Formation of a Propeller Structure by a Moonlet in a Dense Planetary Ring

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A moonlet embedded in a planetary ring tends to open a gap, such as Keeler or Encke gap, due to gravitational scattering [1]. Conversely, viscous diffusion of ring particles tends to close a gap. If a moonlet is sufficiently large, it will form a fully circular gap, whereas a small moonlet will form only a partial gap that consists of two azimuthally aligned lobes shaped like a propeller. Using the viscous fluid model, the formation of propellers by small moonlets was predicted. The Cassini spacecraft discovered propellers in Saturn's A ring [2,3].

The optical depth of the A ring is as high as 0.3–0.5, while that of the B ring is larger than unity. Distinct and large gravitational wakes form in rings with large optical depths [4]. Such large gravitational wakes can alter the structures around an embedded moonlet. We investigated the condition for propeller formation in a dense ring in which gravitational wakes are prevalent.

Figure 1 shows snapshots of the low and high surface density models [5]. In the low surface density model, a propeller-shaped feature is clearly visible in the weak gravitational wakes. The surface density decreases considerably in the two lobes downstream of the moonlet. They are aligned in the orbital direction and are symmetric about the moonlet. In the high surface density model, strong wake structures due to gravitational instability formed but no propeller structures are observed.

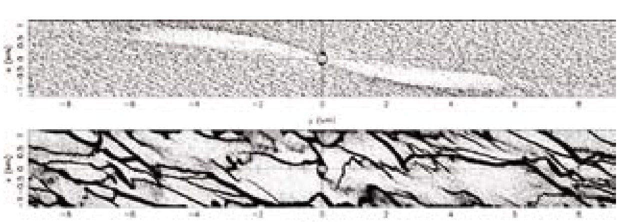

Figure 1: Snapshots of numerical simulations of low and high surface density models.

The numerical simulation results indicate that propeller formation depends on the ring surface density. The clumps in gravitational wakes typically have a mass of ~ $\Sigma\lambda^2$, where Σ is the surface density and λ is the critical wavelength of the gravitational instability. If the clump mass is greater than the moonlet mass, the gravitational wakes may not be affected by gravitational scattering due to the moonlet. Accordingly we derived the critical moonlet size that depends on the surface density around the moonlet.

We performed 25 simulations with different ring surface densities and moonlet radii so as to confirm the condition. As shown in Figure 2, we confirmed that a propeller-shaped structure is clearly observed when this condition is satisfied. If this condition is not satisfied, no distinct steady propeller structure is observed although the ring particles are affected by the moonlet to some extent.

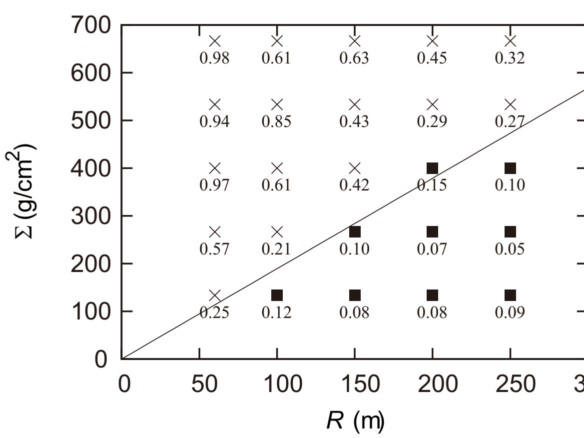

Figure 2: Condition for propeller formation in the R-Σ plane. Filled squares denote models in which clear propellers form and crosses denote models in which no propellers form. We show the ratio of the time-averaged surface density in the propeller region to the initial surface density $\bar{\Sigma}/\Sigma_0$ at each point. The solid line indicates the condition for propeller formation.

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References

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