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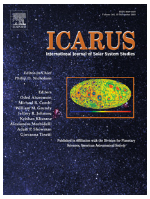

Long-term self-modification of irregular satellite groups

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More than 50 irregular satellites revolve around Jupiter and more than 30 around Saturn. There, at least three collisional families were identified. Among these, the Himalia family of prograde irregular moons at Jupiter is characterised by a velocity dispersion of several hundred m/s, inconsistent with a collisional origin (Nesvorný et al., 2003). Here we investigate whether the dispersion could stem from the mutual gravitational interaction among the family members, especially from perturbations by the largest member Himalia. Using long-term *N*-body simulations, we find that over 1 Gyr, Himalia can disperse its family significantly, particularly in the semimajor axis and eccentricity. By extrapolating our results to 4 Gyr, we show that it is unlikely Himalia's gravity alone is responsible for the observed dispersion. The self-dispersion scenario becomes viable if Himalia is twice as massive as the upper end of current estimates (Brozović and Jacobson, 2017; Emelyanov, 2005). We also find that the collisions with Himalia would have removed $\gtrsim 60\%$ of an initial population of 10km class family satellites over the last 4 Gyr. During this period, the observed satellites have probably been captured into secular resonances with Himalia (Li and Christou, 2017). These resonances can affect the dispersion through resonance captures/escapes and by restricting close encounter configurations. A similar hypothesis is tested for the putative Phoebe family at Saturn, also of large velocity dispersion (Gladman et al., 2001). Again, we find this effect not sufficient to account for the observed orbital distribution. In all simulations, it is found that the rate of dispersion is decreasing with time, owing to the declining frequency of resonance captures/escapes and close encounters.

1. Introduction

All giant planets have two types of satellite. Well separated in semimajor axis *a*, eccentricity *e* and inclination *i*, the two are believed to have distinct origins. The "regular" satellites are close to the host planet with near circular orbits coplanar with respect to the planetary equatorial plane; they formed in the local circumplanetary disk (see, e.g., Canup and Ward, 2002). The so-called "irregular" satellites have wide, highly eccentric and inclined orbits, the short-term orbital evolution of which is controlled by the solar attraction. These satellites are believed to be captured by the host planets in the early solar system.

Back in mid last century Kuiper (1951) proposed that, escaped satellites could be recaptured as irregular satellites. Colombo and Franklin (1971) argued that, the irregular satellite population at Jupiter could have formed via a single collision. Heppenheimer and Porco (1977) suggested that, during the rapid accretion of protoplanetary gas onto a still-forming planet, temporarily captured satellites could turn into permanent captives. Pollack et al. (1979) held the view that, gas friction could help make temporary captures permanent.

Since the late 1990s, CCD-equipped wide-field surveys have increased the number of known irregular moons by an order of magnitude (see, Jewitt and Haghighipour, 2007; Nicholson et al., 2008). Now, the total number of irregular satellites exceeds 100.

Astakhov et al. (2003) and Astakhov and Farrelly (2004) argued that captives on chaotic long-lived orbits might become permanently captured through gas dissipation. Ćuk and Burns (2004a) studied the capture of (J VI) Himalia of Jupiter due to gaseous dissipation and found it energetically possible. In looking into capture due to planetary mass growth, Vieira Neto et al. (2004) and Vieira Neto et al. (2006) found plausible masses of Jupiter at which its irregulars were captured. In the so-called Nice scenario (Gomes et al., 2005; Morbidelli et al., 2005; Tsiganis et al., 2005), the four giant planets migrated long distances due to interaction with a primordial planetesimal disk. There, two type of interactions happened (i) close encounters and resonance crossings between the giants and (ii) close encounters between the planetesimals and the

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planets. Ćuk and Gladman (2006) proposed that the resonant passage between Jupiter and Saturn could pump up the orbits of the moons around Saturn, resembling the observed irregular satellite population. Agnor and Hamilton (2006) brought forward the binary capture mechanism for (N I) Triton at Neptune. Based on Agnor and Hamilton's ideas, Vokrouhlický et al. (2008) investigated orbital distribution of the captured moons and found that the capture efficiency was generally low; Philpott et al. (2010) pointed out that post-capture dissipation was needed to further modify the orbits; Gaspar et al. (2011) put an emphasis on the most favourable capture configurations at Jupiter; Quillen et al. (2012) studied such captures in a background of general exo-two-planet systems. Nesvorný et al. (2007); 2014) investigated capture during planetary close encounters in the Nice scenario, as a universal mechanism to populate all giant planets. Turrini et al. (2009) revisited the collisional capture mechanism at Saturn and constrained possible precapture heliocentric orbits of the parent bodies.

Once permanently captured, the orbits of irregular satellites are subject to various perturbations. Unlike the regular moons whose orbital evolution is dominated by planetary oblateness, the orbital dynamics of irregulars is governed by the Sun, which serves as the definition of "irregular satellite" (e.g., Burns and Matthews, 1986; Goldreich, 1966).

The secular effects of the Sun can be described using the Kozai–Lidov formalism (Kozai, 1962; Lidov, 1962), whereby the orbits precess in the argument of pericentre ω and the longitude of ascending node Ω while the eccentricity e and inclination i oscillate in such a way that the vertical angular momentum $H \propto \sqrt{1-e^2}\cos i$ is conserved (the so-called Kozai–Lidov cycle). This mechanism is responsible for the paucity of objects near an inclination of 90° (Carruba et al., 2002). Specifically, when $i \gtrsim 40°$, ω may librate. Librators have been found around all four giant planets (e.g., Carruba et al., 2004; Ćuk and Burns, 2004b; Vashkov'yak, 2001).

Mean motion resonances (MMRs) may also affect irregular satellites. Saha and Tremaine (1993) showed that the Jovian retrograde moon (J IX) Sinope was influenced by the 6:1 MMR with Jupiter, which was later confirmed by Nesvorný et al. (2003). Hinse et al. (2010) reported the nominal locations of a number of high order MMRs at Jupiter.

Irregular satellites are also influenced by secular resonances. Whipple and Shelus (1993) found that the longitude of pericentre of Jovian retrograde irregular moon (J VIII) Pasiphae was locked to that of Jupiter's, a mechanism to avoid strong solar perturbation. More satellites were found to be influenced by this resonance (Ćuk et al., 2002; Nesvorný et al., 2003; Saha and Tremaine, 1993). Ćuk and Burns (2004b) developed analytical expressions of the solar disturbing function and more satellites were found to have stationary pericentres. Beaugé et al. (2006) and Beaugé and Nesvorný (2007) proposed a high-order secular analytical model and located higher order secular resonances. More recently, Correa Otto et al. (2010) numerically mapped the phase space structure of this secular resonance. Frouard et al. (2011) identified more high-order secular resonances related to the giant planets' eigenfrequencies that arise from their mutual gravitational potential expanded to leading orders in e and i (e.g., Murray and Dermott, 1999).

Collisions should be common among irregular satellites (Kessler, 1981). Nesvorný et al. (2003) estimated the collisional probability among pairs of then known irregular satellites. Turrini et al. (2008) concentrated on Saturnian irregulars, pointing out the dominant role of (S IX) Phoebe, the largest irregular moon in the system. Bottke et al. (2010) argued that the mutual collisions among the population of irregular moons immediately post-capture could result in the self-destruction of 99% of the captured bodies and modify their size distribution.

Jupiter is known to have the largest irregular satellite population of more than 50 objects. Three collisional families were identified with largest members Himalia, (J XI) Carme and (J XII) Ananke (Nesvorný et al., 2003). An intriguing feature of the Himalia family is that it is spread rather widely in a and e with corresponding velocity dispersion of several hundred m/s (Nesvorný et al., 2003), inconsistent with a collisional origin (Michel et al., 2001; 2015).

Himalia is 70 km in radius (Grav et al., 2015) and the largest irregular at Jupiter. The other four family members are (J VII) Elara, (J XIII) Leda, (J X) Lysithea and (J LIII) Dia. Christou (2005) showed that Himalia could give rise to secular resonances and lock the nodal difference $\Delta\Omega$ between it and other family members. This result was recently generalised: Li and Christou (2016); 2017) identified a network of secular resonances where the critical angles were linear combinations of apsidal and nodal differences $b_1\Delta\varpi + b_2\Delta\Omega$. Additionally, using numerical simulations spanning 100 Myr, Christou (2005) suggested that the gravitational interactions among the satellites could be responsible for the dispersion observed for this family. However, the recently recovered Dia[1] has apparently a distinct orbit from the other family members (cf. Fig. 5). It is desirable, therefore, to reexamine Christou's mechanism. We note that Christou (2005) actually studied the dispersion of generated clones of actual satellites according to observational errors. Thus, the dispersion rates obtained there were specific for these satellites, particular points in (a, e, i) space. Since the satellites are slowly drifting, they were not necessarily close to their current positions 4 Gyr ago. In this paper, we are studying how the family evolves, from a compact configuration upon its collisional formation, under the gravitational perturbation of Himalia. As will be shown, the dispersion decelerates as the family disperses, implying that the rate reported by Christou (2005) is significantly lower than those experienced by the family when it is still compact. Thus here we look into the dispersion of a compact collisional family. Furthermore, a dedicated study of the long-term effects of the newly identified secular resonances is needed. Phoebe is the largest irregular satellite at Saturn and a member of a putative inclination family (Gladman et al., 2001; Ćuk et al., 2003; Turrini et al., 2008). Analogous to the Himalia family, the dispersion there is also large (Nesvorný et al., 2003). We want to explore the hypothesis that Phoebe could be similarly responsible for the dispersion of its family.

We note that the orbital elements of some irregular satellites are not well known and some of them are lost (Brozović and Jacobson, 2017). This is, however, not the case for the Himalia family. All members, except Dia, have observations spanning 40 to over 100 years while Dia has an observational arc of ≳ 10 years (Brozović and Jacobson, 2017).

The paper is organised as follows. In Section 2, we identify and compare different factors that can influence an irregular satellite group in the long-term and define our model. Then we perform 1000 Myr N-body simulations for the Himalia family and analyse the results in Section 3. The effects of the secular resonances are examined in Section 4. Collisional evolution within the family is considered in Section 5. In Section 6, we turn our attention to the Phoebe family. Finally, in Section 7 we summarise our results.

2. Model determination

For an irregular satellite group, various types of perturbations affect its evolution, as reviewed in Section 1. Among them are (i) the solar perturbation, (ii) the non-spherical shape of the central planet in which the dominant ellipsoid term is J_2, (iii) the Galilean satellites, (iv) the other giant planets and (v) a massive satellite in

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[1] See http://dtm.carnegiescience.edu/news/long-lost-moon-jupiter-found.

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