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Potential Jupiter-Family comet contamination of the main asteroid belt

Henry H. Hsieh[a,b,*], Nader Haghighipour[c]

[a] Planetary Science Institute, 1700 E. Ft. Lowell Road, Suite 106, Tucson, AZ 85719, USA
[b] Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 10617, Taiwan
[c] Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA

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ABSTRACT

We present the results of "snapshot" numerical integrations of test particles representing comet-like and asteroid-like objects in the inner Solar System aimed at investigating the short-term dynamical evolution of objects close to the dynamical boundary between asteroids and comets as defined by the Tisserand parameter with respect to Jupiter, T_J (i.e., $T_J=3$). As expected, we find that T_J for individual test particles is not always a reliable indicator of initial orbit types. Furthermore, we find that a few percent of test particles with comet-like starting elements (i.e., similar to those of Jupiter-family comets) reach main-belt-like orbits (at least temporarily) during our 2 Myr integrations, even without the inclusion of non-gravitational forces, apparently via a combination of gravitational interactions with the terrestrial planets and temporary trapping by mean-motion resonances with Jupiter. We estimate that the fraction of real Jupiter-family comets occasionally reaching main-belt-like orbits on Myr timescales could be on the order of ~0.1–1%, although the fraction that remain on such orbits for appreciable lengths of time is certainly far lower. For this reason, the number of JFC-like interlopers in the main-belt population at any given time is likely to be small, but still non-zero, a finding with significant implications for efforts to use apparently icy yet dynamically asteroidal main-belt comets as tracers of the primordial distribution of volatile material in the inner Solar System. The test particles with comet-like starting orbital elements that transition onto main-belt-like orbits in our integrations appear to be largely prevented from reaching low eccentricity, low inclination orbits, suggesting that the real-world population of main-belt objects with both low eccentricities and inclinations may be largely free of this potential occasional Jupiter-family comet contamination. We therefore find that low-eccentricity, low-inclination main-belt comets may provide a more reliable means for tracing the primordial ice content of the main asteroid belt than the main-belt comet population as a whole.

1. Introduction

1.1. The Tisserand parameter

The Tisserand parameter, T_P, or Tisserand invariant, of a small Solar System body under the influence of gravity from the Sun and a major planetary perturber is defined by

$$T_P = \frac{a_P}{a} + 2\cos i\left[\left(1-e^2\right)\frac{a}{a_P}\right]^{1/2} \quad (1)$$

where a_P is the semimajor axis of the planetary perturber, and a, e, and i are the semimajor axis, eccentricity, and inclination of the small body in question. Derived from Jacobi's integral, the long-term value of this quantity is largely conserved in the restricted three-body problem (Tisserand, 1896; Vaghi, 1973), even in the event of close encounters with the planetary perturber (Carusi et al., 1995).

In the study of small Solar System body dynamics, the Tisserand parameter with respect to Jupiter, T_J, is frequently employed as a discriminant between asteroids and comets. Main-belt asteroids typically have $T_J > 3$, and comets typically have $T_J < 3$ (Kresák, 1972). However, despite the appealing simplicity of a clear-cut boundary between asteroids and comets at $T_J = 3$, T_J is well-known to be an inexact means of dynamically classifying real Solar System objects. The expression for T_P is derived using an idealized physical approximation in which the orbit of the planetary perturber is assumed to be circular ($e = 0$) and non-inclined ($i = 0°$), but Jupiter's actual orbit has both non-zero e and non-zero i ($e_J = 0.0489$; $i_J = 1.304°$). Furthermore, while Jupiter is the dominant planetary

* Corresponding author at: Planetary Science Institute, 1700 E. Ft. Lowell Road, Suite 106, Tucson, AZ 85719, USA.
E-mail addresses: hhsieh@psi.edu (H.H. Hsieh), nader@ifa.hawaii.edu (N. Haghighipour).

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perturber in the Solar System, the other outer planets as well as the terrestrial planets can also affect cometary orbits (e.g., Morbidelli and Nesvorný, 1999; Levison et al., 2006; Gallardo, 2014). Lastly, non-gravitational forces such as the Yarkovsky effect (cf. Rubincam, 1995) and cometary outgassing (cf. Marsden et al., 1973; Yeomans et al., 2004) can potentially play a significant role in the dynamical evolution of Solar System objects, such as in the case of 2P/Encke (e.g., Steel and Asher, 1996; Fernández et al., 2002; Pittich et al., 2004), but are unaccounted for in the formulation of T_P.

1.2. T_J as an asteroid–comet discriminant

Fernández et al. (2005, 2001) demonstrated that near-Earth objects (NEOs) with $T_J<3$ (sometimes referred to as asteroids in cometary orbits, or ACOs, in the literature) showed significantly lower albedos than NEOs with $T_J>3$, consistent with the low-T_J objects being dormant or extinct comet nuclei. This finding led Binzel et al. (2004) and DeMeo and Binzel (2008) to use a combination of low albedos and low T_J values to identify extinct comet candidates in other NEO surveys. Binzel et al. (2004) reported, however, that dynamical models indicated that ∼35% of low-albedo $T_J\leq 3$ NEOs were likely to originate from the outer asteroid belt, not the outer Solar System as their T_J values might normally suggest. Ziffer et al. (2005) also found that near-infrared spectra of two asteroids with $T_J<3$ showed that they had more in common with X-type asteroids than cometary nuclei. In a study of asteroids with $T_J<3$, Licandro et al. (2006) similarly found a reflectivity gradient distribution more consistent with outer main-belt asteroids than with cometary nuclei, though cautioned that their results were preliminary.

While physical studies indicate that T_J is probably a reasonable first-order indication of an object's probable dynamical origin, the aforementioned caveats mean that it should not be regarded as an absolute criterion. Plots of the orbital elements of the first 50 000 numbered asteroids and all comets catalogued by the Minor Planet Center as of 2014 April 1 (Fig. 1) shows that most asteroids have $T_J>3$, and most comets have $T_J<3$, though there are some asteroids with $T_J<3$ and a handful of comets with $T_J>3$. In particular, jovian Trojan asteroids ($a\sim 5.2$ AU) and Hilda asteroids ($a\sim 3.9-4.0$ AU) comprise a large portion of the $T_J<3$ asteroid population. There are also some $T_J<3$ asteroids within the a bounds of the main asteroid belt (between the 4:1 and 2:1 mean-motion resonances, or MMRs, with Jupiter), where these objects have larger e, larger i, or both, relative to the rest of the main-belt asteroid population. Notably, we see that the vast majority of comets in Fig. 1 have perihelion distances, Q, within 1.5 Hill radii ($1.5R_H$) of Jupiter's perihelion, q_J, or beyond, indicating the possibility of very close encounters with the planet and therefore a strong degree of dynamical coupling. Meanwhile, the vast majority of main-belt asteroids (Hilda and jovian Trojan asteroids aside) do not have Q closer than $1.5R_H$ from q_J, indicating a low degree of dynamical coupling. We therefore find that the locus of orbits in a-e space with $Q=q_J-1.5R_H$ forms a reasonably effective alternative dynamical dividing line separating main-belt asteroids and Jupiter-family comets, consistent with the findings of Tancredi (2014).

Continuing to study Fig. 1, we see that there are very few comets with $T_J>3$. Most of these have a placing them outside the main asteroid belt (i.e., beyond the 2:1 MMR with Jupiter at 3.277 AU). A few other comets have a that actually place them within the main asteroid belt, but also have e values larger than those commonly associated with main-belt asteroids. In almost all of these cases, the orbits of these comets meet the $Q>q_J-1.5R_H$ criterion for cometary orbits discussed above, with the notable exception of main-belt comets (described below).

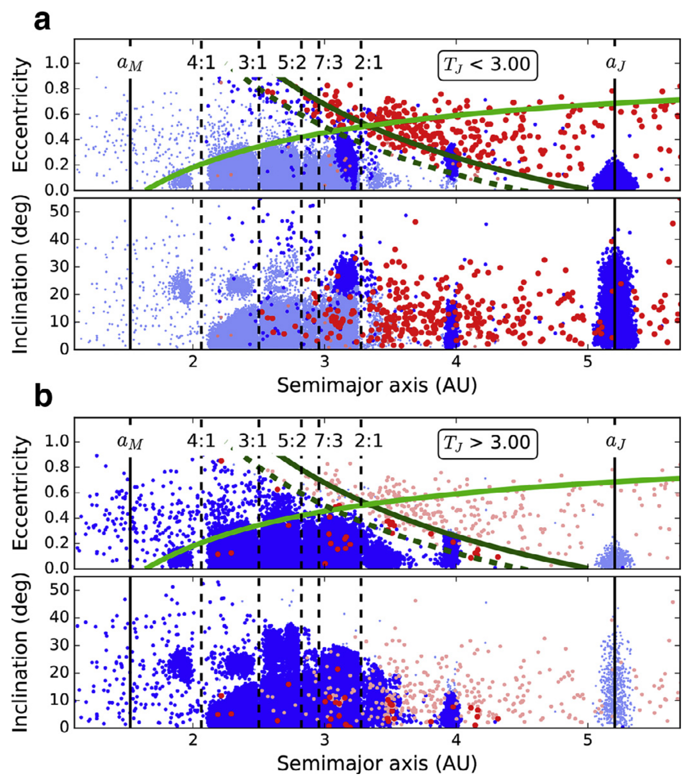

Fig. 1. Plots of a vs. e (top half of each panel) and i (bottom half of each panel) for the first 50,000 numbered asteroids (pale blue dots) and all comets catalogued by the Minor Planet Center as of 2014 April 1 (pale red dots), where asteroids and comets with T_J values of (a) $T_J<3.00$, and (b) $T_J>3.00$ are highlighted with dark blue and dark red dots, respectively. Solid vertical lines mark a for Mars and Jupiter (a_M and a_J), while the 4:1, 3:1, 5:2, 7:3, and 2:1 MMRs with Jupiter are marked with dashed vertical lines. The loci of Mars-crossing orbits (where $q=Q_M$) and Jupiter-crossing orbits (where $Q=q_J$) are marked with light green and dark green curved solid lines, respectively, on each a-e plot, while the loci of orbits for which objects can potentially come within 1.5 Hill radii of Jupiter ($Q=q_J-1.5R_H$) are marked with dark green dashed lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1.3. Main-belt comets

Aside from the aforementioned handful of comets with $T_J>3$ that have a or e placing them beyond the commonly recognized bounds of the main asteroid belt, there exists a newly identified class of comets known as main-belt comets (MBCs; Hsieh and Jewitt, 2006) that exhibit cometary activity indicative of the sublimation of volatile ices, yet have $T_J>3$, have semimajor axes and eccentricities completely consistent with main-belt asteroids, and do not have close encounters with Jupiter. MBCs constitute a subset of the group of small Solar System bodies known as active asteroids (Jewitt, 2012; Jewitt et al., 2015), which also includes disrupted asteroids, which are objects that exhibit comet-like activity that is produced by non-sublimation-driven effects such as impacts or rotational destabilization (cf. Hsieh et al., 2012a). MBCs are particularly interesting from a dynamical perspective though, since the implication that they are icy bodies raises natural questions about whether they may have originated in the outer Solar System like other comets, or whether they were formed in situ as their largely stable main-belt orbits appear to suggest (cf. Hsieh, 2014).

Attempts have been made in the past to find plausible dynamical pathways by which Jupiter-family comets (JFCs) could possibly have evolved onto MBC-like orbits, given the unexpectedness of objects on apparently dynamically stable main-belt orbits currently exhibiting active sublimation, but no such pathways were