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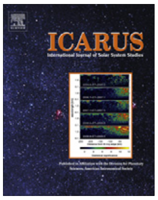

Of horseshoes and heliotropes: Dynamics of dust in the Encke Gap

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ABSTRACT

The Encke Gap is a 320-km-wide opening in Saturn's outer A ring that contains the orbit of the small moon Pan and an array of dusty features composed of particles less than 100 μm across. In particular, there are three narrow ringlets in this region that are not longitudinally homogeneous, but instead contain series of bright clumps. Using images obtained by the Cassini spacecraft, we track the motions of these clumps and demonstrate that they do not follow the predicted trajectories of isolated ring particles moving under the influence of Saturn's and Pan's gravitational fields. We also examine the orbital properties of these ringlets by comparing images taken at different longitudes and times. We find evidence that the orbits of these particles have forced eccentricities induced by solar radiation pressure. In addition, the mean radial positions of the particles in these ringlets appear to vary with local co-rotating longitude, perhaps due to the combined action of drag forces, gravitational perturbations from Pan, and collisions among the ring particles. The dynamics of the dust within this gap therefore appears to be much more complex than previously appreciated.

1. Introduction

The Encke Gap is a 320-km-wide opening in the outer part of Saturn's A ring centered on the orbit of the small moon Pan. In addition to Pan itself, this gap contains several faint ringlets with spectral and photometric properties that indicate they are composed primarily of dust-sized grains less than 100 μm wide. These ringlets attracted interest when they were first observed by the Voyager spacecraft because they contained prominent "clumps" of bright material associated with distinct "kinks" in the ringlets' radial position (Smith et al., 1982; Ferrari and Brahic, 1997). However, it was difficult to investigate the structure and dynamics of these longitudinally-confined features due to the restricted amount of data obtained by the Voyager missions.

Now, thanks to the Cassini spacecraft, a much more extensive data set is available for investigations of the Encke Gap ringlets. In particular, the Encke Gap has now been imaged multiple times since Cassini arrived at Saturn in 2004, allowing the evolution and motion of this material to be tracked over timescales from weeks to years. Cassini data also provide information about other dusty ringlets in Saturn's rings (Porco et al., 2005; Horányi et al., 2009), which can help clarify the dynamical processes operating in the Encke Gap. For example, a ringlet located within the Cassini Division's Laplace Gap demonstrates "heliotropic" behavior: its geometric center is displaced away from Saturn's center towards the Sun (Hedman et al., 2010). This happens because the particles in this ringlet are sufficiently small that solar radiation pressure can induce significant orbital eccentricities. Since the spectral and photometric properties of the Encke Gap ringlets indicate that they are also composed primarily of dust-sized particles (Hedman et al., 2011), their structure should also be affected by such non-gravitational forces.

After a brief introduction to the Encke Gap's architecture (Section 2), this report will describe the Cassini imaging observations of the Encke Gap obtained between 2004 and 2011 that provide the best information about the structure and evolution of material in this region (Section 3). Section 4 documents the distribution and motion of bright clumps in the denser ringlets. This study reveals that the bright clumps do not follow the expected trajectories of test particles under the influence of the combined gravitational fields of Saturn and Pan. Section 5 discusses structures produced by Pan's perturbations on the nearby dusty material. Section 6 examines the orbital properties of the particles in the ringlets and demonstrates that non-gravitational forces like solar radiation pressure are indeed influencing the structure of these ringlets. Finally, Section 7 discusses some of the physical processes that could explain the longitudinal variations in the ringlets' orbital properties, the distribution of both the clumps along each ringlet and the radial locations of the ringlets within the gap. Note that these theoretical considerations only represent an initial examination of some of the dynamical phenomena that could be relevant to the

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Encke Gap ringlets' structure and evolution, and are not meant to provide an exhaustive or complete picture of the ringlets' complex dynamics.

2. Architecture of the Encke Gap

The basic architecture of the Encke Gap is best illustrated by Figs. 1 and 2, which provide images and radial brightness profiles derived from the highest resolution and best signal-to-noise images of the Encke Gap obtained so far by Cassini (cf. Porco et al., 2005). These images and plots show that most of the faint material in this region is organized into three narrow ringlets and one broader feature. One narrow ringlet lies near the center of the gap, close to Pan's orbit at 133,584 km from Saturn's center. This feature is designated the "Pan ringlet" here, although it could just as well be called the "central ringlet". The two other narrow ringlets are situated on either side of the Pan ringlet. For want of a better terminology (thus far, no moon has been found within either of these ringlets), we will call the ringlet centered around 133,484 km the "inner ringlet" and the ringlet centered around 133,720 km the "outer ringlet". Note that the widths, peak brightnesses and locations of all three ringlets are different for the two profiles shown in Fig. 2. This is an example of the longitudinal variability exhibited by all three of these ringlets. Closer inspection of these images and profiles reveals a broad shelf of material extending inward from the outer ringlet to an orbital radius of about 133,680 km. This shelf, which was called the "fourth ringlet" by Porco et al. (2005), is considerably fainter than the other features in the Encke Gap and can only be seen with an appropriate combination of image resolution and viewing geometry. This broad feature also appears to be much more homogeneous than the three narrow ringlets. While wakes can be observed in this feature close to Pan (see Section 5 below), we have never observed anything like the clumps or kinks seen in the other three ringlets.

Fig. 1. One of the highest resolution images of the Encke Gap obtained by the Cassini spacecraft. This observation was made on day 183 of 2004 during Cassini's orbit insertion (N1467351325). The image has been heavily stretched to show the ringlets in the Encke Gap, causing the regions outside the gap to appear saturated. Labels mark the positions of the four ringlets observed in this region. The inner edge of the gap appears scalloped because Pan's gravity has excited radial motions in the nearby ring material (Porco et al., 2005).

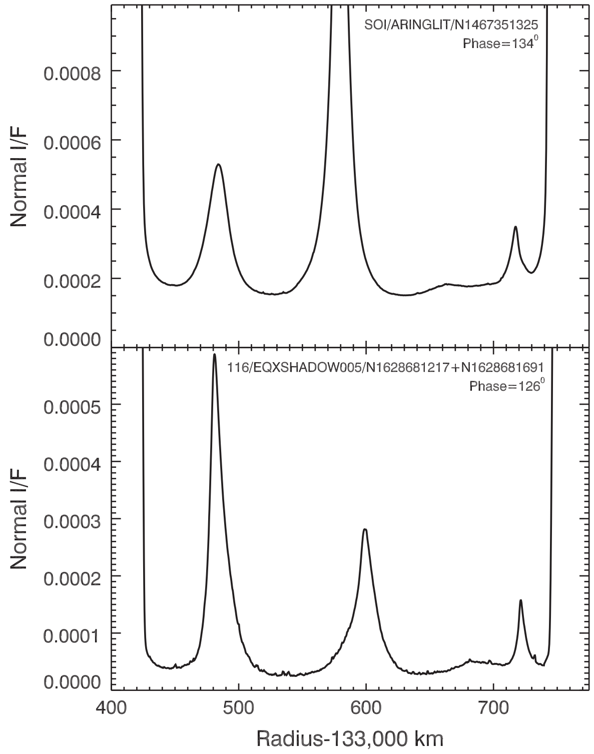

Fig. 2. Profiles of average brightness versus radius through the gap derived from the two observations of this gap with the best combination of resolution and signal-to-noise. Brightness is measured in terms of normal *I*/*F*, which is the observed *I*/*F* values multiplied by the cosine of the emission angle (see Section 3). The upper profile is derived from the same image shown in Fig. 1, while the lower profile is derived from images taken on day 223 of 2009 during Saturn's equinox. Both profiles show the same basic features, including three narrow ringlets and a broad shelf at 133,680 km (for the names of these features, see Fig. 1). Note the differences in radial positions and relative brightnesses of the three narrow ringlets. These are due to the longitudinal variability of these structures.

These ringlets all exist within a complex dynamical environment that is strongly influenced by the gravity of Saturn's small moon Pan (Showalter, 1991). Pan travels in a nearly circular orbit (eccentricity $\sim 10^{-5}$) through the center of the gap with a semi-major axis $a_P = 133{,}584$ km and an orbital period of 0.575 days (Jacobson et al., 2008). Due to Keplerian shear, material within and surrounding the gap drifts in longitude relative to Pan and therefore periodically encounters the moon. Since the gap is so narrow, these relative motions are very slow and encounters with Pan are correspondingly infrequent. For example, particles at the edges of the gap (at orbital radii of 133,423 km and 133,745 km) will reach conjunction with Pan only once every 543 orbits, or roughly every 315 days. Nevertheless, each time a particle has a close encounter with Pan, its orbital parameters will be perturbed by the moon's gravity. Indeed, Pan's influence is clearly visible in both the few-kilometer-high waves on the edges of the gap and the moonlet wakes found in the A-ring material on either side of the gap (Cuzzi and Scargle, 1985; Showalter et al., 1986; Horn et al., 1996; Weiss et al., 2009). Based on the amplitudes of the waves Pan generates at the edge of the Encke Gap, the mass ratio of Pan to Saturn (m_P/M_S) has been estimated to be about 0.8×10^{-11}, which corresponds to a mass $m_P \simeq 5 \times 10^{15}$ kg (Porco et al., 2007; Weiss et al., 2009).

Particles orbiting within the Encke Gap are even more strongly affected by Pan's gravity. Fig. 3 illustrates the expected trajectories of small particles within the Encke Gap, assuming that the only forces acting on the particles come from Pan's and Saturn's gravitational fields. These trajectories are computed using Hill's eqauations (cf. Murray and Dermott, 1999), and the scale of structures