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First observations of the Phoebe ring in optical light

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ABSTRACT

The Phoebe ring, Saturn's largest and faintest ring, lies far beyond the planet's well-known main rings. It is primarily sourced by collisions with Saturn's largest irregular satellite Phoebe, perhaps through stochastic macroscopic collisions, or through more steady micrometeoroid bombardment. The ring was discovered with the Spitzer Space Telescope at 24 μm and has a normal optical depth of $\sim 2 \times 10^{-8}$ (Verbiscer, A.J., Skrutskie, M.F., Hamilton, D.P. [2009]. Nature 461, 1098–1100). We report the first observations of sunlight scattered off the Phoebe ring using the Cassini spacecraft's ISS camera at optical wavelengths. We find that material between ≈130 and 210 saturnian radii (R_S) from the planet produces an I/F of $1.7 \pm 0.1 \times 10^{-11}$ per R_S of the line-of-sight distance through the disk. Combining our measurements with the Spitzer infrared data, we can place constraints on the ring-particles' light-scattering properties. Depending on the particles' assumed phase function, the derived single-scattering albedo can match either photometric models of Phoebe's dark regolith or brighter sub-surface material excavated by macroscopic impacts on Phoebe.

1. Introduction

Each giant planet hosts a population of small irregular satellites orbiting at the outskirts of their respective spheres of gravitational influence (see reviews by Jewitt and Haghighipour, 2007; Nicholson et al., 2008). These moons are theorized to have been captured early in the Solar System's history when the giant planets were likely migrating (Nesvorný et al., 2007), and/or when gas drag was important (Pollack et al., 1979; Ćuk and Burns, 2004; Ćuk and Gladman, 2006). As a result of being captured, these moons move on high-inclination, high-eccentricity paths that can intersect one another. This fact, combined with the irregular statellites' anomalously flat size distributions (Bottke et al., 2010; Kennedy and Wyatt, 2011) suggest a tumultuous collisional history. Using initial conditions from the Nice model, Bottke et al. (2010) find that 99% of the initial mass in the irregular satellites should be ground to dust in the first hundreds of Myr after the moons were captured.

Such circumplanetary disks have important consequences for the larger regular satellites that orbit close to their parent planets. In the Solar System, the orbits of the circumplanetary dust grains will decay in toward the planet through Poynting–Robertson drag on a timescale of millions of years (Burns et al., 1979). The further-in, and tidally locked, regular satellites then plow through this infalling cloud of dust, modifying their leading hemispheres (Soter, 1974). Currently, this is the best explanation for the hemispherical color asymmetries detected on Saturn's moon Iapetus (Denk et al., 2010; Tosi et al., 2010; Tamayo et al., 2011) and on the outer four Uranian regular satellites (Buratti and Mosher, 1991; Tamayo et al., 2013). It likely is also ultimately responsible for Iapetus' famous yin-yang albedo pattern (Tamayo et al., 2011) by triggering a runaway process of ice sublimation (Spencer and Denk, 2010). Finally, Bottke et al. (2013) argue that Jovian irregular-satellite debris explains the dark lag deposits found on the most ancient terrains of Ganymede and Callisto, and that it could be an important source of organic compounds for Europa. In short, in order to accurately interpret the surfaces of the giant planets' outer main satellites, one must first understand the collisional history of their respective irregular moons.

Despite the present day's drastically reduced collision frequencies between irregular satellites, Verbiscer et al. (2009) discovered a vast dust disk around Saturn with the Spitzer Space Telescope. The height of a collisionally generated disk should correspond to its parent moon's vertical orbital excursions (e.g., Burns et al., 1999), and the disk's height of ≈40 saturnian radii (R_S) implicates the largest irregular satellite Phoebe as the source (Verbiscer et al., 2009); however, other smaller satellites that also orbit close to Saturn's orbital plane may also contribute. This "Phoebe ring" is extremely diffuse, with a normal optical depth of $\sim 2 \times 10^{-8}$. Nevertheless, it provides an invaluable opportunity for

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understanding these circumplanetary debris disks. The Wide-field Infrared Survey Explorer (WISE) mission has recently obtained a more complete map of the Phoebe ring's emission at a similar wavelength (band 4, centered at 22 μm) as the 24-μm band on the Multi-Band Imaging Photometer aboard Spitzer (Skrutskie et al., 2011). However, more measurements at widely spaced wavelengths are needed to constrain the dust grains' properties, such as their wavelength-dependent albedo and emissivity. Tamayo et al. (2012) observed the Phoebe ring with the Herschel Space Observatory at 70 and 130 μm; unfortunately, due to scattered light from Saturn, we were only able to set upper limits. In this paper we report the results from our efforts at shorter optical wavelengths. This is challenging because at these higher energies one measures sunlight scattered by dust into the detector, and one expects dust grains derived from Phoebe to absorb most of the incoming light given the parent moon's low geometric albedo of ≈0.085 across the visible spectrum (Miller et al., 2011). This strongly attenuates an already weak signal.

We executed the observations with the Imaging Science System's (ISS) Wide-Angle Camera (WAC) aboard the Cassini spacecraft, which has a unique vantage point as it orbits about Saturn. Relative to observations from Earth, this has the obvious advantage of placing the detector ~300 times closer to the target. However, this also implies that from Cassini's location, the full height of the Phoebe ring subtends ≈20° in the sky. Thus, the debris disk presents a constant background of scattered light across the detector's field of view that cannot be directly measured. We circumvented this problem by exploiting the shadow cast by Saturn (and its dense rings), which extends behind the planet in a quasi-cylindrical tube. By capturing the full width of the shadow within a WAC field of view, we measured the scattered light *missing* from the region receiving no sunlight, thus indirectly probing the dust content.

2. Methods

2.1. Overview

As summarized above, we aim to measure the reduction in flux from the Phoebe ring region lying in Saturn's shadow, relative to the background. The quasi-cylindrical shadow cast by Saturn and its rings pierces the Phoebe ring on the side opposite the Sun, and its full width (≈1°) can be contained in a single WAC field of view (3.5° × 3.5°). We acquired 33 220-s WAC exposures using clear filters, i.e., in a band centered at 635 nm (Porco et al., 2004). All images were aimed at the same star field, capturing the section of the shadow from ≈130R_S to ≈300R_S from Saturn (for details of the data set see Section 2.2). Different pixels in the resulting image represent different lines of sight emanating from the detector that have different pathlengths through the shadow tube (see Fig. 1). Assuming a constant distribution of dust along the shadow, pixels should register a diminished flux in proportion to their associated pathlengths through the shadow. This approximation of constant dust density should be valid in the direction perpendicular to the tube's axis, as the shadow's transverse dimensions are much smaller than those of the Phoebe ring. The magnitude of the radial variation is not well constrained, though the measurements by Verbiscer et al. (2009) show the infrared flux is nearly constant on scales of tens of R_S, at least in the range 130–180R_S from the planet (see their Fig. 3), so we proceed under this assumption for this initial study. By measuring the rate at which the flux decreases with increasing pathlength through the shadow, we thus probe the dust content along the tube, together with grain properties like the albedo and phase function. For details of how we determined the pathlengths through the shadow that correspond to each pixel, see Section 2.3. For an example of an image's modeled pathlengths, and thus of the signature we seek, see the bottom left panel of Fig. 2.

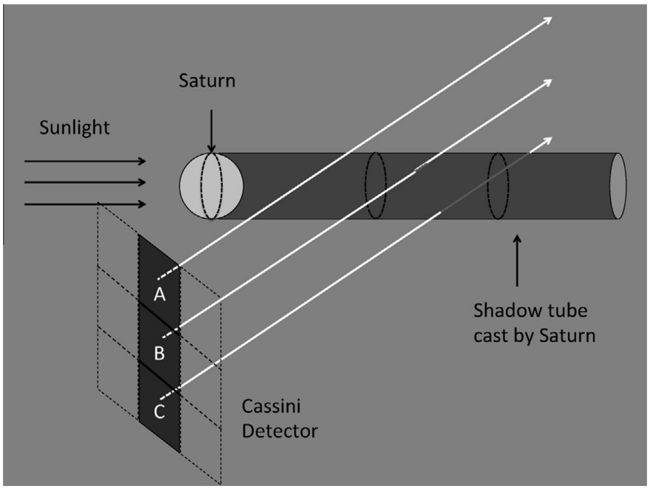

Fig. 1. The shadow cast by the Saturn system (rings not shown) extends in a quasi-cylindrical tube behind the planet. Different pixels on the Cassini detector correspond to different lines of sight, shown in white. As drawn, the line of sight from pixel A misses the shadow tube completely. B grazes the shadow, so this pixel is only missing the scattered light from a short section of dust and should thus only show a slight brightness decrease relative to A. C has the longest pathlength through the shadow and should therefore be darkest. For clarity, the pixel sizes have been exaggerated and the number of pixels has been reduced. The distances and angles in the diagram are not to scale.

The sought signal is fainter than that from any ring yet detected in the Solar System. To motivate our detailed modeling and data analysis below, we first roughly estimate the expected brightness differences between shadowed and non-shadowed regions. We express all our data as values of I/F, which measures the specific intensity received at the detector relative to the incident solar flux at the Phoebe ring, such that an ideal, diffusely reflective surface would yield an I/F of unity.

We want to consider the photons that dust particles in the shadow tube *would* scatter into the detector were they not in shadow. Our pathlengths through the tube ($\lesssim 20R_S$) are comparable to the ring's height ($\approx 40R_S$), so we take the area filling-factor of dust grains along our line of sight to be roughly the ring's normal optical depth $\tau \sim 10^{-8}$ (Verbiscer et al., 2009). The I/F removed by the shadow is then roughly the product of the particles' albedo and this area filling-factor. Estimating an albedo ~0.1 (Phoebe's geometric albedo is ≈0.08, Miller et al., 2011), yields an I/F $\sim 10^{-10}$. To put this into perspective, typical I/F values measured from Saturn's extremely faint G-ring (undiscovered until the Voyager flybys) are three orders of magnitude larger than this.

Standard image processing techniques will fail to extract such a weak signal. We designed our observations to exploit the fact that, over the ≈12 h of data collection, the spacecraft's motion causes the shadow to shift position on the field of view by a few tens of pixels, while the stars remain fixed. By filtering out faulty/noisy pixels (see Section 2.2) and then subtracting images, we attenuated the much brighter and complex background while retaining a signal from the shifted shadow (see Fig. 2). Rather than arbitrarily choosing one of our images as the reference for subtraction, we generated a mean image from our 33 files and subtracted this average field from each of our images.

We thus obtain 33 images with the mean field removed, like the one shown in the top right panel of Fig. 2. For each image we also calculate the signature expected from the shadow, i.e., the associated pathlength differences for each pixel (inverted since longer