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Measuring Centimeter-Sized Particles in the Saturnian Rings by Diffraction of Starlight

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Abstract

Occultations of Saturn's rings have proven to be a useful way to measure the particle-size distribution of ring particles observed when in wavelength regimes where particles of different sizes behave differently. Studies of spacecraft-based radio occultations[1], Earth-based stellar occultations[2], and spacecraft-based solar occultations (Harbison et al., in prep.) have produced an understanding of the distributions of decimeter and meter-sized particles, and upper limits on the presence of micron-sized dust, but centimeter and millimeter-sized particles are less constrained. French and Nicholson also noticed in their stellar occultation work the presence of 'overshoots', places near a sharp edge of the rings, such as the Colombo, Maxwell, Huygens and Encke Gaps, where the transmission of starlight appears to exceed unity. They attributed this to starlight forward-scattered from the nearby ring into their detector.

The Cassini spacecraft, in orbit about Saturn, has also been measuring stellar occultations with the Visible-Infrared Mapping Spectrometer (VIMS), with a total of 74 observed during the period 2004-2009. Similar overshoots are seen in these data. Given that these overshoots are observed over $\sim$ 40 km from a typical distance of $\sim 400,000$ km, subtending an angle of ~ 0.1 milliradian, at a wavelength of 2.92 μm, the particles that produce them must be of a size of $\sim \lambda/\theta$ or $\sim$ 3 cm. Thus, in this work, we are modeling these overshoots to learn the size distribution of millimeter and centimeter sized particles.

1. Data and Data Analysis

Most stellar occultations are observed by VIMS in 'occultation mode'. Once the star is located to within one VIMS pixel, it is observed with a cadence of 20 to 80 ms. Nearby spectral channels are binned by VIMS, such that each channel covers a range of 0.13 microns. We primarily use the channel centered on 2.92 μm, as it occurs at a strong absorption of water ice, making the rings dark to reflection or diffuse transmission of sunlight.

Most occultations observe the star before or after it passes behind the rings. As a result, these observations can be used to calibrate the transmission, and serve as an empirical measure for noise and, in the case of both before and after measurements, drift in the baseline. In most cases, a constant or linear function serves as a good measure of the unocculted starlight; the data is thus divided by this constant to get a measure of the transmission, and to look for places where the starlight exceeds unity in a non-random way near sharp boundaries in optical depth.

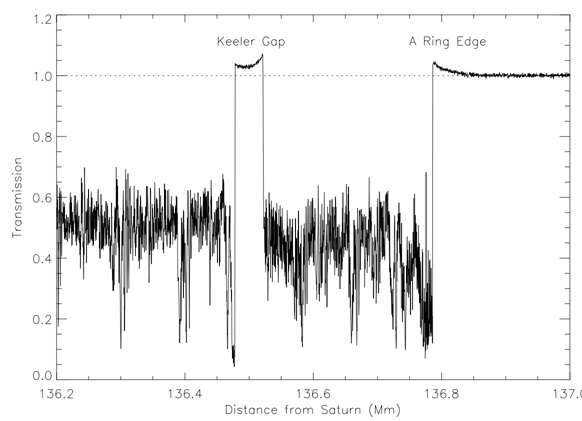

Figure 1: The recorded transmission at 2.92 μm during the Rev. 82 stellar occultation of γ Crucis. The rings are dark at 2.92 μm so all light recorded by VIMS is from starlight. Note the rise above the baseline transmission slightly outside the A Ring edge, falling off with distance, and the double-horned transmission peak in the Keeler Gap.

An example of one of these overshoots can be seen in Figure 1, which shows the outer edge of the A Ring and the Keeler Gap reaching several percent above a transmission of unity. In addition to the Huygens, Columbo, Maxwell and Encke Gap overshoots seen by French and Nicholson, we see these overshoots in the Keeler Gap, the Dawes and Bond Gaps in the C ring, at the edge of the A Ring, and in other gaps in the Cassini Division.

2. Modeling

The phase function of a single spherical ring particle of radius a at small scattering angles, where diffraction dominates, is given by

$$P(\theta) = \left[\frac{2J_1\left(\frac{2\pi a}{\lambda}\sin\theta\right)}{\sin\theta} \right]^2 \quad (1)$$

where λ is the wavelength and J_1 is a first-order Bessel function. Integrating this over a set of discrete particle sizes shows that the flux scattered at a given angle, θ, is a linear combination of different phase functions, with the coefficients measuring the surface number density of ring particles of that size. This lends itself to solving by a least-squares fit, with the constraint that a negative surface density is unphysical. An example of such a fit is shown in Figure 2 below, with a χ^2 per degree of freedom of 0.77 after several data points deviating more than 5σ are removed.

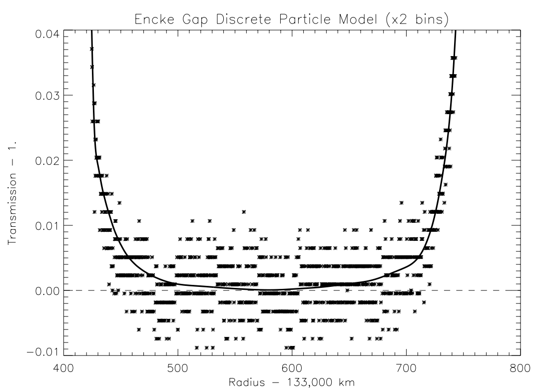

Figure 2: Model of light diffracted from ring particles bordering the Encke Gap (solid line) using a set of discretely-sized particles of 0.4, 0.8, 1.6, 3.2, 6.4, 12.8 and 25.6 cm radius and a set of non-scattering 'large' particles. Stars represent the recorded transmission at 2.92 μm during the Rev. Rev. 82 stellar occultation of γ Crucis.

Our observations are most sensitive to centimeter-sized particles within the rings. Studies of the A Ring near the Encke and Keeler gaps shows that the continuous particle size distribution measured by spacecraft radio occultations[1], [3] continues through the centimeter regime, and is well fit by a power law. The cutoff size for such a power law must be from particles smaller than can be measured by this experiment.

3. Summary and Conclusions

The particles of Saturn's rings are capable of scattering the infrared light seen by VIMS by small angles, such that it can be seen by the finely sampled observations of stellar occultations. These overshoots can be fit well by a simple diffraction model using centimeter and millimeter sized particles, but selection of a model that produces a physical measure of the ring particle-size distribution takes some care. We will present preliminary results on the particle-size distribution in the centimeter and millimeter regime.

References

[1] Zebker, H.A., Marouf, E.A., Tyler, G.L.: Saturn's rings - Particle size distributions for thin layer model, Icarus, Vol. 64, pp. 531-548, 1985.

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[3] Dougherty, M. K., Esposito, L. W., Krimigis, S. M.: Saturn from Cassini, Springer, 2009.