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Radial profiles of the Phoebe ring: A vast debris disk around Saturn

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A B S T R A C T

We present observations at optical wavelengths with the Cassini Spacecraft's Imaging Science System of the Phoebe ring, a vast debris disk around Saturn that seems to be collisionally generated by its irregular satellites. The analysis reveals a radial profile from 80–260 Saturn radii (R_S) that changes behavior interior to $\approx 110 R_S$. *We attribute this to either the moon Iapetus*...sweeping up small particles, or to orbital instabilities that cause the ring to flare up vertically. Our study yields an integrated I/F at 0.635 μm along Saturn's shadow in the Phoebe ring's midplane from 80–250 R_S of $2.7^{+0.9}_{-0.3} \times 10^{-9}$. We develop an analytical model for the size-dependent secular dynamics of retrograde Phoebe ring grains, and compare this model to the observations. This analysis implies that 1) the "Phoebe" ring is partially sourced by debris from irregular satellites beyond Phoebe's orbit and 2) the scattered light signal is dominated by small grains ($\lesssim 20$ μm in size). If we assume that the Phoebe ring is generated through steady-state micrometeoroid bombardment, this implies a power-law size distribution with index >4, which is unusually steep among Solar System rings. This suggests either a steep size distribution of ejecta when material is initially released, or a subsequent process that preferentially breaks up large grains.

1. Introduction

Using the Spitzer infrared space telescope, Verbiscer et al. (2009) discovered a vast dust ring around Saturn, far beyond the bright main rings. This debris disk was dubbed the Phoebe ring after the largest of Saturn's distant irregular satellites, which seems to be the dominant source for the material. Approximately three dozen known irregular satellites (see Jewitt and Haghighipour, 2007; Nicholson et al., 2008, for reviews) form a swarm of mutually inclined, overlapping orbits—a relic of their capture process (Ćuk and Burns, 2004; Ćuk and Gladman, 2006; Nesvorný et al., 2003; 2007; Pollack et al., 1979). This led to a violent collisional history among these bodies continuing since early times (Bottke et al., 2010). Smaller collisions must be ongoing, both with circumplanetary objects too small to detect observationally, and with interplanetary meteoroids (cf., Cuzzi and Estrada, 1998).

While the disk is diffuse, the debris from these dark irregular satellites (Grav et al., 2015) can have important consequences. Iapetus, the outermost of the large, tidally locked, regular satellites has a leading side approximately ten times darker than its trailing side. Many years before its discovery, Soter (1974) (see also Bell et al. 1985; Buratti and Mosher 1995; Cruikshank et al. 1983) hypothesized that inward transfer of such debris through Poynting–Robertson drag might explain Iapetus' stark hemispheric dichotomy. Burns et al. (1996), and more recently Tosi et al. (2010) and Tamayo et al. (2011), showed that indeed, Iapetus should intercept most of the inspiraling material as it plows through the cloud, and that the longitudinal distribution of dark material on Iapetus can be well explained by dust infall under the action of radiation pressure. Additionally, Denk et al. (2010); Spencer and Denk (2010) showed that runaway ice sublimation and redeposition could accentuate initially subtle albedo differences to match the observed stark contrast.

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Furthermore, this process of collisional grinding among the irregular satellites should be ubiquitous among the solar (and perhaps extrasolar) system's giant planets (Bottke et al., 2010; Kennedy and Wyatt, 2011), and this debris should also fall onto the respective outermost regular satellites. Indeed, the uranian regular satellites exhibit hemispherical color dichotomies (Buratti and Mosher, 1991), and Tamayo et al. (2013a) showed that this could similarly be explained through dust infall, though the dynamics are additionally complicated by Uranus' extreme obliquity (Tamayo et al., 2013b). Bottke et al. (2013) argue the same process has occurred in the jovian system. As the only known debris disk sourced by irregular satellites, the Phoebe ring therefore presents a unique opportunity to learn about generic processes around giant planets, both in our Solar System and beyond.

Tamayo et al. (2014), hereafter THB14, detected the Phoebe ring's scattered light at optical wavelengths, using the Cassini spacecraft in orbit around Saturn. THB14 combined these optical measurements with the thermal emission data of Verbiscer et al. (2009), finding that Phoebe ring grains have low albedos similar to the dark irregular satellites (Grav et al., 2015). More recently, Hamilton et al. (2015) combined detailed numerical models of dust grains' size-dependent spatial distributions with new data from the Wide-Field Infrared Survey Explorer (WISE) to extract the particle-size distribution in the disk. They found that the Phoebe ring extends out to at least 270 Saturn radii[1](R_S) and has a steep particle size distribution. However, the Phoebe ring is so faint (normal optical depth $\sim 10^{-8}$) that scattered light from the planet dominates the signal inside $\approx$100 Saturn radii (R_S). This is too far out to detect an inner edge swept out by Iapetus, which orbits at $\approx 59R_S$.

In this paper we present results from a new Cassini data set with a substantially higher signal-to-noise ratio than that of THB14. This renders the faint Phoebe ring signature clearly visible in our images, and we are able to additionally extract the Phoebe ring's radial structure. We begin by presenting our data analysis, and by describing our data reduction methods in Section 2, and our results in Section 3. In Section 4, we then semi-analytically investigate the expected 3-D structure of the Phoebe ring, which should exhibit interesting dynamics closer to Iapetus, where the Sun stops being the dominant perturbation (as it is for grains at large Saturnocentric distances), and Saturn's oblateness becomes important. In Section 5 we compare our model to the data and we summarize our results in Section 6.

2. Methods

2.1. Data reduction

The main observational challenge is that the scattered light signal from Phoebe ring grains is exceedingly weak ($I/F \sim 10^{-9}$). Additionally, from Cassini's nearby vantage point, the Phoebe ring's thickness spans several tens of degrees; the Phoebe ring therefore appears as a uniform background across the 3.5' $\times$ 3.5' field of view of Cassini's Imaging Science System (ISS) Wide-Angle Camera, WAC (Porco et al., 2004). We now briefly summarize the technique that THB14 developed to overcome these obstacles.

The key is to detect the *deficit* of scattered light from unilluminated Phoebe ring grains lying in Saturn's shadow. Not only is the shadow narrow enough to be captured within a single WAC field of view, its apparent position relative to the background stars shifts as the spacecraft moves in its orbit. THB14 examined several exposures of the same star field as Saturn's shadow moved through the images. By subtracting images from one another, the constant background could be attenuated while retaining the moving shadow's signal.

The signal-to-noise ratio can be substantially improved by positioning the spacecraft closer to the long axis of Saturn's shadow, which lengthens the column of Phoebe ring material along lines of sight that intersect the shadow (see Fig. 1 in THB14). On day 269 of 2013 (September 26th), in Rev 197 (Cassini's 198th orbit about Saturn), we executed such an observation with Cassini only $\approx$6 Saturn radii (R_S) from the shadow's axis (compared to $\approx 22R_S$ in the observations of THB14). We also maximized the shadow's movement across the field of view by taking images at the beginning and end of our observation window.

The geometry is summarized in Fig. 1. Over the span of the observation, the spacecraft (red point) does not move appreciably on the scale of the figure, but enough for the shadow to move across a large fraction of the camera's $3.5' \times 3.5'$ field of view (see Fig. 2 and accompanying details below). The bottom panel additionally shows the radial ranges spanned by each observation (material beyond these limits contributed to fewer than 10% of pixels in each pointing). The shadow is wider in the top panel due to shadowing by the rings. We also note that the depicted model for the Phoebe ring is simplified—it has been cut off at the orbital distance of Iapetus, which should intercept most of the material (Tamayo et al., 2011), and it is drawn as symmetric about Saturn's orbital plane. In reality, the Phoebe ring should begin warping toward Saturn's equatorial plane in the innermost regions of the disk (see Section 4).

The corresponding observations for the outer section of the Phoebe ring (rev197o) are shown in Fig. 2.

These observations (rev197o) comprise 50 220-s WAC exposures[2] (using the clear filter CL1), centered on a point in the Phoebe ring 160 R_S from the planet, at right ascension (RA) = 223.7°, declination (Dec) = −13.5°. In addition to the observations shown in Fig. 2 we obtained 47 exposures,[3] centered on a location 110 R_S from Saturn, at RA = 225.0°, Dec = −14.6°. We denote this data set further 'inward' rev197i. The total observation window spanned 18 hours and 45 minutes, and time was evenly split between rev197o and rev197i. We collected all images in 2 $\times$ 2 summation mode due to data-volume constraints, and calibrated them with the standard Cassini ISS Calibration (CISSCAL) routines (Porco et al., 2004; West et al., 2010) to apply flat-field corrections and convert the raw data to values of I/F, a standard measure of reflectance.

[1] For this work we adopt R_S = 60,330 km, the convention used for calculating Saturn's gravitational moments.

[2] Image names W1758855456_1, W1758855824_1, W1758856192_1, W1758856560_1, W1758856928_1, W1758857296_1, W1758857664_1, W1758858032_1, W1758858400_1, W1758858768_1, W1758859136_1, W1758859504_1, W1758859872_1, W1758860240_1, W1758860608_1, W1758860976_1, W1758861344_1, W1758861712_1, W1758862080_1, W1758862448_1, W1758862816_1, W1758863184_1, W1758863552_1, W1758863920_1, W1758864288_1, W1758878396_1, W1758878764_1, W1758879132_1, W1758879500_1, W1758879868_1, W1758880236_1, W1758880604_1, W1758880972_1, W1758881340_1, W1758881708_1, W1758882076_1, W1758882444_1, W1758882812_1, W1758883180_1, W1758883548_1, W1758883916_1, W1758884284_1, W1758884652_1, W1758885020_1, W1758885388_1, W1758885756_1, W1758886124_1, W1758886492_1, W1758886860_1, W1758887228_1.

[3] Image names $W1758887712_1$, W1758888080_1, W1758888448_1, W1758888816_1, W1758889184_1, W1758889552_1, W1758889920_1, W1758890288_1, W1758890656_1, W1758891024_1, W1758891392_1, W1758891760_1, W1758892128_1, W1758892496_1, W1758892864_1, W1758893232_1, W1758893600_1, W1758893968_1, W1758894336_1, W1758894704_1, W1758895072_1, W1758895440_1, W1758895808_1, W1758896176_1, W1758896544_1, W1758910652_1, W1758911020_1, W 1758911388_1, W1758911756_1, W1758912124_1, W1758912492_1, W1758912860_1, W1758913228_1, W1758913596_1, W1758913964_1, W1758914332_1, W1758914700_1, W1758915068_1, W1758915436_1, W1758915804_1, W1758916172_1, W1758916540_1, W1758916908_1, W1758917276_1, W1758917644_1, W1758918012_1, W1758918380_1.