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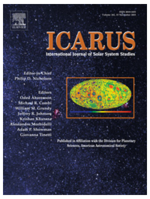

Ring formation around giant planets by tidal disruption of a single passing large Kuiper belt object

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ABSTRACT

The origin of rings around giant planets remains elusive. Saturn's rings are massive and made of 90–95% of water ice with a mass of $\sim 10^{19}$ kg. In contrast, the much less massive rings of Uranus and Neptune are dark and likely to have higher rock fraction. According to the so-called "Nice model", at the time of the Late Heavy Bombardment, giant planets could have experienced a significant number of close encounters with bodies scattered from the primordial Kuiper Belt. This belt could have been massive in the past and may have contained a larger number of big objects ($M_{\rm body} = 10^{22}$ kg) than what is currently observed in the Kuiper Belt. Here we investigate, for the first time, the tidal disruption of a passing object, including the subsequent formation of planetary rings. First, we perform SPH simulations of the tidal destruction of big differentiated objects ($M_{\rm body} = 10^{21}$ and 10^{23} kg) that experience close encounters with Saturn or Uranus. We find that about 0.1–10% of the mass of the passing body is gravitationally captured around the planet. However, these fragments are initially big chunks and have highly eccentric orbits around the planet. In order to see their long-term evolution, we perform N-body simulations including the planet's oblateness up to J_4 starting with data obtained from the SPH simulations. Our N-body simulations show that the chunks are tidally destroyed during their next several orbits and become collections of smaller particles. Their individual orbits then start to precess incoherently around the planet's equator, which enhances their encounter velocities on longer-term evolution, resulting in more destructive impacts. These collisions would damp their eccentricities resulting in a progressive collapse of the debris cloud into a thin equatorial and low-eccentricity ring. These high energy impacts are expected to be catastrophic enough to produce small particles. Our numerical results also show that the mass of formed rings is large enough to explain current rings including inner regular satellites around Saturn and Uranus. In the case of Uranus, a body can go deeper inside the planet's Roche limit resulting in a more efficient capture of rocky material compared to Saturn's case in which mostly ice is captured. Thus, our results can naturally explain the compositional difference between the rings of Saturn, Uranus and Neptune.

1. Introduction

The origin of planetary rings is still a debated question. Saturn's main rings are unique as they are made of 90–95% water ice (Cuzzi and Estrada, 1998; Nicholson et al., 2005; Poulet et al., 2003) with a mass of $\sim 10^{19}$ kg (Charnoz, 2009; Esposito et al., 1983). In contrast, the much less massive rings of Uranus and Neptune are dark and likely to have a higher rock content (Tiscareno et al., 2013) than Saturn's rings. Whereas dusty Saturn's E and G rings are likely to be formed via the destruction or surface erosion of the nearby present satellites (Burns et al., 2001; Colwell, 1994; Esposito, 1993; Hedman et al., 2007; Porco, 2006), Saturn's main rings cannot result from the same process as there is no obvious source of material to feed them today. Note, however, that a recent study shows that the origin of Saturn's F ring and Uranian ϵ ring could be a natural consequence of the collisional destruction between small satellites just outside the main rings (Hyodo and Ohtsuki, 2015) that is formed by the spreading of ancient rings (Charnoz et al., 2010; Crida and Charnoz, 2012; Hyodo et al., 2015).

Several ring formation scenarios have been proposed for massive rings, like those of Saturn: (1) primordial satellite collisional destruction by passing comet (Harris, 1984; Pollack, 1975; Pollack et al., 1973), (2) tidal destruction of a primordial satellite at the Roche Limit after inward migration due to tidal interaction with

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the circum-Saturn gas disk (Canup, 2010) and (3) tidal disruption of passing objects (Dones, 1991). The inward migration of a primordial Titan-sized satellite and the removal of only its pure icy mantle could beautifully explain the silicate deficit of Saturn's rings. However, it requires some fine-tuning of the timing of the event (likely at the end of the evolution of the circum-Saturn circumplanetary disk) so that the disk is still massive enough to allow inward migration of the satellite, but light enough in order to prevent the rapid infall of debris into the planet because of gas drag. In addition, it would be difficult to directly form centimetre- to meter-sized particles that are currently seen in Saturn's main rings by tidal destruction alone. Canup (2010) proposes collision between fragments can form small particles, but detailed studies are still required. Tidal disruption of a passing differentiated object could also potentially explain the high ice/rock fraction by capturing only the icy mantle of the incoming body and letting the remnant core escape from Saturn's gravity field. However, so far this scenario has scarcely been studied and only used a simplified analytical model of a homogeneous body (Charnoz, 2009; Dones, 1991). Thus, direct numerical simulation of the tidal splitting of a big differentiated body is necessary now to investigate this scenario in detail. In addition, even though some mass capturing occurs, the fragments are expected to have highly eccentric orbits around the planet and the long-term evolution of such fragments remains unclear, in particular by which process a ring of cm-sized particles forms. In this work, we investigate, for the first time, the details of tidal disruption of a passing large differentiated object and the long-term fate of its debris by using direct simulations.

Such an event may have occurred, with the most probability, either during the phase of planet formation where the giant-planets' cores are expected to scatter the neighbouring planetesimals efficiently, or later during the Late Heavy Bombardment (LHB). The well known "Nice model" explains not only the Lunar cataclysm or today's orbital architecture of giant planets (Gomes et al., 2005; Tsiganis et al., 2005), but also the implantation of Jupiter's Trojan asteroids as well as the irregular satellites around giant planets (Morbidelli et al., 2005; Nesvorný et al., 2007). During this instability phase, giant planets could have experienced a significant number of close encounters with bodies scattered from the primordial Kuiper Belt that surrounded the giant planets. This belt could have been significantly massive and may have contained a larger number of big objects than what is currently observed in the Kuiper Belt (Levison, 2008; Nesvorný and Vokrouhlicky, 2016). Charnoz (2009) estimated an encounter rate of the primordial Kuiper Belt Objects (KBOs) with the giant planets during the LHB and investigated the captured mass around giant planets using a simplified analytical model assuming homogeneous small bodies like comets. The flux of such undifferentiated small bodies is enormous and isotropic, and thus the average angular momentum of captured mass should be almost zero, resulting in no contribution to the formation of the rings. However, only a single tidal disruption of a large object that deviates from the average could decide the story, and such large objects could be expected to be differentiated like Pluto.

Here we use two different direct simulations and investigate successive processes from tidal destruction of a passing object to the possible formation of planetary rings (Fig. 1). Our work will address (1) the captured mass as well as its ice/silicate fraction due to the tidal disruption of differentiated bodies at different planets, (2) the orbits of the captured fragments, and (3) the long-term orbital and collisional evolution of the captured fragments. To do so, we first investigate the physics of tidal disruption of a differentiated object that is initially on a hyperbolic orbit about Saturn or Uranus, and calculate how much mass is gravitationally captured around these planets by using smooth particle hydrodynamics (SPH) simulations. Then we perform direct N-body simulations in order to see the longer-term evolution of such captured fragments around Saturn, including the effect of oblateness potential of the planet. In Section 2, in light of our newly derived semi-analytical models that take into account spin and self-gravity of a differentiated object, we briefly review a previous analytical formula of the capture efficiency of tidal disruption. In Section 3, we explain our SPH method and model. In Section 4, we show the results from SPH simulations and discuss the mass capture efficiency as well as orbits of captured fragments. In Section 5, using the data obtained from SPH simulations as initial conditions, we perform N-body simulations of subsequent long-term evolution of captured fragments. Then, using results of the simulations as well as analytic estimation, we discuss the fate of the captured fragments. Section 6 summarises our results and discusses the origin of planetary rings.

2. Physical argument

2.1. Previous analytical model

Dones (1991) derived the mass that is captured on bound orbits around a planet during tidal disruption at close encounters. Assuming uniform energy distribution across the body, the amplitude of energy variation is,

$$\Delta E = \frac{GM_0}{q} \times \frac{R}{q} \tag{1}$$

where G, M_0, q and R are the gravitational constant, the mass of the planet, pericenter distance and radius of the body, respectively. The mass fraction that is captured with $E < E_{\rm sta}$ is obtained assuming energy distribution is uniform between $-0.9\Delta E + 0.5v_{\rm inf}^2$ and $0.9\Delta E + 0.5v_{\rm inf}^2$ as

$$\eta = \frac{M_{\rm bound}}{M_{\rm object}} = \frac{0.9\Delta E + E_{\rm sta} - 0.5v_{\rm inf}^2}{1.8\Delta E} \tag{2}$$

where $v_{\rm inf}$ is the velocity of the object at infinity and we take $E_{\rm sta} = -GM_0/R_{\rm Hill}$ where $R_{\rm Hill}$ is the planet's Hill radius. Eq. (2) (hereafter we call this Dones' formula) has been used to estimate mass captured around giant planets in Charnoz (2009). However, it has not been well established if this formula is applicable in any case.

2.2. Semi-analytical model: effects of spin and self-gravity

The above Dones' formula considers only ballistic orbits for all constituent particles of the body. However, the spin state of the body as well as the body's self-gravity could play an important role in the capture efficiency, especially when the body is massive. Here, we consider a spherical body located at pericenter during its close encounter with Saturn (mass $M_{\rm S}$). We three-dimensionally divide a cubic box that contains the body into N^3 cells by using a cartesian grid, with $N = 100$ along 1-dimension. The box width is 1.1 times the diameter of the spherical body and the object's center of mass is located at the center of the box. Each cell i within the body has its mass m_i, position r_i and velocity v_i relative to Saturn's center. Then, we calculate the energy $E_i = \frac{1}{2}m_i v_i^2 - \frac{Gm_iM_{\rm S}}{r_i}$ of each cell, and assume any cell that satisfies $E_i < 0$ is gravitationally captured around Saturn. The body is a differentiated spherical body of mass $M_{\rm body} = 10^{21}$ kg or 10^{23} kg and the mass fraction of the core is 0.5. The densities of the core and the mantle are 3000 kg/m^3 and 900 kg/m^3, respectively. Using the above procedure, we calculate the capture efficiency at different pericenter distances ranging from 25 × 10^3 km to 100 × 10^3 km. Fig. 2 shows an example of our modelled passing body with pericenter distance 70 × 10^3 km and velocity at infinity $v_{\rm inf} = 3$ km/s.

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