RESEARCH ARTICLE
PLANETARY SCIENCES

Earth and Planetary Physics
10: 365–373, 2026
doi: 10.26464/epp2026024

Physical and dynamic characteristics of high-inclination small bodies

Ning Liu[1,2], JianChun Shi[2*], Xian Shi[2], Man-To Hui[2], and Sheng Jin[1*]

[1]School of Physics and Electronic Information, Anhui Normal University, Wuhu Anhui 241000, China;

[2]Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China

Key Points:

- Significant differences exist in many properties between high-inclination and low-inclination small bodies.
- It is possible that high-inclination small bodies have diverse origins and formation mechanisms.

Citation: Liu, N., Shi, J. C., Shi, X., Hui, M.-T., and Jin, S. (2026). Physical and dynamic characteristics of high-inclination small bodies. *Earth Planet. Phys.*, *10*(2), 365–373. http://doi.org/10.26464/epp2026024

Abstract: Most small bodies in the solar system have low orbital inclinations, concentrated near the ecliptic plane. However, some small bodies exhibit high orbital inclinations ($i > 20°$) and are referred to as high-inclination small bodies. The discovery and study of these high-inclination objects are reshaping traditional understanding and challenging classical dynamical models. With the advancement of wide-field sky survey projects, an increasing number of small bodies with high-inclination and even retrograde orbits have been observed. Their unique orbital configurations suggest complex formation mechanisms and evolutionary histories. High-inclination small bodies differ significantly from ecliptic plane objects in terms of surface composition, size distribution, and dynamical behavior. Their formation mechanisms involve various pathways, such as gravitational perturbations and planetary scattering, resonance capture and inclination excitation, and the influence of potential Planet Nine. These objects not only serve as "fossil records" of the early evolution of the solar system but also provide new research perspectives for planetary formation theories, interstellar material exchange, and deep-space resource exploration.

Keywords: high-inclination; small bodies; physical properties; orbital properties; orbital evolution

---

1. Introduction

For a long time, the orbital distribution of small solar system bodies has been widely believed to be concentrated near the ecliptic plane. This conventional understanding was shaped by both the support of planetary formation theory (Duncan et al.,1988; Gomes et al., 2005) and the limitations of early observational data. However, with continued advances in observational technology, this perception is continually being updated. An increasing number of small bodies with high orbital inclinations have been discovered, posing significant challenges to the predictions of classical dynamical models.

Small solar system bodies refer to all celestial bodies orbiting the Sun other than planets and dwarf planets, including asteroids, comets, meteoroids, and so forth. Currently, no consensus exists on the definition of high-inclination small bodies. For instance, Iwai et al. (2017) considered objects with orbital inclinations greater than 10° as high-inclination small bodies, and Terai et al. (2013) and Fernández and Helal (2023) adopted 15° as the threshold, whereas Namouni and Morais (2020) and Hromakina et al. (2021) defined high-inclination small bodies as those with orbital inclinations exceeding 60°. Among them, polar orbits refer to those with inclinations close to 90°, meaning the orbital plane is almost perpendicular to the ecliptic plane, whereas retrograde orbits refer to those with inclinations greater than 90°.

According to data from NASA’s Jet Propulsion Laboratory, near-Earth asteroids (NEAs) with orbital inclinations greater than 20° account for approximately 20% of their total population, and among main-belt asteroids, this proportion is approximately 6%, whereas for trans-Neptunian objects (TNOs) and centaurs, the proportion of high-inclination objects is approximately 30%. From an observational perspective, small bodies with orbital inclinations greater than 20° relative to the ecliptic plane can be considered high-inclination small bodies. It is noteworthy that although asteroids with orbital inclinations greater than 20° constitute a relatively small proportion of the total population (approximately 8%), small bodies with inclinations between 20° and 60° are not uncommon in the solar system, with their distribution being particularly prominent in the outer regions. As demonstrated by Gladman and Volk (2021), the majority of TNOs possess orbital inclinations below 60°. This finding is consistent with numerical simulations of Neptune’s migration presented by Nesvorný et al. (2016). As

---

First author: N. Liu, liuning123@shao.ac.cn
Correspondence to: J. C. Shi, jcshi@shao.ac.cn
S. Jin, jins@ahnu.edu.cn
Received 02 SEP 2025; Accepted 04 DEC 2025.

shown in Figure 1, the left panel displays the semimajor axis versus inclination (*a*–*i*) distribution of all asteroids, whereas the right panel shows the *a*–*i* distribution of centaurs and TNOs. It can be observed that small bodies with orbital inclinations greater than 60° are relatively rare, and this characteristic is particularly pronounced in the outer solar system.

Because most survey telescopes primarily observe regions near the ecliptic plane, high-inclination targets receive less coverage owing to their orbits deviating from the ecliptic. Moreover, their kinematic characteristics differ from those of common small bodies, making the observation of such objects particularly challenging. Nevertheless, the study of high-inclination small bodies holds significant scientific value. They may be relics of early solar system dynamical perturbations, such as planetary migration or stellar flyby events, providing critical clues to the evolution of the solar system. Simultaneously, these bodies may retain unique material compositions, contributing to the understanding of chemical differentiation in the solar nebula. Additionally, some high-inclination small bodies could become potential targets for future deep-space resource exploration.

In the second section of this article, we introduce typical examples of high-inclination small bodies, showing the observational characteristics and dynamical behaviors of these unique objects; in the third section, we provide an in-depth analysis of the properties of high-inclination small bodies, examining their differences from low-inclination bodies across multiple aspects; and in the fourth section, we discuss possible formation and evolution theories for high-inclination small bodies, systematically evaluating potential mechanisms for the formation of such special orbits.

2. Representative Examples of High-Inclination Small Bodies

High-inclination small solar system bodies are distributed across various dynamical populations, including near-Earth objects, main-belt asteroids, outer main-belt objects, and TNOs. In this section, we select representative high-inclination small bodies as examples to demonstrate their unique observational characteristics and dynamical behaviors.

Damocles is a centaur asteroid and the namesake of the Damocloid group. It exhibits a high orbital inclination of 61.9°, a semimajor axis of approximately 11.88 astronomical units (AU), and a notable eccentricity of 0.867. These distinctive orbital characteristics make it a peculiar object intermediate between asteroids and comets. Although classified as an asteroid, its dynamical behavior closely resembles that of Halley-type comets, suggesting it may be a dormant cometary nucleus. Numerical simulations indicate that Damocles' orbit is dominated by resonances with Jupiter and remains relatively stable over short timescales but may evolve into an Earth-crossing trajectory or achieve extreme perihelion states over longer periods (Asher et al., 1994).

Asteroid T514107 Kaʻepaokaʻāwela is approximately 3 km in diameter. It is in orbital resonance with Jupiter, exhibiting co-orbital motion, yet its retrograde orbit makes it particularly unusual. It is the first known asteroid to form a 1 : –1 resonance with a planet. Wiegert et al. (2017) confirmed its co-orbital nature and proposed that it may have originated from a capture event outside the solar system or from early dynamical migration processes involving objects from the Oort cloud or Halley-type comets. Huang YK et al. (2018) systematically studied the phase-space structure of retrograde 1 : 1 resonance through analytical and numerical models and pointed out that this type of orbit can remain dynamically stable over the long term within the solar system's dynamical framework. Some researchers have hypothesized that this object may be an interstellar body captured during the early stages of the solar system (Namouni and Morais, 2018), although this idea was contested by Morbidelli et al. (2020). Research by Greenstreet et al. (2020) suggests that Kaʻepaokaʻāwela likely originated from the main asteroid belt within the solar system. Through simulations, the authors demonstrated that main-belt asteroids can gradually increase their orbital inclination owing to planetary gravitational perturbations, eventually flipping into a retrograde orbit and being temporarily captured into Jupiter's retrograde 1 : –1 resonance region, forming an orbital evolution path similar to that of Kaʻepaokaʻāwela.

Trans-Neptunian object 2008 KV42 exhibits an extreme retrograde orbit with an inclination of 103.4°, making it the first retrograde TNO ever discovered. Its detection challenged conventional understanding of the orbital distribution of TNOs, and its peculiar dynamical properties may indicate the existence of an unknown perturbing source beyond Neptune (Gladman et al., 2009). Another retrograde TNO, (471325) Taowu, orbits the Sun with an

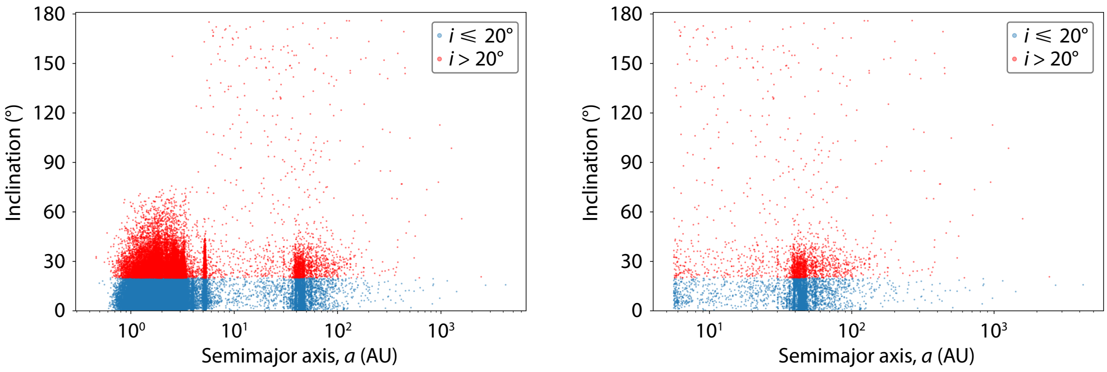

Figure 1. The left panel, based on data from the Minor Planet Center, shows the distribution of the orbital semimajor axis versus inclination (*a*–*i*) for all known asteroids, whereas the right panel presents the *a*–*i* distribution for centaurs and TNOs.

inclination as high as 110°. Its orbital parameters are similar to those of 2008 KV42. Comparative studies of these two bodies suggest that (471325) Taowu, 2008 KV42, and four other high-inclination objects may share a common orbital plane—a configuration unlikely to occur by chance (Chen YT et al., 2016). This clustering in orbital orientation may reflect key events in the early evolution of the solar system or point to the influence of an as-yet undetected external perturber.

3. Research on the Physical and Dynamical Properties of High-Inclination Small Bodies

The physical properties of small bodies include their size, shape, rotation, surface color and composition, and size distribution patterns, whereas their dynamical properties encompass orbital stability, evolution, and lifetime.

3.1 Surface Color Studies

Marsset et al. (2019) conducted a study on the surface colors of high-inclination TNOs, which revealed a significant lack of red spectral slope members among dynamically excited populations in high-inclination regions. Statistical analyses indicate that neutral-color (gray) objects dominate these high-inclination zones, with their orbital inclination distribution differing significantly from that of red objects, which are predominantly concentrated in low-inclination orbits. This color–inclination correlation is consistently observed across all dynamically excited subgroups. This systematic trend suggests that the color dichotomy reflects inherent differences in formation origins: gray high-inclination objects may have formed closer to the Sun, experiencing stronger dynamical perturbations, whereas red objects likely originated farther out in a compositionally distinct primordial planetesimal disk. Further research on the surface colors of high-inclination TNOs has confirmed a significant correlation between color distribution and dynamical orbital parameters (Pfalzner et al., 2025). Observational data show that highly red TNOs with large spectral slopes are exceptionally rare among high-inclination populations; most exhibit neutral or grayish hues. Numerical simulations suggest that this color–inclination correlation may originate from an early close stellar flyby in the solar system: spiral arms excited by the flyby injected gray planetesimals from the outer disk into high-inclination orbits, whereas red objects from the inner disk largely retained their original low-inclination characteristics. These two studies offer divergent explanations for the observed concentration of red TNOs in low-inclination orbits compared with the broad distribution of gray TNOs across all inclinations. The first model presupposes a primordial disk with an “inner gray, outer red” configuration, where Neptune’s orbital migration and dynamical scattering act as the primary drivers. Conversely, the second model postulates an “inner red, outer gray” primordial disk and incorporates an external triggering mechanism—a close stellar flyby in the early solar system—as the pivotal process that reconfigured the TNOs’ orbital distribution. Some researchers argue that the surface colors of high-inclination TNOs are not a result of dynamical evolution but instead reflect their primordial formation locations (Davis et al., 2025).

Furthermore, multiple researchers have found that small bodies with orbital inclinations greater than 60° generally exhibit moderately red surface colors (Hromakina et al., 2021). As shown in Figure 2, the color–color diagram compares the photometric properties of high-inclination small bodies with those of other solar system populations. The comparison reveals that high-inclination small bodies occupy a region of color space similar to that of gray centaurs and moderately red TNOs, while being clearly distinct from the extremely red, primitive bodies in the outer solar system. The color distribution of high-inclination objects is relatively narrow and lacks the strongly red characteristics typical of low-inclination TNOs. This may be related to their dynamical origin, thermal evolution history, or surface alteration attributable to cometary activity.

3.2 Orbital Lifetime Studies

High-inclination small bodies serve as a valuable window into the evolution of the solar system because of their unique orbital dynamics. Studies have shown that the statistical characteristics of their orbital lifetime distributions remain remarkably stable—even when variations in orbital elements span orders of magnitude—whether derived from forward or backward integrations (Hromakina et al., 2021). Furthermore, the influence of the Yarkovsky effect on their orbital evolution has been found to be below the threshold of statistical significance, suggesting that in such highly chaotic dynamical regimes, perturbations from microphysical processes may be overshadowed by macroscopic dynamical effects. This result implies that in regions dominated by strong chaotic dynamics, precise predictions of celestial orbits into the distant past or future are virtually impossible. We can provide only rough statistical estimates for populations of orbits where minuscule differences in initial positions lead to vastly divergent evolutionary paths. Although such statistical methods exhibit considerable robustness against minor perturbations—

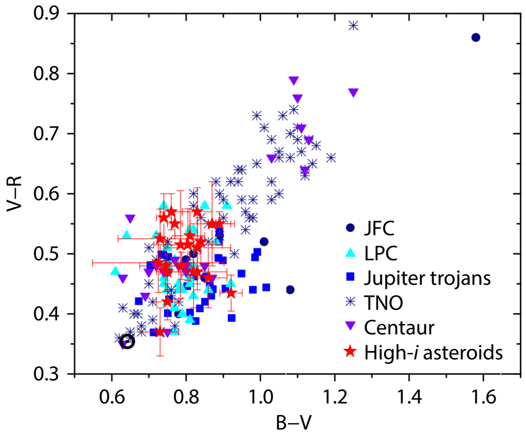

Figure 2. Color–color diagram comparing different dynamical classes of small solar system objects (from Hromakina et al., 2021). Here, JFC refers to Jupiter-family comets, and LPC to long-period comets. The horizontal axis represents the B–V color index, which quantifies the brightness difference between the blue and visual bands, with higher values indicating redder colors. The vertical axis shows the V–R color index, reflecting the contrast between the visual and red bands, where larger values likewise correspond to redder colors.

such as orbital element uncertainties or the Yarkovsky effect—their practical predictive value remains highly limited. It is also noteworthy that a dynamically stable zone exists near an inclination of approximately 150°, where stability becomes particularly pronounced under high-eccentricity conditions, likely due to resonant protection mechanisms and reduced planetary perturbations (Gallardo, 2019).

Studies indicate a substantial difference in evolutionary timescales between high-inclination and low-inclination Mars-crossing asteroids (MCAs). The orbital half-life of high-inclination MCAs is approximately 850 Myr, significantly longer than that of the low-inclination population, which is approximately 70 Myr (Fernández and Helal, 2023). Its exceptionally long dynamical lifetime is primarily attributed to the protective mechanism of the Kozai resonance. This mechanism induces coupled oscillations in the perihelion distance and the argument of perihelion. When the perihelion distance reaches its minimum—bringing the asteroid closest to the orbit of Mars—the argument of perihelion is near 90° or 270°, which elevates the object far above the ecliptic plane. As a result, close encounters with Mars are effectively avoided, preventing rapid chaotic orbital diffusion that would otherwise occur.

3.3 Size Distribution Studies

High-inclination main-belt asteroids exhibit distinct dynamical and collisional evolutionary characteristics compared with their low-inclination counterparts. Through systematic surveys at high ecliptic latitudes, researchers have analyzed the size distribution of these high-inclination small bodies. In the diameter ranges of 0.6–1.0 km and 1.0–3.0 km, the power-law slopes were measured to be 1.25 ± 0.03 and 1.84 ± 0.27, respectively—significantly shallower than the corresponding values for the low-inclination population (Terai et al., 2013). This observational feature suggests that larger bodies within the high-inclination group, which experience higher average collision velocities exceeding 7 km/s, exhibit greater resistance to fragmentation. This finding reflects a dependence of collisional strength parameters on impact velocity.

A study by Fernández and Helal (2023) revealed a significant difference in the absolute magnitude cumulative distribution functions between high-inclination and low-inclination MCAs. The high-inclination population exhibits a distinct bimodal distribution, with a break observed at an absolute magnitude of $H \approx 14.1$, where H denotes the asteroid absolute magnitude, corresponding to a physical diameter $D \approx 5$–6 km under the assumption of a typical geometric albedo. The slope of the distribution is steeper for larger objects than for smaller ones. This "break" in the size distribution cannot be fully explained by observational selection effects; instead, its physical origin is attributed to the size-dependent Yarkovsky effect. The majority of high-inclination MCAs avoid prolonged close encounters with Mars, maintaining long-term dynamical stability. The Yarkovsky effect induces substantial orbital semimajor axis drift in smaller bodies ($D < 5$ km), enabling them to more rapidly enter unstable resonant regions within the main belt and evolve into MCAs, after which they are quickly removed from the population. This process leads to a relative depletion of smaller objects. In contrast, larger bodies ($D > 10$ km) are hardly affected by the Yarkovsky effect. Their extremely long dynamical lifetimes allow them to accumulate continuously in the Mars-crossing region, resulting in an observed enrichment of large, high-inclination MCAs compared with both their smaller counterparts and the overall low-inclination population.

3.4 Orbital Evolution Studies

Dynamical studies of high-inclination small bodies are crucial for understanding the complex gravitational interactions and evolutionary history of the solar system. Studies have been conducted on the long-term orbital evolution mechanisms of high-inclination centaurs, particularly their evolutionary pathways in the inclination–semimajor axis plane. The dynamical essence of this evolution can be interpreted through the Tisserand relation within the restricted three-body problem (Namouni, 2022). This relation divides the inclination–semimajor axis parameter space into four characteristic regions and defines specific evolutionary paths—referred to as Tisserand inclination paths—that objects follow when crossing planetary orbits. As illustrated in Figure 3, the Tisserand relation governs how planet-crossing asteroids evolve within this parameter space. The figure compares three different initial encounter conditions through subplots; although the initial conditions vary, each curve is determined by a conserved Tisserand parameter, revealing the strict dynamical constraints underlying the chaotic evolution of such objects. Research shows that the Tisserand parameter is a key conserved quantity that determines whether an object can enter the inner planetary region: when $T \leq -1$, objects cannot penetrate into the planetary region and are reflected back to the outer solar system, whereas retrograde and high-inclination prograde orbits are confined to the range of $-1 \leq T \leq 2$. When an object temporarily deviates from this path, its orbit remains strongly constrained by long-term planetary perturbations, manifesting as dispersions in eccentricity and inclination around the Tisserand path, with the smallest dispersion amplitudes occurring near polar orbits. Further studies indicate that the injection of TNOs into the giant planet region occurs through two distinct modes: when $T > 0.1$, entry is dominated by unstable motion, leading to ejection or collision, whereas when $T \leq 0.1$, the injection process exhibits significant stability, allowing objects to survive over the long term and eventually become high-inclination centaurs (Namouni, 2023). Numerical simulations further reveal that in the polar orbital region with $T \leq -0.1$, the dynamical timescales can exceed the age of the solar system, suggesting the possible existence of a long-term stable, ancient reservoir of polar or retrograde TNOs that continuously supplies objects to the centaur population.

4. Formation Mechanism Theories

In this section, we introduce several leading potential origins and formation mechanisms for high-inclination small bodies, analyze the efficiency of different mechanisms, and discuss the main challenges and unresolved issues currently faced by each theoretical model.

4.1 An Oort Cloud Origin

During their migration, small bodies can undergo gravitational interactions with giant planets and be scattered into high-inclina-

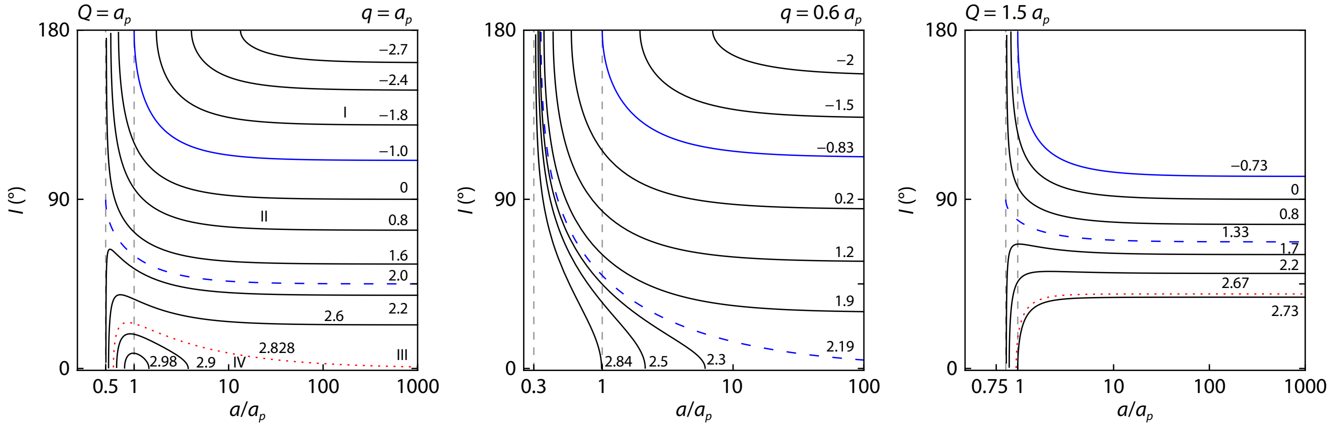

Figure 3. Inclination pathways as a function of the semimajor axis for various values of the Tisserand parameter (from Namouni, 2022). The horizontal axis a/a_p represents the ratio of the asteroid's semimajor axis to that of the planet, and the vertical axis I denotes the orbital inclination. Each curve corresponds to a constant value of the Tisserand parameter T. The three panels illustrate inclination pathways defined by the Tisserand relation under different orbit-crossing conditions. Here, q and Q are the asteroid's perihelion and aphelion distances, and a_p is the planet's semimajor axis.

tion orbits. For instance, objects may be gravitationally scattered by Uranus or Neptune into such orbits. High-inclination bodies in the outer solar system are generally thought to originate from the Oort cloud, the Kuiper Belt, or the scattered disk. Some researchers have also proposed the possibility of an as-yet unobserved source region. The discovery of the first retrograde TNO, 2008 KV24, by Gladman et al. (2009), posed a challenge to classical origin theories: neither the Kuiper Belt nor the Oort cloud easily explains its high inclination. Scattering processes in the Kuiper Belt rarely produce stable orbits with inclinations exceeding 50°, whereas the probability of an outer Oort cloud object reducing its semimajor axis to tens of astronomical units is extremely low. Further studies suggest that a region with a semimajor axis of several hundred astronomical units, a perihelion distance of 35–45 AU, and high inclinations (50°–110°) may be a more plausible source. However, this hypothesis still lacks sufficient observational support. Research also indicates that for inclinations above approximately 70°, the Oort cloud becomes the dominant source of high-inclination, high-perihelion centaurs, whereas contributions from the classical Kuiper Belt or scattered disk decrease significantly (Brasser et al., 2012). Over long-term evolution, the perihelion distances of Oort cloud objects can decrease because of galactic tidal forces, bringing them into the gravitational influence zones of Uranus and Neptune. Subsequent gravitational scattering by these planets significantly reduces their semimajor axes while preserving or even increasing their orbital inclinations, ultimately forming high-inclination, high-perihelion centaurs. Ito and Higuchi (2024) revealed through numerical simulations that small bodies with high inclinations are likely to originate from the Oort cloud. Under the combined effects of galactic tides and stellar encounters, the Oort cloud evolves from its original flattened structure into an isotropic spherical shell, resulting in a very wide distribution of cometary orbital inclinations. When these high-inclination comets enter the inner solar system, they preferentially pass through a dynamical pathway called the "polar corridor," which effectively weakens their gravitational interactions with the giant planets, allowing them to penetrate the planetary region relatively stably and subsequently evolve into the high-inclination populations of small bodies we observe, such as centaurs and Jupiter-family comets.

Within the inner solar system, gravitational perturbations from giant planets such as Jupiter can also eject small bodies into high-inclination orbits. Studies have found that the proportion of D-type asteroids among high-inclination main-belt asteroids (7.3 ± 2.0%) is significantly higher than that in low-inclination samples (3.0 ± 1.1%), suggesting that some D-type asteroids may have formed in the ecliptic region between the main belt and Jupiter and were later scattered inward by Jupiter's gravitational influence, acquiring high-inclination orbits in the process (Iwai et al., 2017). In contrast, the proportions of C-type and S-type asteroids are similar between high- and low-inclination populations, implying that Jupiter's dynamical influence diminishes for asteroids formed farther from its orbit.

4.2 Resonance Capture and Inclination Excitation

Secular resonance refers to a long-term gravitational interaction that occurs when the precession frequency of an orbital element, such as the perihelion or ascending node of a small body, matches the corresponding precession frequency of a planet, thereby gradually altering the body's eccentricity and inclination. According to Nagasawa et al. (2000), during the dissipation of the solar nebula, the gradual weakening of the nebular gravitational potential caused variations in the precession frequencies of Jupiter's and Saturn's perihelia and nodes, leading to the slow sweeping of secular resonances through space. This "resonance sweeping" process can significantly increase the orbital eccentricities and inclinations of small bodies located within the resonance regions, and under nonuniform nebular dissipation, such as inside-out clearing or the gap-opening effect of Jupiter, the inclination excitation becomes particularly efficient. Furthermore, as shown by Li J et al. (2006), during the early solar system's long-term stochastic migration of Neptune, Neptune's secular resonances effectively excited the orbital eccentricities of outer small bodies, causing their perihelia to approach Neptune's orbit; subsequent close encounters with Neptune further elevated their orbital inclinations to approximately 20° or even higher.

Planetary gravitational perturbations induce periodic oscillations in the inclination and eccentricity of small bodies, with some objects being excited to high-inclination orbits. The formation of high-inclination and retrograde orbits among NEAs may be attributed to their complex dynamical evolution. For instance, some small bodies originating from the main asteroid belt may, after long-term orbital diffusion, enter the 3 : 1 mean-motion resonance with Jupiter. Under the influence of this resonance, their orbital inclination gradually increases, eventually flipping into a retrograde state (Greenstreet et al., 2012a). This process is often accompanied by Kozai oscillations, which causes coupled variations in orbital eccentricity and inclination, further promoting inclination growth. Figure 4 illustrates the evolution of orbital parameters throughout this simulated process. Studies predict that approximately 0.1% of the steady-state NEA population may reside in retrograde orbits, with lifetimes ranging from several thousand to several million years. The dynamical pathway, although potentially extant, constitutes a highly inefficient process for generating retrograde NEAs from main-belt precursors.

Researchers have investigated the dynamical evolution of comet 96P/Machholz 1 and have demonstrated that while within the 9:4 mean-motion resonance with Jupiter, Kozai resonance can increase its orbital inclination from 10° to 80° (de la Fuente Marcos et al., 2015). Under high-eccentricity conditions, its orbit may eventually flip, resulting in retrograde motion. A similar mechanism may apply to extreme TNOs, whose high-inclination and high-eccentricity orbital distributions could indicate the presence of a distant, massive perturber. Furthermore, such dynamical processes may trigger orbital instabilities that drive the migration of small bodies from the outer to the inner solar system, ultimately forming high-inclination or retrograde near-Earth objects.

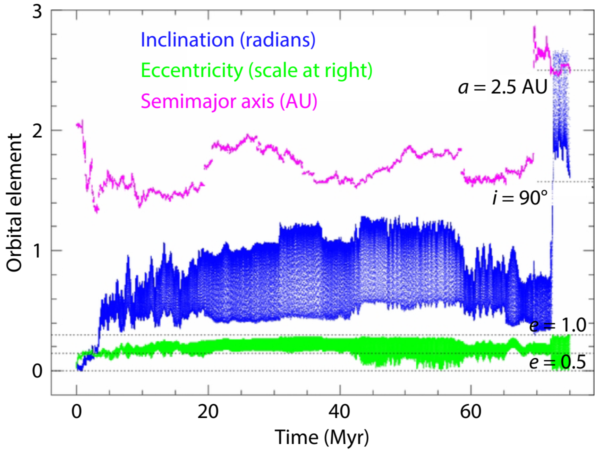

Figure 4. *a*, *e*, *i* history from the high-precision numerical integrations of the Greenstreet et al. (2012a) near-Earth object orbital distribution model, illustrating the dynamical evolution of an asteroid from the main belt that transitions into a retrograde NEA. Here, *a* is the semimajor axis, *e* is the orbital eccentricity, and *i* is the orbital inclination (from Greenstreet et al., 2012a).

The orbital flipping mechanism of high-inclination small bodies can be attributed to the coupling effect of resonance capture and long-term perturbations (Li M et al., 2018, 2019). When a small body enters the mean-motion resonance zone of a giant planet, its orbital eccentricity can be excited by the resonant interaction. Simultaneously, under the influence of long-term perturbations such as the Kozai–Lidov mechanism, periodic exchange between orbital inclination and eccentricity occurs, leading the orbital inclination to flip from prograde through a high-inclination state to retrograde. This flipping mechanism, driven jointly by resonance and long-term dynamical processes, can stably capture some small bodies into retrograde co-orbital resonance with planets. This provides a key theoretical basis for explaining the existence of high-inclination and retrograde small bodies with relatively long dynamical lifetimes in the outer planetary region of the solar system. In nonhierarchical three-body systems, such as the Sun–Jupiter–small body system, orbital crossing can induce strong nonlinear perturbations, thereby triggering an orbital flipping mechanism that is not fully accounted for by classical theories (Li M et al., 2021). Meanwhile, in hierarchical three-body systems, the phenomenon of orbital flipping can be explained by the classical eccentric Kozai–Lidov effect. The dynamical essence of this effect has been identified as apsidal resonance under the octupole-order approximation, which couples orbital eccentricity and inclination, leading to extreme orbital evolution, including orbital flipping (Lei HL and Gong YX, 2022). Furthermore, in the outer solar system's Kuiper Belt, high-order mean-motion resonances play a role in capturing and stabilizing small bodies during Neptune's migration. The dynamical structure of these resonances is constrained by "permissible regions," which determine the existence and long-term stability of high-inclination resonant populations (Li J et al., 2023).

Subsequent studies have shown that resonances with Jupiter—particularly the 3:1, 5:2, 7:3, and 2:1 resonances—can transport low-inclination asteroids into the near-Earth region with inclinations exceeding 20° (Granvik et al., 2017). These same resonances can also reduce inclination, enabling originally high-inclination asteroids to enter the near-Earth region with inclinations below 20°. Further research indicates that NEAs originating from these four resonances, as well as the ν6 resonance, can dynamically increase their inclinations after entering the near-Earth region. Therefore, high-inclination main-belt asteroids are not necessarily the primary source of high-inclination NEAs; only a fraction may originate directly from high-inclination main-belt populations, whereas others likely acquire their high inclinations through subsequent dynamical evolution.

4.3 Influence of Potential Planet Nine

The existence of high-inclination small bodies may be a consequence of gravitational perturbations from Planet Nine. These objects likely originated in the scattered disk at the outer reaches of the solar system, with their orbits undergoing significant evolution under the long-term gravitational influence of a hypothetical massive planet. This hypothesis not only offers an explanation for the presence of extreme TNOs, such as Drac and Niku, but also predicts a nonuniform distribution of high-inclination TNOs in orbital parameter space, providing a testable theoretical framework for future observations (Batygin and Brown, 2016a). The 2015 BP519, currently the known extreme TNO with the highest orbital inclination ($i \approx 54°$), exhibits orbital parameters highly consistent with predictions from the Planet Nine model (Becker et al., 2018). In a study of the retrograde Jupiter trojan 514107 Kaʻepaokaʻāwela, Köhne and Batygin (2020) numerically cloned its orbit and traced its evolution over 100 million years. They found significant overlap between the orbital distribution of these clones and that of high-inclination centaurs generated in Planet Nine simulations. Furthermore, forward simulations demonstrated how TNOs could be driven into retrograde resonant orbits under the combined gravitational effects of Planet Nine and the giant planets. These results provide additional support for the hypothesis of a distant massive planet in the outer solar system.

However, the hypothesis of Planet Nine's existence remains contentious. Batygin and Brown (2016b) pointed out that TNOs with semimajor axes greater than 250 AU exhibit clustering in both the longitude of the ascending node and argument of perihelion, suggesting the presence of an unobserved planet shaping the distant trans-Neptunian region. In contrast, Shankman et al. (2017) found no significant evidence of such clustering, arguing that previously reported orbital alignments likely resulted from uncorrected observational biases and small-sample statistical fluctuations rather than gravitational perturbations from Planet Nine. Further challenging the hypothesis, Sefilian and Touma (2019) demonstrated that a massive, moderately eccentric disk of TNOs could naturally reproduce the observed orbital distribution without requiring an additional planet. Most recently, Chen YT et al. (2025) reported the discovery of a new Sedna-type object, Ammonite. In multiple simulations based on predicted parameters of Planet Nine, Ammonite exhibited a dynamical evolution inconsistent with the three previously known Sedna-like objects. These discrepancies appear difficult to reconcile within the Planet Nine framework, suggesting that current observational data may not be fully explained by a single massive perturber.

4.4 Capture from the Interstellar Medium

A 4.5-billion-year backward orbital evolution analysis of high-inclination centaurs and TNOs suggests that these bodies already exhibited near-polar orbital characteristics—with inclinations between 70° and 90°—by the end of the planet formation era and were predominantly distributed in the scattered disk and inner Oort cloud regions. This finding poses a significant challenge to standard solar system formation theories, which require a highly planar primordial planetesimal disk to account for the low-inclination structure of the present-day asteroid belt and Kuiper Belt. Numerical simulations further indicate that solar system primordial material in these regions should have been scarce during the planet formation period. Consequently, the study supports the idea that high-inclination small bodies are more likely to have been dynamically captured from the interstellar medium, potentially during the Sun's early cluster phase when dense interstellar gas and close stellar encounters provided favorable conditions for the capture of interstellar objects (Namouni and Morais, 2020). However, this origin mechanism remains contested. Some researchers argue that there is no robust evidence for the existence of captured interstellar planetesimals in the solar system (Morbidelli et al., 2020). Despite the ongoing debate, the capture hypothesis continues to offer a valuable alternative perspective for understanding the origin of high-inclination small bodies.

4.5 Stellar Flyby

During the early formation stages of the Sun within its birth cluster, close gravitational interactions with neighboring stars may have occurred. Such flybys would have strongly perturbed the primordial disk of small bodies in the outer solar system through gravitational disturbances, significantly altering the orbital inclinations and eccentricities of these objects. Kenyon and Bromley (2004) showed, based on dynamical simulations of distant solar system bodies such as Sedna, that their high orbital inclinations and large eccentricities could be reasonably explained by an early stellar flyby event. Similarly, dynamical simulations by Jílková et al. (2015) suggested that high-inclination small bodies in the outer solar system, like the Sedna family, may have originated from a close flyby of a stellar companion in the early solar system. This mechanism provides a plausible origin for such objects, which could not be formed through internal solar system dynamics alone. In a comprehensive study, Pfalzner et al. (2024) conducted extensive simulations to identify flyby parameters—such as stellar mass, distance, and orbital inclination—that could simultaneously match all observed TNO populations. This mechanism also successfully reproduced populations of retrograde TNOs that have been difficult to explain with conventional theories.

5. Discussion and Conclusions

On the basis of the aforementioned research, studies on the physical and dynamical properties of high-inclination small bodies have revealed their unique formation histories and evolutionary pathways. Systematic distributions in surface colors indicate that high-inclination objects, particularly TNOs, generally exhibit neutral or grayish hues and lack extremely red surfaces—a notable contrast to the low-inclination population. Some studies suggest that gray high-inclination bodies may have formed closer to the Sun in regions experiencing stronger dynamical perturbations, whereas red objects originated farther out in a compositionally distinct primordial planetesimal disk. Others attribute the color differences to early stellar flyby events in the solar system, and causal graph models further indicate that color may be the cause rather than the consequence of inclination, reflecting intrinsic differences in primordial formation locations. In terms of size distribution, high-inclination populations display unique power-law slopes and bimodal features, revealing the coupling effect of collisional evolution and orbital dynamics. The shallow size distribution of high-inclination main-belt asteroids reflects the enhanced impact resistance of larger bodies under high-velocity collision environments, whereas the "break" in the size distribution of MCAs highlights the size-dependent filtering mechanism of the Yarkovsky effect and resonant dynamics. Studies on orbital lifetime and evolution further demonstrate that high-inclination bodies can maintain exceptionally long lifetimes despite chaotic dynamical environments, primarily because of protective mechanisms, such as the Kozai resonance, which help them avoid close encounters with planets. Additionally, the Tisserand parameter, as a conserved quantity, constrains the evolutionary paths of high-inclination objects and suggests the possible existence of a long-term stable ancient reservoir in the polar orbital region that continuously supplies objects to the centaur population. These findings collectively indicate that high-inclination small bodies serve as key probes for exploring the early formation and evolution of the solar system, with their properties deeply encoding the structure of the primordial disk, dynamical excitation events, and the complex history of long-term planetary perturbations.

Beyond the main formation mechanisms mentioned above, other possibilities exist, such as a tilted primordial planetesimal disk from which remnant small bodies inherited high inclinations, or large collision events that altered orbital inclinations. However, each of these mechanisms has its limitations. The tilted primordial disk hypothesis provides an initial condition assumption for the origin of high-inclination bodies but requires explaining the dynamical stability of the tilted disk and its maintenance during early solar system evolution. If the disk was locally tilted, its subsequent evolution must be consistent with planet formation processes; otherwise, the tilt could be erased by gravitational interactions or gas damping. Gravitational scattering is an important pathway for explaining high-inclination small bodies, yet its efficiency in producing extremely high-inclination objects remains debated, and it struggles to account for the orbital clustering observed in some high-inclination groups. Perturbations from stellar encounters or galactic tides typically apply to distant objects, such as those in the Oort cloud, but operate over long timescales and have weak effects on inner solar system regions. Resonance capture and inclination excitation mechanisms couple inclination with eccentricity through orbital dynamics, producing high-inclination orbits over long-term evolution. This mechanism has observational support in Jupiter trojans and TNOs, but its efficiency depends on initial orbital configurations and the stability of the planetary system. For example, resonance jumping during planetary migration may temporarily enhance inclination excitation, but subsequent evolution must avoid resonance disruption or orbital diffusion. Collisional evolution may effectively alter inclinations in local small body groups but is inadequate to explain large-scale distributions of high-inclination populations. The stochastic nature of collisions also makes it difficult to match observed orbital clustering features. The Planet Nine hypothesis offers a potential unified explanation for orbital clustering of high-inclination TNOs. However, this mechanism faces observational challenges—Planet Nine has not been directly detected, and its formation and orbital stability require further verification.

In summary, current research suggests that no single theory can fully explain the observed orbital distribution of high-inclination small bodies. Different mechanisms may dominate during different epochs or in different regions of the solar system. According to the studies by Granvik et al. (2018) and Greenstreet et al. (2012b), numerical simulations involving only the eight known planets can produce asteroids with inclinations greater than 60°, and even retrograde orbits, in the inner solar system (Greenstreet et al., 2012a). This finding suggests that these high-inclination asteroids may have originated from the main asteroid belt and evolved to their current orbits through planetary perturbations and resonances. However, in the outer solar system, high-inclination centaurs and TNOs cannot be produced in simulations that include only the eight planets. Therefore, additional mechanisms are required to explain their origins. In the inner solar system—such as among main-belt asteroids and near-Earth objects—high-inclination orbits most likely result from a combination of planetary perturbations and orbital resonances, where gravitational scattering ejects bodies into high-inclination orbits, and subsequent resonant effects further stabilize and amplify these inclinations. Alternatively, some may originate from the Kuiper Belt or scattered disk and retain their primordial high inclinations after being gravitationally scattered inward by planets. Additionally, long-term Yarkovsky effect evolution and impact-generated fragments may contribute to the high-inclination population. In the outer solar system, high-inclination bodies may require additional mechanisms, such as the Planet Nine hypothesis or stellar encounters, to explain their peculiar orbital features, alongside gravitational scattering and resonance effects. This regional differentiation reflects inherent differences in dynamical environments across the solar system and underscores the complexity of its evolutionary history.

The study of high-inclination small bodies provides a crucial window into understanding the complexity and diversity of the solar system's dynamical evolution. Although these objects constitute a small fraction of all small bodies in the solar system, they exhibit unique orbital and physical characteristics, making them key carriers of information about the formation and evolution of the solar system. However, our current understanding of high-inclination small bodies remains limited, and research in this area still lacks sufficient observational data and theoretical support. With advances in observational technology and refinements in theoretical models, breakthrough progress is expected in the future.

Acknowledgments

The research was supported by the Operation, Maintenance and Upgrading Fund for Astronomical Telescopes and Facility Instruments, budgeted from the Ministry of Finance of China (MOF) and administrated by the Chinese Academy of Sciences (CAS), the National Natural Science Foundation of China (Nos. 12173093 and 11973094), and the science research grants from the China Manned Space Project (No. CMS-CSST-2021-B08).

References

Asher, D. J., Bailey, M. E., Hahn, G., and Steel, D. I. (1994). Asteroid 5335 Damocles and its implications for cometary dynamics. *Mon. Not. R. Astron. Soc.*, *267*(1), 26–42. https://doi.org/10.1093/mnras/267.1.26

Batygin, K., and Brown, M. E. (2016a). Generation of highly inclined Trans-Neptunian objects by planet nine. *Astrophys. J. Lett.*, *833*(1), L3. https://doi.org/10.3847/2041-8205/833/1/L3

Batygin, K., and Brown, M. E. (2016b). Evidence for a distant giant planet in the solar system. *Astron. J.*, *151*(2), 22. https://doi.org/10.3847/0004-6256/151/2/22

Becker, J. C., Khain, T., Hamilton, S. J., Adams, F. C., Gerdes, D. W., Zullo, L., Franson, K., Millholland, S., Bernstein, G. M., … DES Collaboration. (2018). Discovery and dynamical analysis of an extreme trans-Neptunian object with a high orbital inclination. *Astron. J.*, *156*(2), 81. https://doi.org/10.3847/1538-3881/aad042

Brasser, R., Schwamb, M. E., Lykawka, P. S., and Gomes, R. S. (2012). An Oort cloud origin for the high-inclination, high-perihelion Centaurs. *Mon. Not. R. Astron. Soc.*, *420*(4), 3396–3402. https://doi.org/10.1111/j.1365-2966.2011.20264.x

Chen, Y. T., Lykawka, P. S., Huang, Y. K., Kavelaars, J., Fraser, W. C., Bannister, M.

T., Wang, S. Y., Chang, C. K., Lehner, M. J., … Zhou, J. L. (2025). Discovery and dynamics of a Sedna-like object with a perihelion of 66 au. *Nat. Astron.*, *9*(9), 1309–1316. https://doi.org/10.1038/s41550-025-02595-7

Chen, Y. T., Lin, H. W., Holman, M. J., Payne, M. J., Fraser, W. C., Lacerda, P., Ip, W. H., Chen, W. P., Kudritzki, R. P., … Lehner, M. (2016). Discovery of a new retrograde trans-Neptunian object: Hint of a common orbital plane for low semimajor axis, high-inclination TNOs and centaurs. *Astrophys. J. Lett.*, *827*(2), L24. https://doi.org/10.3847/2041-8205/827/2/L24

Davis, B. L., Ali-Dib, M., Zheng, Y. J., Jin, Z. H., Zhang, K., and Macciò, A. V. (2025). Causal evidence for the primordiality of colours in trans-Neptunian objects. *Mon. Not. R. Astron. Soc.: Lett.*, *543*(1), L34–L42. https://doi.org/10.1093/mnrasl/slaf089

de la Fuente Marcos, C., de la Fuente Marcos, R., and Aarseth, S. J. (2015). Flipping minor bodies: What comet 96P/Machholz 1 can tell us about the orbital evolution of extreme trans-Neptunian objects and the production of near-Earth objects on retrograde orbits. *Mon. Not. R. Astron. Soc.*, *446*(2), 1867–1873. https://doi.org/10.1093/mnras/stu2230

Duncan, M., Quinn, T., and Tremaine, S. (1988). The origin of short-period comets. *Astrophys. J. Lett.*, *328*, L69. https://doi.org/10.1086/185162

Fernández, J. A., and Helal, M. (2023). On the observed excess of large Mars-crossers in high-inclination orbits. *Icarus*, *394*, 115398. https://doi.org/10.1016/j.icarus.2022.115398

Gallardo, T. (2019). Orbital stability in the Solar System for arbitrary inclinations and eccentricities: Planetary perturbations versus resonances. *Mon. Not. R. Astron. Soc.*, *487*(2), 1709–1716. https://doi.org/10.1093/mnras/stz1419

Gladman, B., Kavelaars, J., Petit, J. M., Ashby, M. L. N., Parker, J., Coffey, J., Jones, R. L., Rousselot, P., and Mousis, O. (2009). Discovery of the first retrograde transneptunian object. *Astrophys. J. Lett.*, *697*(2), L91–L94. https://doi.org/10.1088/0004-637X/697/2/L91

Gladman, B., and Volk, K. (2021). Transneptunian space. *Annu. Rev. Astron. Astrophys.*, *59*(1), 203–246. https://doi.org/10.1146/annurev-astro-120920-010005

Gomes, R., Levison, H. F., Tsiganis, K., and Morbidelli, A. (2005). Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. *Nature*, *435*(7041), 466–469. https://doi.org/10.1038/nature03676

Granvik, M., Morbidelli, A., Vokrouhlický, D., Bottke, W. F., Nesvorný, D., and Jedicke, R. (2017). Escape of asteroids from the main belt. *Astron. Astrophys.*, *598*, A52. https://doi.org/10.1051/0004-6361/201629252

Granvik, M., Morbidelli, A., Jedicke, R., Bolin, B., Bottke, W. F., Beshore, E., Vokrouhlický, D., Nesvorný, D., and Michel, P. (2018). Debiased orbit and absolute-magnitude distributions for near-Earth objects. *Icarus*, *312*, 181–207. https://doi.org/10.1016/j.icarus.2018.04.018

Greenstreet, S., Gladman, B., Ngo, H., Granvik, M., and Larson, S. (2012a). Production of near-earth asteroids on retrograde orbits. *Astrophys. J. Lett.*, *749*(2), L39. https://doi.org/10.1088/2041-8205/749/2/L39

Greenstreet, S., Ngo, H., and Gladman, B. (2012b). The orbital distribution of Near-Earth Objects inside Earth's orbit. *Icarus*, *217*(1), 355–366. https://doi.org/10.1016/j.icarus.2011.11.010

Greenstreet, S., Gladman, B., and Ngo, H. (2020). Transient Jupiter co-orbitals from solar system sources. *Astron. J.*, *160*(3), 144. https://doi.org/10.3847/1538-3881/aba2c9

Hromakina, T., Belskaya, I., Krugly, Y., Rumyantsev, V., Golubov, O., Kyrylenko, I., Ivanova, O., Velichko, S., Izvekova, I., … Molotov, I. (2021). Small solar system objects on highly inclined orbits: Surface colours and lifetimes. *Astron. Astrophys.*, *647*, A71. https://doi.org/10.1051/0004-6361/202039737

Huang, Y. K., Li, M., Li, J. F., and Gong, S. P. (2018). Dynamic portrait of the retrograde 1:1 mean motion resonance. *Astron. J.*, *155*(6), 262. https://doi.org/10.3847/1538-3881/aac1bc

Ito, T., and Higuchi, A. (2024). An estimate of resident time of the Oort Cloud new comets in planetary region. *Planet. Space Sci.*, *253*, 105984. https://doi.org/10.1016/j.pss.2024.105984

Iwai, A., Itoh, Y., Terai, T., Gupta, R., Sen, A., and Takahashi, J. (2017). Optical spectroscopy and photometry of main-belt asteroids with a high orbital inclination. *Res. Astron. Astrophys.*, *17*(2), 17. https://doi.org/10.1088/1674-4527/17/2/17

Jílková, L., Zwart, S. P., Pijloo, T., and Hammer, M. (2015). How Sedna and family were captured in a close encounter with a solar sibling. *Mon. Not. R. Astron. Soc.*, *453*(3), 3157–3162. https://doi.org/10.1093/mnras/stv1803

Kenyon, S. J., and Bromley, B. C. (2004). Stellar encounters as the origin of distant Solar System objects in highly eccentric orbits. *Nature*, *432*(7017), 598–602. https://doi.org/10.1038/nature03136

Köhne, T., and Batygin, K. (2020). On the dynamical origins of retrograde Jupiter Trojans and their connection to high-inclination TNOs. *Celest. Mech. Dyn. Astron.*, *132*(9), 44. https://doi.org/10.1007/s10569-020-09985-1

Lei, H. L., and Gong, Y. X. (2022). Dynamical essence of the eccentric von Zeipel–Lidov–Kozai effect in restricted hierarchical planetary systems. *Astron. Astrophys.*, *665*, A62. https://doi.org/10.1051/0004-6361/202243746

Li, J., Zhou, L. Y., and Sun, Y. S. (2006). Formation of the Kuiper belt by long time-scale migration of Jovian planets. *Chin. J. Astron. Astrophys.*, *6*(5), 588–596. https://doi.org/10.1088/1009-9271/6/5/11

Li, J., Lawler, S. M., and Lei, H. L. (2023). A study of the high-inclination population in the Kuiper belt – IV. High-order mean-motion resonances in the classical region. *Mon. Not. R. Astron. Soc.*, *523*(4), 4841–4854. https://doi.org/10.1093/mnras/stad1751

Li, M., Huang, Y. K., and Gong, S. P. (2018). Centaurs potentially in retrograde co-orbit resonance with Saturn. *Astron. Astrophys.*, *617*, A114. https://doi.org/10.1051/0004-6361/201833019

Li, M., Huang, Y. K., and Gong, S. P. (2019). Survey of asteroids in retrograde mean motion resonances with planets. *Astron. Astrophys.*, *630*, A60. https://doi.org/10.1051/0004-6361/201936117

Li, M., Lei, H. L., Huang, Y. K., and Gong, S. P. (2021). Flip mechanism of Jupiter-crossing orbits in the non-hierarchical triple system. *Mon. Not. R. Astron. Soc.*, *502*(4), 5584–5592. https://doi.org/10.1093/mnras/stab363

Marsset, M., Fraser, W. C., Pike, R. E., Bannister, M. T., Schwamb, M. E., Volk, K., Kavelaars, J. J., Alexandersen, M., Chen, Y. T., … Wang, S. Y. (2019). Col-OSSOS: Color and inclination are correlated throughout the Kuiper belt. *Astron. J.*, *157*(3), 94. https://doi.org/10.3847/1538-3881/aaf72e

Morbidelli, A., Batygin, K., Brasser, R., and Raymond, S. N. (2020). No evidence for interstellar planetesimals trapped in the Solar system. *Mon. Not. R. Astron. Soc.: Lett.*, *497*(1), L46–L49. https://doi.org/10.1093/mnrasl/slaa111

Nagasawa, M., Tanaka, H., and Ida, S. (2000). Orbital evolution of asteroids during depletion of the solar nebula. *Astron. J.*, *119*(3), 1480–1497. https://doi.org/10.1086/301246

Namouni, F., and Morais, M. H. M. (2018). An interstellar origin for Jupiter's retrograde co-orbital asteroid. *Mon. Not. R. Astron. Soc.: Lett.*, *477*(1), L117–L121. https://doi.org/10.1093/mnrasl/sly057

Namouni, F., and Morais, M. H. M. (2020). An interstellar origin for high-inclination Centaurs. *Mon. Not. R. Astron. Soc.*, *494*(2), 2191–2199. https://doi.org/10.1093/mnras/staa712

Namouni, F. (2022). Inclination pathways of planet-crossing asteroids. *Mon. Not. R. Astron. Soc.*, *510*(1), 276–291. https://doi.org/10.1093/mnras/stab3405

Namouni, F. (2023). Orbit injection of planet-crossing asteroids. *Mon. Not. R. Astron. Soc.*, *527*(3), 4889–4898. https://doi.org/10.1093/mnras/stad3570

Nesvorný, D., Vokrouhlický, D., and Roig, F. (2016). The orbital distribution of trans-Neptunian objects beyond 50 au. *Astrophys. J. Lett.*, *827*(2), L35. https://doi.org/10.3847/2041-8205/827/2/L35

Pfalzner, S., Govind, A., and Zwart, S. P. (2024). Trajectory of the stellar flyby that shaped the outer solar system. *Nat. Astron.*, *8*(11), 1380–1386. https://doi.org/10.1038/s41550-024-02349-x

Pfalzner, S., Wagner, F. W., and Gibbon, P. (2025). TNO colours provide new evidence for a past close flyby of another star to the solar system. arXiv:2507.06693. https://doi.org/10.48550/arXiv.2507.06693

Sefilian, A. A., and Touma, J. R. (2019). Shepherding in a self-gravitating disk of trans-Neptunian objects. *Astron. J.*, *157*(2), 59. https://doi.org/10.3847/1538-3881/aaf0fc

Shankman, C., Kavelaars, J. J., Bannister, M. T., Gladman, B. J., Lawler, S. M., Chen, Y. T., Jakubik, M., Kaib, N., Alexandersen, M., … Volk, K. (2017). OSSOS. VI. Striking biases in the detection of large semimajor axis trans-Neptunian objects. *Astron. J.*, *154*(2), 50. https://doi.org/10.3847/1538-3881/aa7aed

Terai, T., Takahashi, J., and Itoh, Y. (2013). High ecliptic latitude survey for small main-belt asteroids. *Astron. J.*, *146*(5), 111. https://doi.org/10.1088/0004-6256/146/5/111

Wiegert, P., Connors, M., and Veillet, C. (2017). A retrograde co-orbital asteroid of Jupiter. *Nature*, *543*(7647), 687–689. https://doi.org/10.1038/nature22029