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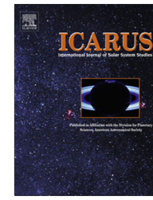

How Janus' orbital swap affects the edge of Saturn's A ring?

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ABSTRACT

We present a study of the behavior of Saturn's A ring outer edge, using images and occultation data obtained by the Cassini spacecraft over a period of 8 years from 2006 to 2014. More than 5000 images and 170 occultations of the A ring outer edge are analyzed. Our fits confirm the expected response to the Janus 7:6 Inner Lindblad resonance (ILR) between 2006 and 2010, when Janus was on the inner leg of its regular orbit swap with Epimetheus. During this period, the edge exhibits a regular 7-lobed pattern with an amplitude of 12.8 km and one minimum aligned with the orbital longitude of Janus, as has been found by previous investigators. However, between 2010 and 2014, the Janus/Epimetheus orbit swap moves the Janus 7:6 LR away from the A ring outer edge, and the 7-lobed pattern disappears. In addition to several smaller-amplitudes modes, indeed, we found a variety of pattern speeds with different azimuthal wave numbers, and many of them may arise from resonant cavities between the ILR and the ring edge; also we found some other signatures consistent with tesseral resonances that could be associated with inhomogeneities in Saturn's gravity field. Moreover, these signatures do not have a fixed pattern speed. We present an analysis of these data and suggest a possible dynamical model for the behavior of the A ring's outer edge after 2010.

1. Introduction

The saturnian satellite system is endowed with an unusually large number of orbital resonances (Peale, 1986). Among these are several small satellites in corotation resonances like Anthe, Methone and Aegaeon (El Moutamid et al., 2014), and Trojan satellites that are in 1:1 resonance with the medium-sized moons Tethys and Dione (Murray et al., 2005; Robutel et al., 2012), as well as the pair of co-orbital satellites, Janus and Epimetheus. The latter are unique in the Solar System, and represent an extreme form of 1:1 resonance where the two bodies are similar in mass. Both objects share a common mean orbit, with a period of $\sim$16.7 h, but at any given instant their semimajor axes differ by $\sim$48 km (see Fig. 1) and their mean motions by $0.25^{\circ}\ \mathrm{day}^{-1}$. Their mean radii are 89.2 ± 0.8 and 58.2 ± 1.2 km, respectively (Thomas et al., 2013).

Every four years, the two moons approach one another closely, exchange angular momentum via their mutual gravitational attraction and then recede again, having switched their relative orbital radii (Murray and Dermott, 1999). At each orbital exchange, Janus' semimajor axis shifts inwards or outwards by $\sim$21 km while that of Epimetheus shifts in the opposite direction by $\sim$76 km, reflecting their mass ratio of 3.6. Their overall configuration repeats itself every 8.0 years. Their relative motion is analogous to the horseshoe libration of a test particle in the restricted three body problem around the Lagrange points L_4 and L_5. In a reference frame rotating at their long-term average mean motion, Janus moves in a small, bean-shaped orbit, while the less massive Epimetheus moves in a more elongated horseshoe-type orbit. The reader is referred to Yoder et al. (1983) or Murray and Dermott (1999) for a more detailed description of the dynamics involved, supported by numerical integrations. The relative libration amplitudes of the two moons combined with their observed libration period make it possible to determine their individual masses quite accurately, despite their relatively small sizes (Yoder et al., 1989; Nicholson et al., 1992).

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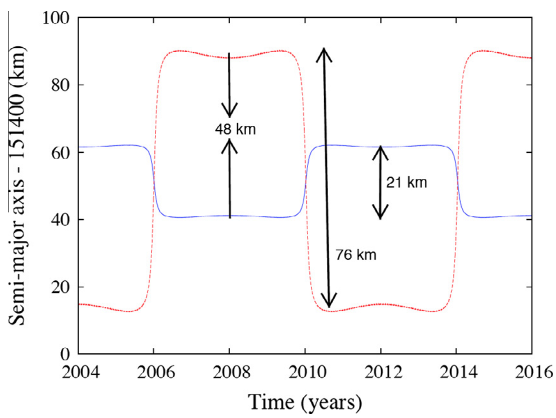

Fig. 1. This figure displays the orbital semimajor axes – computed from the epicyclic theory (Renner and Sicardy, 2006) – of Saturn's small moons Janus (blue) and Epimetheus (red) over 12 years. The two moons occupy very nearly the same mean orbit and swap orbital positions relative to Saturn once every four years, with Janus moving by ±21 km and Epimetheus by ±76 km. Their mean orbital separation is ~48 km, less than the physical radius of either body. The long-term mean semimajor axis is 151451.6 km (Jacobson et al., 2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Current estimates for the mean orbital elements, masses and radii of the coorbital moons are based on observations by the *Cassini* spacecraft, combined with earlier *Voyager* and ground-based measurements (Jacobson et al., 2008). In Fig. 1 we illustrate the predicted variations in both satellites' semimajor axes over a period of 12 years, based on a numerical integration with initial conditions obtained for epoch 2004 from the JPL Horizons on-line database. This diagram illustrates two aspects of their motion that should be kept in mind: (1) neither satellite's semimajor axis is precisely constant even when the two bodies are far apart, and (2) the actual orbital exchanges are not instantaneous, but occur over a period of a few months, or quite slowly relative to orbital timescales.

Many of Saturn's satellites generate observable features within the planet's extensive ring system, either in the form of spiral density waves driven at mean motion resonances or at the sharp outer edges of several rings (Tiscareno et al., 2007; Colwell et al., 2009). In addition to driving several strong density waves, as well as numerous weaker waves (Tiscareno et al., 2006), the coorbital satellites appear to control the location and shape of the outer edge of the A ring. Based on a study of Voyager imaging and occultation data, Porco et al. (1984) concluded not only that this edge is located within a few km of the Janus/Epimetheus 7:6 ILR, but that it exhibits a substantial 7-lobed radial perturbation that rotates around the planet at the same rate as the satellites' average mean motion. The situation appeared to be quite analogous to the control of the outer edge of the B ring by the Mimas 2:1 ILR, also studied by Porco et al. (1984). But the limited quantity of high-resolution Voyager data, combined with the fact that the Voyager 1 and 2 encounters were separated by only 9 months, meant that it was not possible to examine the effect of the coorbital swap on the ring edge.[1]

The Cassini mission, launched in 1997, arrived at the Saturn system in July 2004 and the spacecraft has been taking data continuously for over 10 years. In this time, it has been able to observe the effects of the coorbital satellites' orbital exchanges in January 2006, January 2010 and in January 2014. During this period, over 30 sequences of images covering most of the circumference of the A ring edge have been obtained, to study both the F ring and the outer edge of the A ring, and over 150 stellar and radio occultation experiments have been performed. This dataset provides the first opportunity to study the behavior of the A ring edge throughout the complete 8-year coorbital cycle, including both configurations of the Janus–Epimetheus system.

At the time of Cassini's orbital insertion, Janus was the outer satellite, similar to the situation in 1980/81 when the Voyager flybys occurred. At this time, Janus' 7:6 ILR was located at a radius of 136,785 km, approximately 15 km exterior to the mean radius of the A ring's outer edge. The Epimetheus 7:6 resonance was located ~28 km interior to the ring edge. In January 2006, the first orbital swap occurred and Janus moved to the inner position, with its ILR now located at 136,766 km, only ~4 km interior to the ring edge. Four years later, in January 2010, Janus again moved to the outer position and its ILR moved away from the ring edge. Fig. 2 illustrates the changing geometry of the satellites' orbits and the corresponding locations of the two 7:6 Lindblad resonances.

Spitale and Porco (2009) analyzed a series of 24 Cassini imaging sequences of the outer A ring, obtained between May 2005 and February 2009, in order to characterize the shape of the outer edge. Starting about 8 months after the co-orbital swap in January 2006, they found a strong $m = 7$ radial perturbation rotating at a rate of $518.354 \pm 0.001^\circ\ \mathrm{day}^{-1}$ which closely matched the mean motion of Janus at that time. The mean radial position of the edge was found to be 136,769 km and the amplitude of the $m = 7$ variation was 14.4 ± 0.4 km. One minimum of this pattern was approximately aligned with Janus, as expected for resonant forcing. Prior to January 2006, however, the Cassini mosaics showed a more irregular and disorganized appearance, with no clear periodicity and radial amplitudes as small as 4–5 km. Spitale and Porco (2009) ascribed this to a period of readjustment associated with the change in location of the 7:6 resonance in January 2006. They also noted that a similar readjustment might account for the smaller amplitude (6.7 ± 1.5 km) and slightly lower pattern speed obtained by Porco et al. (1984) from Voyager observations, most of which were made only 5 months prior to the January 1982 coorbital swap.

This paper is organized as following: In Section 2 we present some theoretical background useful for our data analysis; the data are described in Section 3, our main results are presented in Section 4, and finally, in Section 5 we propose some possible explanations and interpret our results.

2. Theoretical background

We begin by assuming that the ring edge is perturbed by resonant interactions, specifically by an inner or outer Lindblad resonance (ILR or OLR) and/or normal modes. Following the notation of Nicholson et al. (2014a,b), for each such resonance or mode the radius of the edge may be described by

$$r(\lambda, t) = a[1 - e\cos(m[\lambda - \Omega_p(t - t_0) - \delta_m])], \quad (1)$$

where r and λ are the orbital radius and inertial longitude, respectively, of a ring particle at a given time t, a and e are the semi-major axis and orbital eccentricity of streamlines at the ring edge, m is an integer describing the resonance, t_0 is a reference epoch (assumed here to be J2000), and Ω_p is the appropriate pattern speed. The phase angle δ_m is the longitude of one of the m minima at time $t = t_0$. The pattern speed is given by

$$m\Omega_p = (m - 1)n + \dot{\varpi}, \quad (2)$$

where n is the ring particle's keplerian mean motion and $\dot{\varpi}$ is the local apsidal precession rate, as determined by the planet's zonal gravity harmonics. For $m > 0$ this equation describes either an ILR

[1] The Voyager encounters occurred in November 1980 and August 1981, while the nearest orbital swaps occurred in January 1978 and January 1982. At the time of both encounters, Janus was the outer satellite.