collision) or benefit (by in-situ exploration) our civilization on the Earth. Among this group of asteroids, there exist a group of asteroids that experienced co-orbital motion with the Earth. The orbit of a co-orbital asteroid was locked in a 1:1 mean motion resonance (MMR) with its nearby planet such as Earth and easily identified by its distinct, orderly pattern in a co-rotating frame of the restricted circular three-body problem with Earth. Besides a similar orbital period, co-orbital asteroids recognized by its semi-major distance (a) that oscillate against Earth’s semi-major distance, or \( \bar{a}_{\text{asteroid}} \approx \bar{a}_{\text{Earth}} \) with \( \bar{a} \) indicates an average over Earth’s period [1]. Even further, Christou & Asher (2011) use \( \Delta a_{\text{max}} \approx 10^{-2} \text{ au} \) as an arbitrary limit to allow an asteroid possess co-orbital motion [2].

There are three main groups within the co-orbital classification, with each of them exist in the Sun-Earth system (see [3] and [4]): tadpole (TP), horseshoe (HS), and quasi-satellite (QS). Additionally, Morais & Namouni (2017) indicates the fourth group, called trisectrix, currently possessed by 2015 BZ509 on Sun-Jupiter system [5]. An asteroid might have a stable motion during an extended time frame, alternating neatly between two or more configurations (e.g. [6]) or even between its initial state and passing phase (e.g. [7]). From those configurations, QS asteroids holds as the most unique
between those groups, as it appears moving alongside Earth for a while. The Earth itself currently has 5 QS asteroids: (164207) 2004 GU₉, (277810) 2006 FV₃₅, 2013 LX₉₉, 2014 OL₁₃₉, and 469219 Kamo‘oalewa. The latter, which classified as a near-Earth Apollo asteroid, became an interesting object to study because of its proximity and stability [8].

Since its discovery in 2016, the orbital solution of 469219 Kamo‘oalewa has been updated, with the latest data on 27 April 2019, based on 307 observations that spanned from 2004 to 2018. As such, it feels necessary to revisit this object and figure out the current and future trajectory based on this new dataset. In this article, we ran an N-body calculation to investigate its orbital dynamics over extended time and study some characteristics that emerge from the results, which might indicate the future of this asteroid’s trajectory towards Earth.

![Figure 1. The heliocentric (left) and Sun-Earth co-rotating (right) orbit of 469219 Kamo‘oalewa.](image)

### 2. Numerical Integration

The N-body calculation of asteroid 469219 Kamo‘oalewa has been carried out using IAS15 integrator which based on a Gauss–Radau scheme [9] and available on REBOUND, an open-source multi-purpose N-body code which freely available at http://github.com/hannorein/rebound [10]. The calculation includes the perturbation from eight planets of the Solar system and the Moon, with its initial orbital elements as well as 469219 Kamo‘oalewa and the Sun provided by JPL HORIZONS system (available on http://ssd.jpl.nasa.gov/?horizons) from their position at JD 2458600.5 (2019 April 27, 00:00:00.000 TDB), the current orbital solution epoch of 469219 Kamo‘oalewa. The numerical integration then performed for 1,000,000 years forward and backwards from the epoch and only account for gravitational forces from the Sun and perturbing objects. Although the orbit uncertainty parameter of this asteroid is 0, 50 clones were produced by generating random number within the uncertainty limits of six orbital elements to represent some possible orbits of the asteroid. The time-step used in the integration was 1/365.25 year.

| Orbital elements                    | Value                                  |
|-------------------------------------|----------------------------------------|
| Semimajor axis                      | 1.001 117 8944 ± 0.000 000 0031 (au)    |
| Eccentricity                        | 0.103 557 7799 ± 0.000 000 2407         |
| Inclination                         | 7.781 628 ± 0.000 017 (°)               |
| Longitude of ascending node         | 66.249 403 ± 0.000 017 (°)              |
| Argument of perihelion              | 306.526 109 ± 0.000 021 (°)             |
| Mean anomaly                        | 202.348 840 ± 0.000 027 (°)             |
3. Results and Discussion

Figure 2 shows the evolution of various orbital elements for the nominal and ±1σ orbits of 469219 Kamo‘oalewa during the integration time interval. This figure also includes 4 additional measures: its relative distance towards Earth (\(d_\oplus\)) in panel A, its relative mean longitude (\(\lambda_r\)) in panel C, its Kozai–Lidov parameter (\(H_K\)) in panel F and the distance from the Sun to ascending (blue) and descending (green) node in panel H (as \(d_{\text{nodes}}\)). The co-orbital state of the asteroid was determined from \(\Delta \alpha\), while QS state within the co-orbital state was determined from its \(\lambda_r \rightarrow 0\). \(\lambda\) itself is given by equation

\[
\lambda = M + \Omega + \omega.
\]  

(1)

Other measurements such as \(H_K\) is given by equation

\[
H_K = \sqrt{1 - e^2} \cos i,
\]  

(2)

while \(d_{\text{nodes}}\) is given by equation

\[
d_{\text{nodes}} = a(1 - e^2)/(1 \pm e \cos \omega),
\]  

(3)

where the ‘+’ sign is for ascending node and the ‘-’ sign is for descending node. We also added a red line in panel A to indicate the Earth’s Hill radius (0.0098 au). At the end of the simulation, the relative error in the total energy of the system is in order of \(10^{-14}\), while the relative error in angular momentum is in order of \(10^{-15}\).

![Figure 2](image)

Figure 2. The orbital evolution of 469219 Kamo‘oalewa during the time interval (-1, 1) million years, shown sequentially by its -1σ, nominal, and +1σ orbital evolution.

3.1. Co-orbital motion of 469219 Kamo‘oalewa

The nominal orbit of 469219 Kamo‘oalewa in figure 2 shown that the co-orbital motion happens between time interval \((-19.7, 19.5)\) thousand years, with \(\Delta a_{\text{max}} \sim 3 \times 10^{-2} \text{ au}\). This result alone shows the difference with past studies indicates the co-orbital motion will hold for hundreds of
thousands of years (see [8] and [11]). The co-orbital motion period also presents in almost all of the asteroid’s clones, with the same manner but varying range of period within 100,000 years before and after epoch. Within the co-orbital period, 469219 Kamo’oalewa experienced alternating HS and QS configuration, with passing phases interrupt the pattern on some occasions. Currently, it is experiencing QS motion with Earth that happens during time interval ($-15.00, 50.75$) years, shown in figure 3. QS configuration itself accounts for 7.88% of total co-orbital duration, with average duration at 83.5 years and longest duration at 169.5 years that happened during time interval ($-4864.25, -4694.75$) years.

As for the orbital evolution itself, the nominal orbit shows that 469219 Kamo’oalewa shifted its orbit inward from the beginning of simulation before stabilizing itself inside Earth’s orbit from around 250 thousand years before epoch and then trapped as an Earth’s co-orbital at 20 thousand years ago. These shifts mainly caused by its gravitational interaction with Earth and Venus. Both of these planets are also responsible for the orbital instability at 19.5 thousand years from now before losing its co-orbital motion and continue its orbit as an Apollo asteroid. For the majority of our simulation, we found that the chance of 469219 Kamo’oalewa getting closer to the Earth until passing Hill’s radius is small. There might be some points that show the opposite, like the backward simulation on -1σ orbit at figure 1, but it doesn’t occur at nominal and +1σ orbit. As for the asteroid clones, at least 55% of all generated orbits follows roughly the similar behavior as the nominal orbit and ended up as an Apollo asteroid.

![Figure 3](image.png)

**Figure 3.** The orbital evolution of 469219 Kamo’oalewa during the time interval ($-1, 1$) thousand years, shows its alternating QS – HS configuration and its relation between each orbital element.

3.2. $e_r - \omega_r$ portrait of 469219 Kamo’oalewa

As shown in figure 3, we noticed a coupled oscillation between $i$ and $e$, which indicate that this asteroid might possess some characteristics of Kozai–Lidov resonance state in a brief period. While we know from figure 2 that the resonance generally does not happen at long term simulation, we
investigate whether Kozai–Lidov resonance may happen for a shorter period during the simulation. The assessment based on $e_r - \omega_r$ portrait, presented by Namouni (1999) to study the secular evolution in co-orbital objects [12].

Figure 4 and 5 show two kinds of secular evolution that happen during the co-orbital period of 469219 Kamo‘oalewa. Figure 4 shows that domain III pattern in Namouni (1999) happens in the time interval (−1, 1) thousand years, with $\omega_r$ librates around 30° and 180° towards Earth, 150° towards Venus, and 0° towards Jupiter. Even though the libration angle doesn’t match with the description provided by Namouni, it still matches with the nature of domain III as signs of stable HS – QS periodic transitions which happen for the majority of the co-orbital period. Figure 5 shows that domain II pattern happens on some occasion with $\omega_r$ librates around 180° towards Earth and Venus and 120° towards Jupiter. This domain happens where the QS–HS transition became less frequent and HS dominates for a while. While it suggests that Kozai–Lidov resonance might happen during the evolution, it doesn’t last long before the transition resumes.

![Figure 4. The domain III pattern on $e_r - \omega_r$ portrait of 469219 Kamo‘oalewa during the time interval (−1, 1) thousand years.](image)

![Figure 5. The domain II pattern on $e_r - \omega_r$ portrait of 469219 Kamo‘oalewa during the time interval (−4, −2) thousand years.](image)

4. Conclusion
In this paper, we have performed numerical integration on the latest orbital solution of asteroid 469219 Kamo‘oalewa and showed its dynamics along (−1, 1) thousand years period. We found that the co-orbital motion of the asteroid towards Earth happens during the time interval (−19.7, 19.5) thousand years, much shorter than previous studies suggest. QS–HS transitions occur during this period, with current QS motion started 15 years ago and will be transitioning to HS at around 50 years from now. After losing its co-orbital motion, it will stay near Earth as an Apollo asteroid. We also investigate the secular evolution of this asteroid, based on $e_r - \omega_r$ portrait, with a result that supports the QS–HS
transition nature on its orbital dynamics. Domain II or Kozai–Lidov domain is also found on some occasions like a long period of HS, but it doesn’t hold long before the transition to QS resumes.

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