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Dynamics and kinetics of narrow dusty ringlets

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Abstract

Several narrow dusty rings have been discovered in the Saturn system, such as the F ring, ringlets in the C Ring, the Cassini division, and the Encke Gap [1] [2]. The kinky and clumpy structures in the F ring are considered as the result of embedded moonlets which are dynamically dominated by shepherding moons [3]. Similar features are found in Encke ringlets which we hypothesize to be associated with embedded moonlets [4] [5]. On the other hand, these ringlets are believed to be composed of micron-sized particles [6], which are strongly perturbed by solar radiation pressure and their lifetime is restricted. Therefore mechanisms must be at work to replenish these ringlets. We develop a model for the kinetic balance of dust production, dynamical evolution, and sinks by assuming that dust is freed and annihilated by moonlets embedded in the ringlet. The dynamics of particles ejected from these putative moonlets is explored and the contribution of impact-ejecta to the ringlet is estimated [7] [8]. We found that the optical depth sustained by embedded moonlets is too low (orders of magnitude), indicating that other sources or processes should be responsible for supporting the Encke ringlet.

1. Introduction

The source of dusty ringlets is not clear so far. These ringlets are believed to be composed of micron-sized particles [6], the lifetime is restricted due to the perturbing forces.

The central Encke ringlet shares the orbit with the moon, Pan. This ringlet is kinky and clumpy (fig. 1), which may be associated with embedded moonlets. We develop a model for the kinetic balance of dust production, dynamical evolution, and sinks by assuming that dust is freed and annihilated by moonlets embedded in the ringlet. The model is applied to Encke central ringlet.

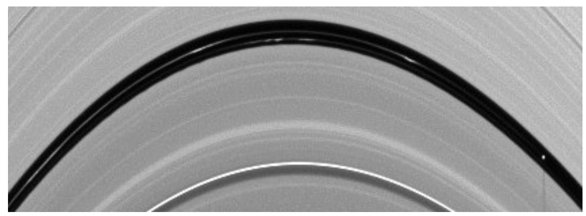

Fig. 1: Clumps in the central and inner Encke ringlet. Pan is on the right. Credit: NASA/JPL/Space Science Institute

2. Model

We assume that there are 100 moonlets with diameter 250 meter embedded in the Encke central ringlet (which corresponds to an optical depth of $\sim 10^{-7}$). Dust particles are 'born' on the surface of these moonlets due to impact of micrometeoroids, 'evolve' under gravity of Saturn, Pan, planetary oblateness and radiation pressure, and 'die' due to collision with moonlets.

2.1. Dust production rate

Following Spahn et al. 2006 and Koschny and Grün 2001, the mass flux of projectiles (F_{imp}) at the location of the Encke ringlet is $\sim 1.16 \times 10^{-16}\,\mathrm{g\,cm^{-2}\,s^{-1}}$, and the ejecta yield is ~ 22000. Note that there is an order of magnitude uncertainty on F_{imp} [7]. Considering particles in the size range of $10-100\mu\mathrm{m}$, using equation (4) in Spahn et al. 2006, the number of particles generated per unit time from the surface of all moonlets is

$$N^{+} = 7.5 \times 10^{6} s^{-1} \quad (1)$$

2.2. Simulation of the dust evolution

Particles are ejected from the Hill sphere of moonlets with zero velocity. The location of moonlets is assumed to be randomly distributed in the central Encke ringlet and they are in horseshoe orbits with Pan.

In the simulations, gravity of Saturn and Pan is considered, as well as the oblateness of Saturn (J2, J4, J6), solar radiation pressure, and includes the effect of planetary shadow. Lorentz force is ignored due to it's small contribution to the precession rate (compared to the contribution from oblateness).

Solar radiation pressure sets a lower limit for size of particles. For particles smaller than $8.7\mu\mathrm{m}$, their eccentricity increases rapidly to 1.2×10^{-3} and they collide with the gap edge in several orbital periods. In our simulations the size of test particles is always larger than $10\mu\mathrm{m}$.

Loss mechanisms for dust particles include collision with Pan, the gap edges, or moonlets. Most particles are in horseshoe orbits with Pan, so they do not collide with that moon. Moreover, since there are no ways to increase the eccentricity of dust particles other than radiation pressure, these particles are safe from collision with the gap edges. Therefore, in our simulations all particles collide effectively with moonlets.

These simulations are carried out with the RADAU integrator [9]. The lifetime of several tens of thousands of particles have been calculated.

3. Result

The total number of particles generated by impact-ejecta mechanism after reaching a steady state is

$$N = N^{+} t_{life} + N_0 \quad (2)$$

where N_0 is the number of particles in the beginning and is assumed to be zero, t_{life} is the typical lifetime of dust particles. From simulation, the typical lifetime is about 20 years. Combine with N^{+} from eq. (1), the number of particles at steady state is 4.7×10^{15}, or in optical depth

$$\tau = \frac{\sigma_{eff} N}{A} = 6 \times 10^{-7} \quad (3)$$

where $\sigma_{eff}(\sim 37\mu\mathrm{m})$ is effective radius of dust in the range from $10-100\mu\mathrm{m}$, and A is the area of the Encke central ringlet.

4. Discussion

The value of optical depth is about 5 order of magnitude smaller than observation ($0.016 - 0.21$, [2]). Increasing the total cross section of moonlets can increase the mass production rate, but this will also increase the killing rate proportionally. Therefore, impact ejecta from the surfaces of putative embedded moonlets is not likely a sufficient source. Other sources or processes must be taken into account, such as mutual collision of moonlets.

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