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What confines the rings of Saturn?

Radwan Tajeddine (1), Philip D. Nicholson (2), Pierre-Yves Longaretti (3,4), Maryame El Moutamid (1), Joseph A. Burns (5)

(1) Center for Astrophysics and Planetary Science, Cornell University, Ithaca, NY 14853, USA (tajeddine@astro.cornell.edu)
(2) Department of Astronomy, Cornell University, Ithaca, NY 14853, USA
(3) Université Grenoble Alpes (UGA), France
(4) CNRS/INSU – Institut de Planétologie et d'Astrophysique de Grenoble (IPAG), UMR 5274, France
(5) College of Engineering, Cornell University, Ithaca, NY 14853, USA

Abstract

The viscous spreading of planetary rings is believed to be counteracted by satellite torques, either through an individual resonance or through overlapping resonances (when the satellite is close to the ring edge). For the A ring of Saturn, it has been commonly believed that the satellite Janus alone can prevent the ring from spreading via its 7:6 Lindblad resonance. We discuss this common misconception and show that, in reality, the A ring is confined by the contributions from the group of satellites Pan, Atlas, Prometheus, Pandora, Janus, Epimetheus, and Mimas, whose resonances gradually decrease the angular momentum flux (AMF) transported outward through the ring via density and bending waves. We further argue that this decrease in angular momentum flux occurs through the mechanism of 'flux reversal'.

Furthermore, we use the magnitude of the satellites' resonance torques to estimate the effective viscosity profile across the A ring, showing that it decreases from ~50 $cm^2\ s^{-1}$ at the inner edge to less than ~11 $cm^2\ s^{-1}$ at the outer edge. The gradual estimated decrease of the angular momentum flux and effective viscosity are roughly consistent with results obtained by balancing the shepherding torques from Pan and Daphnis with the viscous torque at the edges of the Encke and Keeler gaps, as well as the edge of the A ring.

1. Introduction

The confinement of the rings of Saturn was for a long time an unsolved matter. The satellite Atlas might be expected to play a major role in confining the A ring through the shepherding mechanism since it is the closest satellite to its outer edge. However, Voyager imaging and occultation data showed that the edge of the A ring appears to be in a 7:6 Inner Lindblad Resonance (ILR) with the more massive satellite Janus [1]. Thus, it has been generally believed that the torque exerted by this resonance confines the entire A ring. On the other hand, the B ring's outer edge has been clearly shown to be controlled by the 2:1 ILR with Mimas [1, 2, 3]. This resonance, the strongest anywhere in Saturn's rings, is believed to prevent the B ring from spreading outwards and also to be responsible indirectly for the existence of the Cassini division [4].

In this work, we study the effect of resonance torques due to multiple satellites on the confinement of the A and B rings of Saturn, as well as on the orbital evolution of the satellites. We also estimate the viscosity in the A and B rings by balancing satellite and ring torques. See [5] for more details.

2. Satellite resonance torques

At a Lindblad (Vertical) resonance, perturbations from the satellite excite the ring particles' eccentricities (inclinations). As the ring particles oscillate radially (vertically), their perturbations are transferred via self-gravity to the neighboring ring particles closer to the satellite and farther from the resonance location. As a result, a trailing spiral density wave is created, which propagates radially towards (away from) the perturbing satellite across the ring for a Lindblad (Vertical) resonance. Subsequently, the density wave is damped by collisions between the ring particles as it propagates through the ring causing these particles to lose (for a satellite outside the rings) or gain (for a satellite inside the rings) angular momentum and drift back towards the resonant location.

If the resonant torque from a satellite's Inner Lindblad Resonance (ILR) is stronger than the local viscous torque in the ring, we expect that a gap with a sharp inner edge should open at the resonance location. However, even if the resonant torque is smaller and no gap forms, then the satellite resonance will still exert a negative torque on the ring, via a density wave, which will reduce the outward flux of angular momentum through the rings. In this scenario, the Janus 7:6 ILR is responsible only for removing the flux that has 'survived' all of the previous similar satellite resonances. To quantify this picture, we calculate the variation of the AMF across the A ring taking into account *all* of the first and second order Lindblad resonances due to the satellites Pan, Atlas, Prometheus, Pandora, Janus, Epimetheus, and Mimas, as well as the strongest (i.e., second-order) vertical resonances due to Mimas, counting a total of 397 satellite resonances present in the A ring.

Figure 1 shows the resulting upper and lower limits on the AMF and the inferred viscosity as a function of radius across the A ring. As might be expected, this plot shows a gradual outward decrease in the AMF (Fig. 1a) through the ring as we encounter successive resonances with the external satellites. On the other hand, calculations of satellite resonance torques on the B ring show that the Mimas 2:1 ILR alone can confine this ring.

3. Discussion and Conclusion

A careful accounting of all known satellite resonances in the A and B rings reveals that, in the A ring, the radial confinement of the ring against viscous spreading is distributed over many resonances. As a result, the AMF is expected to decrease outwards across the ring. For the B ring, on the other hand, almost all of the work is done by the Mimas 2:1 ILR located at the outer edge. By equating the computed AMF with that expected to be transported by collisional interactions within the rings, we derive a radial profile of transport viscosity across both rings. In the A ring this is found to be roughly consistent with viscosities inferred from torque balancing at the Encke and Keeler gaps, but no such direct test is possible for the B ring. We speculate that the observed steep decrease in AMF in the trans-Encke region of the A ring may be due to "flux reversal" associated with the disturbed streamlines produced by the large concentration of density waves driven by satellite resonances in this region, which translates into a decrease in effective viscosity.

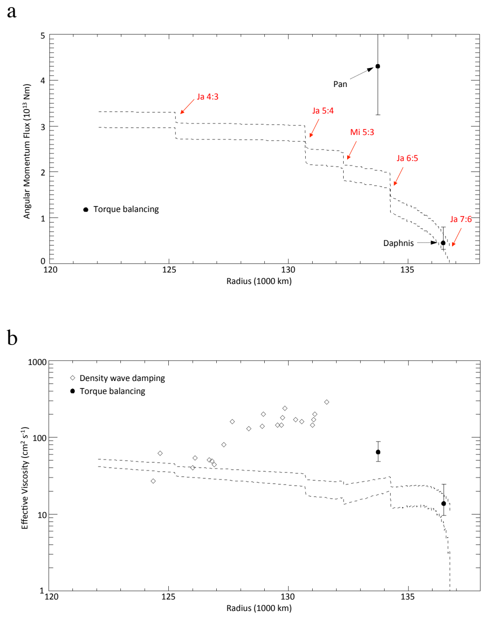

Figure 1: Upper and lower limit estimates (dashed lines) of (a) the AMF and (b) the effective viscosity (on a log scale) in the A ring as a function of radius, taking into account all the first and second order Lindblad resonances from the satellites and the 5:3 bending wave from Mimas.

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