READING SATURN'S RING SPOKES

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ABSTRACT. The micron-sized dust forming the radial spoke-like features in Saturn's rings are studied using radiative transfer analysis. Theories for their likely origin and evolution are discussed in light of these results, and future work is outlined.

1. Introduction.

Radial cloud-like features were first confirmed to exist in the outer B Ring of Saturn in October 1980 by the Voyager spacecraft. (A number of observers over the preceeding century had observed such features in the B and A Rings; see Doyle and Grün 1990 for a review.) These *spokes* were observed to be dark in backscatter, but brighter in forward scatter, indicative of micron-sized particles. Spokes are classified into three categories, *extended*, *narrow*, and *filamentary*, depending on shape, radial-azimuthal extent, location in the outer B Ring, and optical depth. Extended spokes were observed to form radially with the trailing edge maintaining a semi-corotating radial orientation and the leading edge taking on a Keplerian shear during the formation process, giving the spokes a triangular appearance. After complete formation, both edges of the spokes were observed to take on a Keplerian motion (Grün *et.al.* 1983).

Enhanced magnetic field activity (longitudinal regions of the rings where both the Saturn Electrostatic Discharge as well as the Saturn Kilometric Radiation originate) has also been correlated with periodically enhanced spoke optical depth, indicating that the spokes phenomena is closely tied to electromagnetic processes in the Saturn system (Porco and Danielson 1982, Porco 1988). One suggestion, for example, is that spokes may be related to turbulence in Saturn's magnetosphere (Burns *et.al.* 1983). However, the most popular theory for spoke formation is that they result from a plasma produced by the impact onto the rings of large *macro*meteoritic particles (meter-sized) (Goertz and Morfill 1983). This plasma, under Lorentz forces, propagates radially, electrostatically levitating regolithic dust off the surfaces of the larger B Ring boulders and producing the spokes. When the contribution from a secondary plasma (from the neutral hydrogen cloud) is taken into account, the effective size of the individual spoke particles is predicted to be around $0.6\mu m$ (Goertz 1984).

Several factors can be observed to differentiate between some of these theories and see what else the spokes can tell us about processes in the Saturn system. For example, there appears to be an asymmetry in the optical depth distribution of the spokes (they appear to be enhanced on the morning compared to the evening ansa). This can be understood in terms of the greater kinetic energy produced by the increased impact velocity of macrometeoritic material onto the midnight side compared to the noon side of the rings. This occurs because Saturn's orbital velocity vector happens to add to the rings rotational velocity vector on the midnight region of the rings, while it subtracts from the rotational velocity vector on the noon side of the rings (Durisen *et.al.* 1989). The individual size of the spoke particles themselves would also provide useful constraints on the plasma strength necessary to levitate these particles off the larger B Ring boulders. Such determinations can begin with radiative transfer modeling of the spoke and ring photometric data.

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2. Phase Curve Analysis of Spokes.

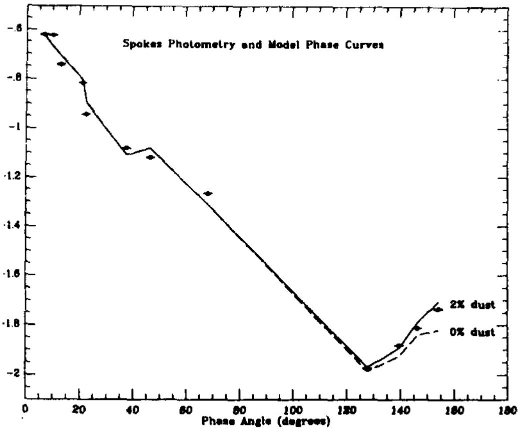
The optical depth of the spokes can be determined through an analysis of the forward scattering portion of the spokes-rings phase curve - the low phase angle region being dominated by the backscattering regolith of the larger B Ring boulders. A typical spoke phase curve, where I is the reflected flux, and πF is the solar incident flux, is plotted in Figure 1. (We have shown the logarithm of the reflectivity to emphasize the high phase angle data, plotting the most accurately known data after Doyle *et.al.* 1989; jagged edges being due to varying geometry from image to image.) We modeled this phase curve with full multiple scattering considerations (including the effects of Saturnshine as well as the solar flux) varying the large and small particle albedos, phase functions, and ratios (Doyle *et.al.* 1989). Among other results we found that the B Ring is very backscattering, so that a Callisto large particle phase function fits best, while the small particle (dust) optical depth of the spokes was best fit at 2% (with the 0% model also shown), an amount significantly less than previous estimates. (This latter result significantly limits the effects of angular momentum transport by dust in the rings.)

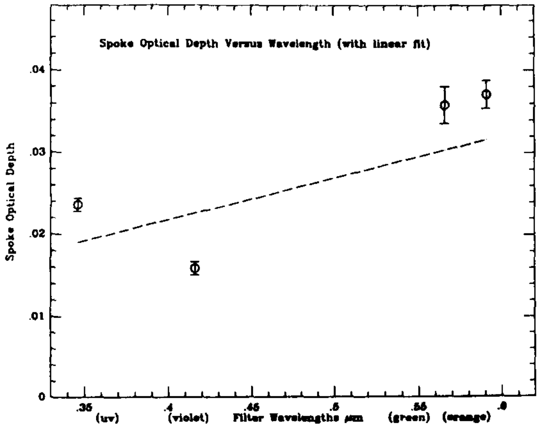
We also found essentially *zero* free micron-sized dust outside the spoke regions in the outer B Ring, so that it can be expected that the larger B Ring boulders can sweep up free dust very rapidly (a more intuitive result when one considers the spokes' lifetimes of only a few hours). The large boulders' phase function also is seen to change slightly under the spokes, a strong indication that this regolith is indeed the source of the spoke particles. We found a rather high large particle albedo (about 0.56) indicating that the rings contain less than about 1% mass fraction of darker interplanetary *micro*meteoritic dust. Conservatively assuming that the micrometeoritic flux has been constant in time, and has the same density at 9 AU as at 1 AU, we find that the rings could not have been "catching" micrometeoritic dust for more than about 2×10^8 years, a time significantly younger than the age of the solar system.

3. Color Analysis of the Spokes.

We then examined identical spokes in various Voyager filter bandpasses. Accounting for possible changes in the large particle phase function under spokes (since the spoke particles appear to originate from the large particles' regolith) as well as the effects of multiple scattering and the large particle color albedo, the spoke particles nevertheless seem to increase in optical depth with increasing wavelength, as shown in Figure 2 (with a linear least-squares fit). This increase, we have found, is likely due solely to the single scattering efficiency term in the optical depth of the spoke particles. With this result we can scale a spoke's optical depth to extinction efficiency (Q_e), and the wavelengths of observations to size parameter, $x = 2\pi r/\lambda$, (where r is the particle effective radius and λ is the wavelength of observation), putting at least a lower bound on the spoke particle sizes. We have therefore scaled reflectivity to extinction efficiency, and wavelength to size parameter in order to use the spoke particles' sloping scattering properties (as indicated by their location on the extinction efficiency curve) as a template constraining the range of their effective radii. This is illustrated in Figure 3, where typical spoke photometric data from four separate filters is shown superimposed on the extinction efficiency curve (the solid curve for a single particle size and the dotted curve for a size distribution of about $r \pm \sqrt{0.1}r$, see Doyle *et.al.* 1989).

From this work we find that the effective spoke particle sizes themselves must be larger than about $0.4 - 0.5\mu m$ in radius and, in some cases, narrowly constrained around $0.6 \pm 0.2\mu m$. This result agrees surprisingly well with the effective spoke particle radius predicted by the theory for the spokes originating by a macrometeoroid-impact-produced plasma. Although such a narrow size distribution may be unusual in longer-lived phenomena, an individual spoke lasts only a few hours. The smaller constraint on size is likely due to the need for a large enough impact cross section to "catch" at least one electron from the propagating plasma, while the upper constraint is likely due to centrifugal disruption (Meyer-Vernet 1984). Our results here, then, appear to support again a macrometeoroid impact model for spoke formation.





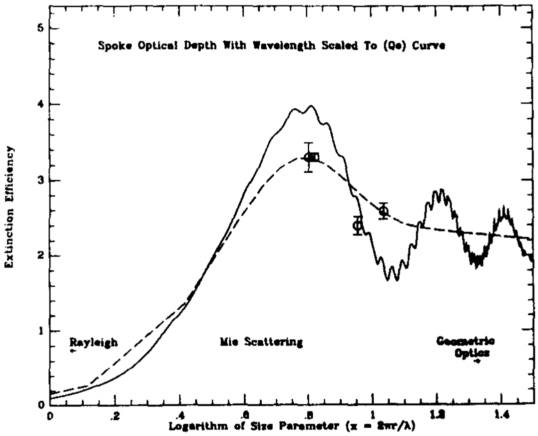


Figure 1: Spokes Phase Curve (*above*)

Figure 2: Spokes Color Optical Depth (*upper right*)

Figure 3: Spokes Extinction Efficiency (*right*)

4. Conclusions.

Our study of the photometry and modeling of the spokes in Saturn's rings has lead to a number of interesting conclusions. First, we have determined that the spokes contain virtually all of the free dust in the outer B Ring (in the A Ring as well, from other work; Dones 1987). This result mitigates against theories of ring formation by loosely held particles. We have also determined that the spokes optical depth is only about 2%, allowing some relaxation on the total plasma strength required for their formation and propagation. We have also found that the spoke particle sizes we obtained support macrometeoroid impacts as a major source for the origin of spokes with effective spoke particle sizes, in general, narrowly constrained to a size distribution of around $0.6\mu m$. Finally, we have found that the general ring large particle albedo is too large to contain more than about 1% by mass of darker micrometeoritic dust, and so could not have been out in this interplanetary "rain" for more than a couple of hundred million years. The rings have about the same mass as Saturn's moon Mimas (3.65×10^{22} grams) which, as a sphere, has only about 10^{-5} the surface area of the rings. We therefore conclude that the ring material could have been in this form until disruptive capture by Saturn, and therefore that the rings of Saturn did not originate at the same time as Saturn formed, but are instead a fairly recent phenomena.

5. Future Work.

First: We would like to further deconvolve the processes by which spokes originate by examining the Fourier spectrum of spoke events. If a large contribution to spokes structure is due to Saturn ionospheric turbulent, then the spokes may occur with a turbulence or Kolmogoroff-like spectrum while, if they are due to macrometeoroid bombardment, a Fourier spectrum resembling, for example, a cratering distribution should be more evident.

Second: Polarization data on the spokes would also allow a better estimate of the spokes formational and evolutionary dependence on magnetic field effects. These could be obtained with the Hubble Space Telescope at low phase angles, but would have to await the Cassini Saturn Orbiter spacecraft for high phase angle coverage. The Cassini orbital insertion phase will also likely allow the only near-term opportunity to obtain wide phase angle coverage over a short enough time period (a few hours) to very accurately characterize the particle properties of individual spokes and determine how these characteristics (size distribution, for example) evolve over short time periods.

Third: We would like to model the spoke particles' formation trajectories and "sweep up" times onto the vertical cross-sections of the larger B Ring boulders. The B Ring contains fully 3/4 ths of the mass of Saturn's rings, and its optical depth has not yet been measured (only a lower limit has been determined by the saturation of the photopolarimeter occultation experiment aboard Voyager). With this approach we could estimate for the first time the vertical cross-sectional area of the optically thick outer B Ring and determine its optical depth as well as resolve if it is a many layered or mono-layered ring structure.

Fourth: Finally, if we can learn to read these "hieroglyphics" of the rings, we may likely be able to accurately determine the macrometeoroid flux in the outer solar system, a determination that would not only tell us more about conditions in the outer solar system and possibly formation processes in the outer part of the early protoplanetary disc, but also provide much better impact safety estimates for outer solar system bound orbiting spacecraft such as Cassini, as well.

6. References.

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