Analysis of the Dynamical Properties of Active Asteroid 311P/PANSTARRS (Postprint)

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Abstract

311P/PANSTARRS is an active asteroid that

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Dynamical Characteristics of Active Asteroid 311P/PANSTARRS

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Abstract

311P/PANSTARRS is an active asteroid exhibiting characteristics of both asteroids and comets, and it is one of the targets of China' s Tianwen-2 mission. With a relatively small diameter of about 400 m, non-gravitational effects may significantly influence its long-term dynamical evolution. By assuming different surface compositions, we investigated the influence of the Yarkovsky effect on the orbital evolution of 311P/PANSTARRS, discussed non-gravitational effects including close encounters, non-destructive collisions, and the YORP (Yarkovsky-O' Keefe-Radzievskii-Paddack) effect, calculated the probabilities of close encounters and collisions between the asteroid and major planets, and estimated the timescale for 311P/PANSTARRS to reach its rotational period splitting limit. Simulation results show that, compared with a pure gravitational model, the Yarkovsky effect may accelerate 311P' s departure from its current resonance region. Approximately 10 Myr later, 311P will leave its present resonance zone, and with a regolith-covered surface, it may have an opportunity to become a Mars-crossing asteroid through the $_6$ secular resonance. When the YORP effect is considered, 311P can reach its rotational period splitting limit within a 2 Myr timescale. Taking into account the Yarkovsky effect, YORP effect, and other factors, 311P/PANSTARRS can maintain its dynamical stability within a 10 Myr timescale, and the YORP effect does not significantly affect its semi-major axis drift.

Keywords: celestial mechanics, methods: statistical, planets and satellites: dynamical evolution and stability, minor planets, asteroids: individual: 311P/PANSTARRS

Comets are remnants from the formation period of the solar system that preserve primitive information from that epoch. Traditional distinctions between comets and asteroids are based on differences in orbital dynamics, composition, and observational characteristics. However, recent observational studies have discovered that many asteroids in the main belt exhibit comae and tails similar to cometary activity, leading to the introduction of the concept of "active asteroids." Active asteroids are small bodies with asteroid-like orbits that display comet-like activity. Various mechanisms can cause mass loss in small bodies, including ice sublimation, impact ejection, rotational instability, electrostatic forces, thermal fracture, thermal dehydration, shock dehydration, and radiation pressure. Among these, small bodies in the main belt that exhibit periodic activity due to ice sublimation are called main-belt comets, while those showing transient activity bursts due to other mechanisms are termed "disrupted asteroids." To date, approximately 40 active asteroids have been discovered. Most of these have stable orbits and likely originated in the main belt, though some have unstable orbits and may be temporarily captured comets. Therefore, studying the orbital evolution of active asteroids can help explore their distribution patterns and provide theoretical predictions for discovering new active asteroids, while analyzing their orbital migration mechanisms can constrain the physical causes underlying their activity.

311P/PANSTARRS, also known as P/2013 P5 (hereafter 311P), was first discovered on August 27, 2013, by the Pan-STARRS (Panoramic Survey Telescope and Rapid Response System) survey. In September 2013, the Hubble Space Telescope (HST) observed at least six linear tail structures, with this activity lasting approximately five months (from April 15 to September 4, 2013). According to Jewitt et al., these dust tails were produced by rapid rotational splitting of the nucleus. Unlike the dynamical properties of comets, 311P has a Tisserand parameter T_J = 3.66, which falls within the asteroid range (comets have T_J < 3). These characteristics all indicate that 311P is an active asteroid. 311P is a target of the Tianwen-2 mission, which plans to launch around 2025 using a Long March 3B rocket to explore both the co-orbital near-Earth asteroid (469219) Kamo' oalewa and the main-belt active asteroid 311P.

311P' s orbit lies at the inner edge of the asteroid main belt, with a semi-major axis of approximately 2.189 au, moderate eccentricity of about 0.142, and small orbital inclination of about 4.968°. Its proper orbital elements are similar to those of the ancient Flora family (10^9 yr), suggesting it may be a member. The Flora family is a large group with 500 members, and spectroscopic observations reveal that most members are S-type asteroids. Additionally, color index measurements by Jewitt et al. indicate that 311P is most likely an S-type asteroid. Using Hubble observations from September 10 and 23, 2013, Jewitt et al. calculated an absolute magnitude H_V = 18.69–18.54 and, assuming a geometric albedo consistent with the Flora family average of 0.29 ± 0.09, derived an effective radius of approximately (0.24 ± 0.04) km. Later, Jewitt et al. (2015) used high-resolution Hubble images from September 2013 to February 2014 to obtain an absolute magnitude lower limit of 18.98 ± 0.10, corresponding to an effective radius upper limit of (0.20 ± 0.02) km (assuming geometric albedo of 0.29 ± 0.09). Hainaut et al. used observations from the 3.56 m New Technology Telescope (NTT) between August and October 2013 and S-type asteroid albedos to estimate 311P' s radius in the range 0.25–0.29 km. Jewitt et al. (2018) attempted to find evidence for rapid rotation using Hubble data from March to July 2015 but found no conclusive evidence, only establishing a rotation period lower limit of 5.4 h. From this data, they obtained an absolute magnitude of (19.14 ± 0.02) and an effective radius of about (0.19 ± 0.03) km (assuming geometric albedo of 0.29).

These data show that compared to other active asteroids, 311P is relatively small and has a short Lyapunov timescale (T_{ly} = 31.6 kyr), meaning that non-gravitational effects, particularly the Yarkovsky and YORP effects, significantly influence its orbit. Although the Yarkovsky effect is often considered small in orbital evolution, recent observations have revealed that small asteroids can experience noticeable semi-major axis drift due to this effect. Therefore, reliable conclusions about dynamical stability can only be drawn when both gravitational and non-gravitational effects are considered simultaneously. Based on these data, this paper investigates the stability of 311P under the influence of the Yarkovsky effect. Since many physical properties and parameters of 311P remain unknown, we employ a statistical approach similar to that recently used by Fenucci et al. to estimate the semi-major axis drift caused by the Yarkovsky effect. The paper is organized as follows: Section 2 describes the initial conditions, numerical simulation methods, and theoretical model foundations; Section 3 investigates stability, possible evolutionary paths, close encounters, and residence timescales in resonance zones; Section 4 discusses the effects of close encounters, non-destructive collisions, and the YORP effect on orbital evolution; and Section 5 presents our conclusions.

2.1 Pure Gravitational Model and Initial Conditions

The numerical integrator used in this work is based on the BS (Bulirsch-Stoer) and MVS (Mixed-Variable Symplectic) algorithms from the Mercury package developed by Chambers, as well as a modified version of the Mercury package by

Fenucci et al. The gravitational component of the dynamical model includes the eight major planets and the Moon (all treated as massive bodies, with the Moon considered as part of the Earth-Moon system), while 311P is treated as a test particle with zero mass. The integrator precision is set to 10^{-12}, and the integration step size is 8 days. We consider two dynamical models: a pure gravitational model and a gravitational model with the Yarkovsky effect added (referred to as the Yarkovsky model for brevity). In the pure gravitational model, only gravitational forces act on the test particle, with all non-gravitational effects ignored. The Yarkovsky model adds the Yarkovsky effect to the gravitational model, as detailed in Section 2.2.

Initial conditions are taken from JPL Horizons osculating orbital elements. All massive bodies use instantaneous orbital elements at Julian Day 2459000.5 (May 31, 2020), while 311P' s nominal orbit uses elements at JD 2456894.5 (August 25, 2014). Specific values and uncertainties are listed in Table 1 , where a is semi-major axis, e is eccentricity, i is inclination, ω is argument of perihelion, Ω is longitude of ascending node, and M is mean anomaly. To further investigate the possible dynamical characteristics within the observational error range, we adopt the 1σ value as 311P's observational uncertainty. The method for selecting orbital test particles is as follows: Let $\mathbf{x}$ ^{6} be the nominal orbit and $\mathbf{\Sigma}$ $^{6\ 6}$ be the corresponding covariance matrix from the JPL Small-Body Database. The probability density distribution of the nominal orbit is then a six-dimensional Gaussian distribution with mean $\mathbf{x}$ and variance $\mathbf{\Sigma}$. According to Gaussian distribution properties, if $\mathbf{u}$ ^{6} is a standard Gaussian distribution, then the linear form:

$$\mathbf{x} = \mathbf{x} + \mathbf{A}\ \mathbf{u} \qquad (1)$$

follows the nominal orbit' s probability density distribution, where $\mathbf{A}$ $^{6\ 6}$ can be obtained from $\mathbf{\Sigma}$ via Cholesky decomposition, i.e., $\mathbf{\Sigma} = \mathbf{AA}$, with $\mathbf{A}$ being a lower triangular matrix. Using this method, we first generate standard normal random vectors $\mathbf{u}$, then obtain orbital test particles from the six-dimensional Gaussian distribution using equation (1).

2.2 Yarkovsky Effect and Initial Conditions

The Yarkovsky effect is a thermal effect caused by solar radiation that can influence the trajectories of asteroids smaller than 30 km. A rotating body absorbs solar heat radiation and re-radiates it as thermal radiation, producing a small but persistent thrust. Due to non-zero thermal inertia, radiation is delayed, so when the body rotates, the thrust direction is not parallel to the heliocentric position vector but is slightly tilted toward the orbital velocity vector, causing the semi-major axis to drift. The Yarkovsky effect consists of two components: the diurnal effect (da/dt)_d and the seasonal effect (da/dt)_s, with the total drift being the superposition of both.

When considering the Yarkovsky effect, the following assumptions are typically made: (i) the body is spherical, (ii) the orbit is circular around the Sun, (iii) the surface satisfies linear boundary conditions, and (iv) the spin axis is fixed. The magnitude of the Yarkovsky effect depends on several orbital and physical parameters: a, diameter D, density , thermal conductivity K and specific heat capacity C of the surface, spin axis obliquity γ, rotation period P, absorption coefficient α, and surface emissivity . To estimate 311P' s semi-major axis drift rate, we use the formula (detailed calculations are in the appendix) to compute:

da/dt = f(a; D; ; K; C; γ; P; α;) (2)

Since most parameters are unknown, we follow the method of Fenucci et al. and use Monte Carlo simulations to predict possible values of the semi-major axis drift given by equation (2).

2.2.1 Initial Parameter Settings for the Yarkovsky Effect

Semi-major axis: The 1σ uncertainty in semi-major axis is very small, on the order of 10^{-8} au (see Table 1), which hardly contributes to the error in estimating semi-major axis drift. Therefore, we use the nominal osculating elements.

Diameter and density: The diameter can be calculated using:

D = 1329 km / √p_V × 10^(-H/5) (3)

where p_V is geometric albedo and H is absolute magnitude. Since no accurate geometric albedo has been determined, we estimate it using the following method. First, we apply hierarchical clustering method (HCM) in proper element space to identify the asteroid family. HCM determines a distance threshold (in m/s) in proper element space to select all asteroids within this threshold and identify the family. Hsieh et al. previously used HCM to identify all asteroids related to 311P, naming it the Behrens family. We re-identify 311P using the AstDys database, finding 25 members of the Behrens family at a distance threshold of 49 m/s. Figure 1 [Figure 1: see original paper] shows the distribution of the Behrens family in proper element space. 311P lies between two three-body mean motion resonances, 6M-3S-10A and 4M+1S-7A (where "M" represents Mars, "S" Saturn, and numbers indicate the ratio of orbital periods completed in the same time interval), adjacent to the 11:3 resonance with Jupiter, resulting in a short Lyapunov time of 31.6 kyr. Only four larger members of the Behrens family have known geometric albedos, shown in Table 2 . Using these four members, we calculate an average geometric albedo of $p\_V = 0.285 \pm 0.025$ for the Behrens family, which we adopt for 311P. Compared to the Flora family average albedo assumed by Jewitt et al., the Behrens family may be younger and share a common origin, making this assumption more reasonable. The absolute magnitude $H = 18.8 \pm 0.6$ is taken from JPL. Using equation (3), we obtain $D = 433 \pm 121$ m.

For 311P' s density, color index measurements suggest it is more likely an S-type asteroid, so we adopt the average density for S-type asteroids: $= 2720 \pm 540$ $\mathrm{kg \cdot m^{-3}}$.

Thermal conductivity: Thermal conductivity depends on 311P's composition, porosity, and surface temperature, and can vary by several orders of magnitude depending on regolith properties, introducing significant uncertainty. Typically, surfaces with regolith have low thermal conductivity, generally in the range 0.0001-0.1 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$; bare rock surfaces have higher conductivity, generally 1-10 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$; and surfaces containing metallic components have conductivity >10 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$. This parameter is usually unknown and requires additional data such as infrared observations or Yarkovsky effect detections for estimation. For this parameter, we consider both that 311P is likely a rocky S-type asteroid and that Fenucci et al. found small, rapidly rotating asteroids may retain some surface regolith. Therefore, we select five values related to different surface compositions: K $\{0.001, 0.01, 0.1, 1, 5\}$ $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$. The first three values consider possible regolith coverage, while the latter two consider bare rock with different porosities.

Specific heat capacity: Specific heat capacity also depends on asteroid composition and surface temperature, but varies less widely than thermal conductivity. For main-belt asteroids with regolith-covered or bare rock surfaces, typical values are 600–700 $\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$. Moreover, uncertainty in specific heat capacity has less impact on da/dt compared to thermal conductivity.

Spin axis obliquity: 311P' s spin axis obliquity is unknown, so we select random values for $\cos(\gamma)$ [-1, 1].

Rotation period: Rotation periods are typically determined from light curves. However, limited observational data have not provided direct light curve evidence proving 311P is a rapidly rotating asteroid. To estimate the rotation period, we assume equatorial velocity equals escape velocity using $v\_e = \sqrt{}$(2Gm/r), where G is the gravitational constant, r is 311P' s radius, and m is 311P' s estimated mass from density ($= 2720 \pm 540$ $\mathrm{kg \cdot m^{-3}}$). This yields a critical rotation period $P\_\{crit\}$ 1.4 ± 0.2 h. Since 311P is a rotationally disrupted active asteroid, we take the critical rotation period as the initial value.

Surface emissivity and absorption coefficient: Ostrowski et al. studied meteorite emissivity, finding values around 0.9-1. Since emissivity does not significantly alter the semi-major axis drift rate, we adopt the average meteorite emissivity of 0.984. The absorption coefficient α measures the fraction of solar radiation absorbed by the asteroid surface, estimated by $\alpha = 1$ - A_B, where A_B is Bond albedo. Generally, asteroid Bond albedos are <0.15, so α is approximately 0.85-1. Similarly, due to large uncertainties in other parameters, the absorption coefficient' s error does not significantly affect semi-major axis drift in our model, so we set $\alpha = 1$.

2.2.2 Estimation of the Yarkovsky Effect Using the Yarkovsky model described above, we generate 100,000 sets of Gaussian-distributed initial data to estimate 311P's semi-major axis drift rate da/dt via equation (2). Kernel density estimation is then used to obtain continuous probability density functions for different thermal conductivity values K, with results shown in Figure 2 [Figure

2: see original paper].

For the first four thermal conductivities \$ $1W \cdot m^{\text{\{-1\}} \cdot K}$\{-1\}$, therearetwolikelyvalues:$ $onepositiveandonenegative. Thisoccursbecausethediurnaleffecttermdominatesinequation(2)andisproportio$ $K* = 0.001W \cdot m^{\text{\{-1\}} \cdot K}$\{-1\}$, thepositiveandnegativesidesarenearlysymmetricaboutda/dt =$ $0au/Myr. As*K*increases, thenegativevalueproportiongraduallyincreases, andat*$ $K* = 5.0W \cdot m^{\text{\{-1\}} \cdot K}$\{-1\}$, thedistributionisalmostentirelyonthenegativeside, withtwopeaksonthenegativeside$ $0.0001au/Myr). Thisarisesbecausetheseasonaleffecttermbecomescomparabletothediurnaleffectterm, andth$ $majoraxisdrift, resultinginabiastowardnegativevalues. Forsmallthermalconductivities(*K* =$ $0.001, 0.01W \cdot m^{\text{\{-1\}} \cdot K}$\{-1\}\$), semi-major axis drift can be relatively fast, reaching \$$\pm 0.0008au/Myr, whilefor * K* = 0.1W \cdot m^{\text{\{-1\}} \cdot K}$\{-1\}\$, it is about \$$\pm 0.0003au/Myr. Forlargerthermalconductivities(*K* = 1.0W \cdot m^{\text{\{-1\}} \cdot K}$\{-1\}$), thedistributionismainlyonthenegativesideat \approx -0.0002au/Myr, andfor * K* = 5.0W \cdot m^{\text{\{-1\}} \cdot K}$\{-1\}\$, there are two negative peaks at -0.0004 au/Myr and -0.0001 au/Myr.

We generate 500 test particles using the method in Section 2.1 for orbital evolution simulations under the pure gravitational model, then repeat the simulations with the same test particles adding the Yarkovsky effect initial parameters described in Section 2.2.

3.1 Long-term Evolution

The nominal orbit under the pure gravitational model is shown in Figure 3 [Figure 3: see original paper]. The 6M-3S-10A resonance center is at a 2.1886 au with a width of about 0.0012 au, while the 4M+1S-7A resonance center is at a 2.1895 au with a width of about 0.0017 au. Therefore, 311P lies in the resonance region [2.1874, 2.1912] au. The figure shows that at 17 Myr, 311P jumps from the 6M-3S-10A three-body resonance to the 4M+1S-7A three-body resonance, then oscillates between these two weak three-body resonances. However, chaotic diffusion is not significant under the influence of these weak resonances, with eccentricity, inclination, and perihelion distance q remaining stable within ranges of e [0.05, 0.22], i [2°, 8°], and q [1.70, 2.05] au, indicating that the two weak three-body resonances do not overlap to cause chaotic diffusion.

Figure 4 [Figure 4: see original paper] shows the evolution of the semi-major axis range for 500 test particles in the pure gravitational model over the time interval (-1, 1) Myr. The black curve represents the average semi-major axis of all particles, and the gray region shows the standard deviation range. Eccentricity and inclination show little variation over this timescale. The deviation is minimal near the starting time, indicating all test particles have similar orbits. After about 200 kyr of evolution, the standard deviation begins to increase gradually, but the average remains near 2.1886 au, suggesting that under the pure gravitational model, the 6M-3S-10A resonance has a stronger influence.

Figure 5 [Figure 5: see original paper] shows the orbital evolution range for test particles with the Yarkovsky effect added. In contrast, the standard deviation begins to increase after about 60 kyr when the Yarkovsky effect is included, with the average slightly higher than in the pure gravitational model. The introduction of the Yarkovsky effect causes a 2×10^{-3} au bias in the average semi-major axis, while eccentricity and inclination show almost no change over this timescale.

To study the Yarkovsky effect' s influence on 311P' s long-term evolution, we plot the orbital distribution $R(a,\ e,\ i)$ for 100 test particles under both the pure gravitational model and the Yarkovsky model with $K = 0.001$ $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$. The orbital element space $(a,\ e,\ i)$ is divided into bins with $\Delta a = 0.004$ au, $\Delta e = 0.001$, and $\Delta i = 0.1°$. Test particles are evolved for 50 Myr with output intervals of 10 kyr, and we count the number of occurrences in each bin, finally normalizing the distribution such that $R(a,\ e,\ i)\ da\ de\ di = 1$. This distribution essentially gives the time intervals that test particles spend in each orbital element space region.

The orbital distributions under the pure gravitational model and Yarkovsky model are shown in Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper], respectively. In both models, the densest region is near a 2.1886 au, with eccentricity <0.2 and inclination <8°. When the Yarkovsky effect is introduced, the distribution density in this region is slightly lower than in the pure gravitational model. Outside this region, about 10% of test particles disperse to near-Earth orbits, even experiencing close encounters with Venus.

Figure 8 [Figure 8: see original paper] shows the residence time in 311P' s resonance region for five test particles under the Yarkovsky model. Under the pure gravitational model, no test particles leave the resonance region within 50 Myr. Under the Yarkovsky model, most test particles leave the resonance region around 10 Myr, with only 18 test particles remaining. The first bin in Figure 8 shows that for $K = 0.001$ and 0.01 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$, the median residence time is about 2 Myr and 3 Myr, respectively, increasing to about 5 Myr for $K = 0.1$, 1.0, and 5.0 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$. The median values indicated in the figure show that as thermal conductivity increases, the median of the distribution also increases.

3.2 Statistics of Close Encounters and Impacts with Major Planets

This section statistics the impact and close encounter frequencies between 311P' s 500 test particles and major planets over 50 Myr.

Figure 9 [Figure 9: see original paper] shows close encounter statistics for 311P's 500 test particles under Yarkovsky models with different thermal conductivities. For $K = 0.001$ $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$, close encounters with Mars appear within 20–25 Myr, with the number increasing over time: 27 test particles experience 1926 close encounters with Mars. Close encounters with the Earth-Moon system increase significantly around 50 Myr, with 8 test particles experiencing 1160 encounters. Statistics of close encounters versus Hill radius show that 311P enters the Hill radii of the Earth-Moon system and Mars comparable numbers of times within 50 Myr. The trend for $K = 5.0$ $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ is similar to $K =$

0.001 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$, with comparable encounter numbers with Earth-Moon and Mars, though $K = 0.001$ $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ shows slightly more Mars encounters while $K = 5.0$ $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ shows slightly more Earth-Moon encounters. This may be because the Yarkovsky effect mostly decreases the semi-major axis drift for $K = 5.0$ $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$. Notably, although total encounter numbers with Mars and Earth-Moon are comparable, fewer test particles encounter Earth-Moon than Mars. For $K = 0.001$ $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$, 8 test particles encounter Earth-Moon, while for $K = 5.0$ $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$, only one test particle encounters Earth, reaching the co-orbital region $\mathrm{T}_1{:}_1$ (the 1:1 orbital resonance region with Earth, 0.994 au $\leq a \leq$ 1.006 au). Thus, the probability of 311P becoming a near-Earth asteroid is small but non-zero.

Compared to the $K = 0.001$ $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ model, the other four models show significantly fewer close encounters with Mars and no encounters with Jupiter that would eject particles from the solar system.

Table 3 gives the percentage statistics of test particles that collided or were ejected. Most test particles survive the entire 50 Myr, but 7% collide with the Sun (5% of these under $K = 0.001$ $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$), and 2% are ejected from the solar system due to close encounters with Jupiter. Although close encounters with major planets are frequent, collision probabilities are very small; none of the 500 test particles end their orbital evolution by colliding with a major planet. This is because close encounters with terrestrial planets are insufficient to place small bodies on hyperbolic orbits, and the Yarkovsky effect over this timescale is insufficient to cause close encounters with Jupiter, Saturn, or Neptune that would eject them from the solar system.

Table 4 shows the close encounter frequencies with three terrestrial planets (Venus, Earth, and Mars). Mars encounters are most frequent, particularly under the Yarkovsky model with $K = 0.001$ $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$, where 27% of test particles encounter Mars and become Mars-crossing asteroids. This simulation result is consistent with Vokrouhlický et al., who found that 100 m-scale bodies with regolith-covered surfaces are primarily influenced by the diurnal Yarkovsky effect, allowing their semi-major axes to random-walk to the $_6$ resonance and become Mars-crossing or near-Earth asteroids.

In summary, 311P will become a Mars-crossing asteroid on a timescale of about 20–40 Myr, while the probability of becoming a near-Earth asteroid is small: only 15 of 500 test particles reach near-Earth regions ($q < 1.3$ au), with 7 colliding with the Sun and one reaching Earth’ s co-orbital region $\mathrm{T}_1{:}_1$.

Discussion of Other Influencing Factors

Our approach to including the Yarkovsky effect applies a constant equivalent force in the orbital velocity direction. This simplified method has certain limitations regarding orbital and spin axis evolution.

Regarding orbital evolution, the Yarkovsky effect primarily depends on heliocentric distance, i.e., the orbit' s semi-major axis and eccentricity. The effect is stronger when the body is closer to the Sun, so the semi-major axis drift should change as the orbit evolves. However, our simulations show the Yarkovsky effect mainly influences test particles in weak three-body resonances in the main belt (a [2.1874, 2.1912] au). When they become Mars-crossing or near-Earth asteroids, gravitational effects dominate semi-major axis changes, justifying our assumption of constant drift. Another factor affecting orbital drift is eccentricity. Spitale et al. found that for 100 m-scale asteroids, the Yarkovsky diurnal effect increases by about an order of magnitude when eccentricity changes from 0.1 to 0.9. In such cases, constant drift may no longer apply, but Figure 7 shows only a small fraction (1.4%) of test particles that collide with the Sun or are ejected reach high eccentricities. Additionally, test particles in the resonance region mostly have eccentricities <0.3, so order-of-magnitude changes in Yarkovsky drift due to high eccentricity would not alter our results, particularly for evolution within the resonance region.

Regarding spin axis evolution, the YORP effect, non-destructive collisions, and close encounters can all alter asteroid rotation states. Small asteroids not experiencing collisions are primarily influenced by the YORP effect, but non-destructive collisions can significantly change rotation parameters. Statler' s analysis of YORP effects on small-scale bodies indicates that spin axis evolution is likely random, later confirmed by Cotto-Figueroa et al. using hard-sphere discrete element numerical simulations. Wiegert also argues that non-destructive collisions re-randomize spin axes, making them as important as the YORP effect, especially for small bodies like 311P. According to Farinella et al.' s study on impact frequencies, the timescale for collisional re-randomization of spin axes in the main belt depends on asteroid size and rotation period. Bodies of 311P' s size do not experience frequent impact events on 100 Myr timescales, i.e., they do not frequently randomize spin axis direction, which is much longer than the timescale for test particles to leave the resonance region. Therefore, collisions and close encounters have limited influence on spin axis distribution during the evolution.

YORP effect estimation is more complex and requires further simulation and discussion. The YORP effect is a thermal torque that drives obliquity γ toward asymptotic states (0°, 90°, or 180°) while causing rotation rate to slow down or speed up. However, this effect is closely related to body shape and thermal properties, which are unknown for most small bodies. We therefore adopt the static YORP model of Fenucci et al., where the evolution of obliquity γ and rotation rate ω' = 1/P (using ω' to denote rotation rate to avoid confusion with argument of perihelion ω) is given by:

$$d\gamma/dt = f(\gamma) \qquad (5)$$

where f and g are torque magnitudes (see Fenucci et al. for f and g selection). The YORP effect influences orbital dynamics by affecting the Yarkovsky effect. Therefore, during orbital evolution, γ and P are updated at each integration step via equation (5) to update the semi-major axis drift in equation (2). Initial conditions follow Section 2.2. Since $K = 0.001\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$ produces the largest semi-major axis drift, we only evaluate differences between Yarkovsky and YORP models for this case. Figure 10 [Figure 10: see original paper] shows the residence time distributions in 311P' s resonance region for both models, which can be well-fitted by log-normal distributions with parameters = -0.689, $\sigma = 0.830$ for the Yarkovsky model and = -0.650, $\sigma = 0.806$ for the YORP model. Thus, the timescale distributions for test particles leaving 311P' s resonance region are nearly identical in both models.

On the other hand, Golubov et al. point out that after several YORP cycles, small bodies reach an equilibrium state (asymptotic state). To assess the timescale for 311P' s spin axis to reach asymptotic state and rotation period to reach the splitting limit, we conduct additional 10 Myr orbital evolution simulations. Initial conditions remain unchanged except for an initial rotation period of $P = 6$ h. Results are shown in Table 5 and Figure 11 [Figure 11: see original paper]. The median timescale for rotation period to evolve from 6 h to 1.6 h is about 2 Myr. Since simulations show reaching the asymptotic state occurs within the first 1 Myr, with semi-major axis drift <0.02 au, the YORP effect has minimal impact on overall semi-major axis drift and does not significantly affect our final results.

Conclusions

Through forward integration of 500 test particles over 50 Myr, we studied the long-term dynamical evolution of 311P and considered the Yarkovsky effect' s influence on its semi-major axis evolution. The simulation results are as follows:

1. The Yarkovsky effect only significantly affects dynamical stability at low thermal conductivity. Compared to the pure gravitational model, the Yarkovsky effect accelerates 311P' s departure from the resonance region: about half of test particles leave within 5 Myr, and about 80% leave within 10 Myr.
2. There is a 12.4% probability of becoming a Mars-crossing asteroid through the $_6$ resonance within 20–40 Myr, but the probability of becoming a near-Earth asteroid within 50 Myr is small, with the probability of reaching Earth' s co-orbital region being nearly zero.
3. Under low thermal conductivity (regolith-covered rocky asteroid), 311P has a higher probability (27%) of becoming a Mars-crossing asteroid due to the Yarkovsky diurnal effect.
4. If the YORP effect is the cause of 311P' s rotational instability, its rotational fission timescale is about 2 Myr.
5. Close encounters, non-destructive collisions, and the YORP effect have minimal influence on 311P's orbital evolution, so only the Yarkovsky effect needs to be considered for its dynamical evolution on 50 Myr timescales.

In summary, considering all factors, 311P will leave its resonance region on a 10 Myr timescale and may become a Mars-crossing asteroid if its surface is regolith-covered, while the probability of becoming a near-Earth asteroid is low.

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Appendix

The diurnal and seasonal Yarkovsky effects are calculated to determine the corresponding semi-major axis drift rates, with Monte Carlo experiments performed. The semi-major axis drift rates caused by diurnal and seasonal effects are given by:

$$\left.\frac{da}{dt}\right|_d = -\frac{8\alpha}{4\alpha}\frac{F(R'_d;\Theta_d)\sin^2\gamma}{aW\odot}\Phi$$

$$\left.\frac{da}{dt}\right|_s = -\frac{4\alpha}{4\alpha}\frac{F(R'_s;\Theta_s)\cos\gamma}{aW\odot}\Phi$$

where α is surface absorption coefficient, Φ is radiation pressure coefficient, $\Phi =$ L /(2πc_v), W represents solar radiation flux at distance a (au), c_v is vacuum light speed, R_a and m_a are asteroid radius and mass, *ω_{rev}* is mean motion angular velocity, γ is spin axis obliquity, and F is a function related to asteroid radius and thermal parameters. The dimensionless scaled radii *R' _s* and *R' _d* are defined as:

$$R'_s = \frac{R_a}{l_s}; \quad R'_d = \frac{R_a}{l_d}$$

where l_s and l_d are thermal wave penetration depths for seasonal and diurnal effects:

$$l_s = \sqrt{\frac{K}{\rho C\omega_{rev}}}; \quad l_d = \sqrt{\frac{K}{\rho C\omega_{rot}}}$$

The thermal parameters Θ_d and Θ_s are determined by:

$$\Theta_d = \frac{\rho KC\omega_{rot}}{2\epsilon\sigma_b T^3}; \quad \Theta_s = \frac{\rho KC\omega_{rev}}{2\epsilon\sigma_b T^3}$$

where *σ_b* is the Stefan-Boltzmann constant, is surface emissivity, and T is subsolar temperature calculated by $\sigma T^4 = \alpha W$. The function F in equations (6) and (7) depends on the corresponding scaled radius and thermal parameters and determines the magnitude of semi-major axis drift. The expression for F is:

$$F(R';\Theta) = -\frac{k_1(R')\Theta}{1 + 2k_2(R')\Theta + k_3(R')\Theta^2}$$

where coefficients k_1, k_2, k_3 are positive analytic functions of scaled radius, whose definitions are given in detail in Vokrouhlický. Note that since F is always negative, the seasonal effect always causes semi-major axis decrease, reaching maximum at obliquity 90° and zero at 0° or 180°. The diurnal effect increases semi-major axis when $\gamma < 90°$, decreases it when $\gamma > 90°$, is maximum at 0° or 180°, and zero at 90°.

Note: Figure translations are in progress. See original paper for figures.