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Random walk migration of moonlets in Saturn's rings

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Abstract

Propeller features discovered in Saturn's rings betray the presence of moonlets, about 200 meters in size. These moonlets interact gravitationally with the rings, and therefore, their orbit should evolve with time. Last year, we presented the calculation of their migration rate, assuming the rings are a smooth, laminar particle disc. Actually, the A-ring is marginally gravitationally unstable, and we expect clumps to form and disappear continuously in it. These clumps exert torques on a moonlet, giving rise under some conditions to a varying migration rate, and a random walk of the moonlet. The amplitude and the timescales we find are compatible with the observations.

1. Introduction

The Cassini spacecraft has been orbiting the Saturnian ring system since 2004, offering the possibility to observe the coupled evolution of the ring system and the satellites. Due to short orbital timescales (1 year is equivalent to about 700 orbits of the A ring) it may be possible to observe the exchange of angular momentum between the two systems. One of the most striking discoveries of the Cassini spacecraft is the observation of propeller shaped features in the A ring (located between 122 000 and 137 000 km from Saturn), with longitudinal extent about 3 km [8, 9, 7]. They are most probably caused by the presence of moonlets about hundred meters in size, embedded in the ring, and scattering ring particles [6]. As they are embedded in the ring, these small bodies should exchange angular momentum with the ring, and migrate [2]. This migration could be detected by Cassini observations through the cumulative lag, or advance with time t of the orbital longitude ϕ induced by a small variation of the semi-major axis and the angular velocity Ω ($\delta\phi = \delta\Omega \times \delta t$), offering for the first time the possibility to confront directly the planetary migration theory with observations, and to give insights and constrains on the physical properties of the rings and of the moonlets.

2. Migration of the propellers in a particle ring

2.1. Non-self-gravitating ring

We compute (numerically and analytically) the interaction between a moonlet and a ring test particle. In this analysis, the gravity of the other ring particles is neglected, and there is no pressure effect (in contrast to the standard theory of type I migration in a gaseous protoplanetary disc). This leads to the torque exerted on the moonlet by an initially unperturbed, homogeneous ring. We find that the migration rate of a moonlet of mass m located at a distance r_m from the centre of Saturn should be

$$\frac{dr_m}{dt} = -35.6\,\frac{\Sigma r_m^{\,2}}{M_{\rm Saturn}}\left(\frac{m}{M_{\rm Saturn}}\right)^{1/3} r_m\Omega\ ,$$

where Σ is the surface density of the ring and Ω the orbital angular velocity. This gives typically ~ -1 m yr^{-1}, inwards. This is not compatible with observations, that show migration rates two orders of magnitude larger, in both directions inwards and outwards.

2.2. Self-gravitating ring

Saturn's A ring is marginally gravitationally stable [3]. The Toomre Q parameter, which is a measure of the importance of self-gravity, is expected to be of the order of $2 \sim 7$, indicating that the ring particles' mutual gravity is indeed a strong effect. It leads to the regular formation and dispersion of gravity wakes, which are local density enhancements elongated in parallel directions by the Keplerian shear. Those over-densities give rise to stochastic forces which act on the embedded moonlet.

Using N-body numerical simulations, we have computed the force felt by a test particle on a fixed orbit in a clumpy disc for various surface densities of the disc and sizes of the disc particles. We find that a moonlet would feel a torque strongly varying with time. We measure the amplitude and the correlation time of the stochastic forces in all simulations, from which the diffusion coefficient D can be derived [4]. The change in semi major axis a due to the effect of stochastic forces with diffusion coefficient D after time t is then given by [4] :

$$\Delta a = \frac{2}{\Omega}\sqrt{Dt}\,.$$

In our simulations, we find $10^{-17}\mathrm{m}^2\,\mathrm{s}^{-3} < D < 10^{-11}\mathrm{m}^2\,\mathrm{s}^{-3}$, allowing for a migration Δa between 2.7 and $270\sqrt{t/(1\ \mathrm{year})}$ metres, depending on the disc parameters. This range embraces the observations, so that this mechanism could well be an explanation for the observed migration of the propellers in Saturn's rings.

3. Conclusion

In this paper [1], we have shown that the interaction of a moonlet with a homogeneous, non self-gravitating particle disc can't account for the observed migration of the propellers. However, taking the ring's self-gravity into account, one finds that the gravitational wakes exert a random force on the moonlets, which leads to their stochastic migration ; this migration has variable rate and direction. As the rate and direction of the observed migration change with time as well (with rates compatible with our model), it seems likely to us that the moonlets are undergoing such a random walk migration.

The dependence of the migration rate on the ring's parameters offers an exciting possibility to constrain the nature of the ring particles and the physical processes occurring in the rings by measuring the migration of the moonlets. Bringing together a more detailed version of our model [5] with future, more numerous observations of propellers, should therefore be very helpful to understand Saturn's rings.

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