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THE RINGS OF SATURN: STATE OF CURRENT KNOWLEDGE AND SOME SUGGESTIONS FOR FUTURE STUDIES

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ABSTRACT

In this brief overview, the state of our current knowledge of the properties of the ring system as a whole, and of the particles individually, is assessed. More detailed review papers are cited for further discussion and attention is primarily devoted to recent results and possibilities for exploration of the ring system by a Saturn orbiter. In particular, the infrared and microwave properties of the ring system are discussed. The behavior of the ring brightness is not well understood in the critical transition spectral region from ~ 100 μm to ~ 1 cm. Also, the dynamical behavior of the ring system is discussed. Recent theoretical studies show that ongoing dynamical effets continually affect the ring structure in azimuth (possibly producing the A ring brightness asymmetry) and in the vertical direction (possibly preventing the rings from flattening to a monolayer).

Orbital spacecraft-based studies of the rings will offer several unique advantages and impact important cosmogonical questions. Bistatic radar studies and millimeter-wavelength spectrometry/radiometry will give us the particle size and composition limits needed to resolve the question of the density of the rings, and provide important boundary conditions on the state of Saturn's protoplanetary nebula near the time of planetary formation.

Detailed study of the radial structure of the rings near resonance "gaps" will shed light on the whole question of ring formation and in a larger sense on planetary formation as influenced by dynamical effects. The recent discovery of the rings of Uranus further motivates such dynamical studies. Topics which would benefit from further study, either from spacecraft or from Earth, are noted.

I. INTRODUCTION

Due to their great beauty and uniqueness, the rings of Saturn have been studied as much or perhaps more in the past than Saturn itself. Their scientific importance is in fact also quite great. Trapped within the Roche limit of Saturn by the gravitational perturbations of the satellite Mimas, the ring particles have been unable either to escape or to accrete into a large body. Thus, if the rings formed in their current place, they represent a practically untouched remnant of the protoplanetary nebula, a direct condensate unaffected by thermal, chemical, or impact metamorphosis. However, it is also possible that the rings formed through tidal breakup of a pre-existing comet or satellite. Knowledge of the size distribution and bulk composition of these particles could permit final discrimination between these two origin hypotheses. For instance, the existence or absence of kilometer-sized "particles" would permit or disprove the breakup hypothesis. Even the bulk composition of the particles has not been definitely established. Current work indicates that cosmogonically plentiful ices could compose the bulk of the ring material. However, fairly pure metal may not as yet be ruled out. Thus, study of the rings could provide valuable constraints on theories of Solar System origin and evolution. In Section II the global structure of the rings (radial, vertical, azimuthal) is reviewed. In Section III current knowledge of particle size and composition is discussed. In Section IV likely advances due to Pioneer, Voyager, and interim Earth-based studies are mentioned. In Section V, important scientific questions will be presented which are appropriate for study by SOP^2. This brief paper will only touch the surface of existing research on Saturn's rings. For further background, the reader is referred to review papers by Bobrov (1970) Cook, Franklin, and Palluconi (1973), and Pollack (1975).

II. OVERALL PHYSICAL STRUCTURE OF THE RING SYSTEM

Radial Structure

The ring system exhibits obvious radial structure which has evolved a particular nomenclature. Currently accepted values for, and uncertainties in, ring element boundaries are given along with standard nomenclature in Table 1. Below we discuss

Table 1. Ring Element Boundaries (After Cook *et al.*, 1973)

Ring Region	Radius (km)	Boundaries Planetary (Equatorial) Radii*	Arc sec at 9.5388 AU
A Outer	137,400 ± 700 (est)	2.29	19.82" ±0.1" (est)
A Inner	121,800 ± 700	2.03	17.57" ±0.1" (est)
Cassini Division: Width	4,800 ± 700	0.08	0.7"
B Outer	117,000 ± 700	1.95	16.87 ±0.1" (est)
B Inner	91,800 ± 700	1.53	13.21 ±0.1" (est)
C Inner	72,600 ± 1,400	1.21	10.5 ±0.2"

*R_e = 8.65" ±0.02 at 9.5388 AU (Cook *et al.* 1973)

= 6×10^4 km (Dollfus 1970)

the radial structure in some detail and then review currently accepted values for optical depth of the rings at visible wavelengths as a function of radial distance.

1. Mechanisms governing radial structure.

The most likely explanation for the radial structure of the rings is that it arises from the effects of gravitationally induced perturbations in ring particle orbits which lie near commensurability with Mimas, one of Saturn's smaller satellites (see, e.g., Franklin and Colombo, 1970). The perturbation characterizing commensurability increases the eccentricity of the "resonant" particle until a collision removes the particle from the resonant orbit. Thus such commensurate orbits are unstable. This simple explanation serves very well to explain the inner and outer boundaries of the ring system. Given that only empty space exists beyond the resonance in either case, the collision which removes the particle from its unstable orbit is most likely to be with another particle *within* the rings and in such a case the final orbit will be more likely *within* the ring boundary than *beyond* the ring boundary. In this way the resonances are seen to present at least partially effective barriers to mass flow. The inner edge of the B ring, inner edge of Cassini's division, and the outer edge of the A ring represent such unstable orbits with periods equal to 1/3, 1/2, and 2/3 of the period of Mimas, respectively. The real radial brightness distribution is, of course, more complex (see Figure 1). However, the picture is more complex regarding the widths of the resonances.

2. Gaps within the rings

It has been recently realized (Greenberg and Franklin 1977) that the above mechanism will "clear out" only a region of radial extent ≤ 30 km, much less than the observed width of the Cassini division (see Table 1). Particles moving under the resonance, but more than ~30 km distant from it, do so "in phase" in their orbits and do not collide. Several mechanisms have been proposed to explain the observed width. Goldreich and Tremaine (1978) suggest that a density wave, induced at the resonances, travels outward and decreases the angular momentum of particles in a range which agrees well with the width of Cassini's division. Cook (1976) suggests that the system is evolving radially outwards, due possibly to magnetic or gaseous drag. High-quality observations near the edges of all the resonances and within Cassini's division will be necessary to supply further constraints on these hypotheses.

3. Optical depths in the rings

The optical depth, τ_0, provides an important boundary condition relating particle volume densities to particle sizes. By definition,

$$\tau_0 = \iint n(r, z)\, \pi r^2 dr dz$$

where r is particle radius and n(r, z) is volume density. The normal optical depth of the rings, τ_0, varies significantly with radial distance from the planet. Values of τ_0 have been obtained by two general methods: transmission of light through the rings ($I_{trans} = I_{inc}\, e^{-\tau_0/\cos\theta}$), where θ

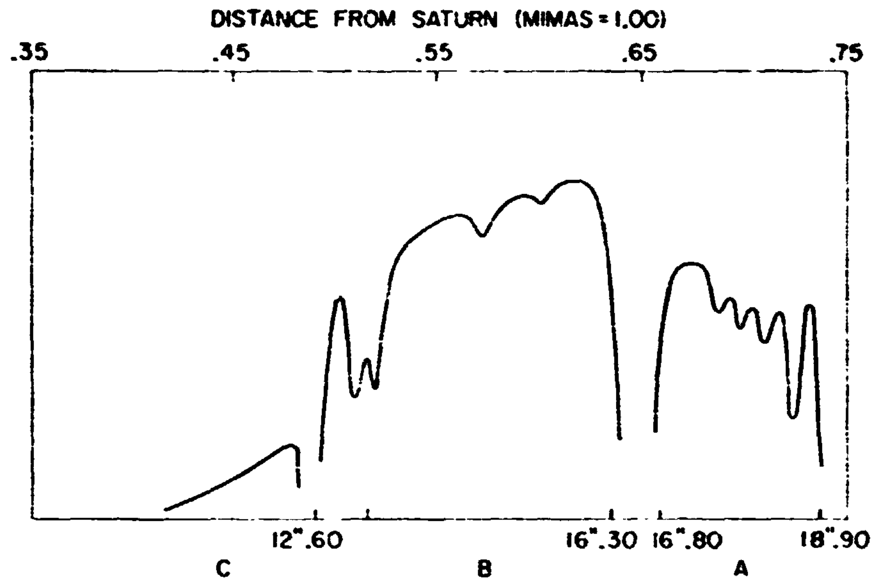

Figure 1. Brightness of the ring system as a function of radial distance from the center of Saturn at 10 AU (Dollfus 1970).

is the angle from the ring normal, and reflection of light from the rings. The former method is more direct as fewer assumptions about the ring structure, particle albedos, and phase functions are required. However, most quoted values have been obtained from the latter method, in which a simple scattering-layer model is used to calculate reflected brightness. Using the variation of brightness with tilt angle, one solves for both a particle albedo and local optical depth. Uncertainties in the optical depths so obtained may be quite large and the values themselves may be systematically low (Pollack, 1975; Cuzzi and Pollack 1978). Best current values for optical depth as a function of radial position are given in Figure 2 along with their sources and likely uncertainties. The optical depth of the Cassini Division is highly uncertain due to the many difficult and important corrections which must be applied to observations (smearing, scattered light, etc.) These values are azimuthal averages. Azimuthal variations are discussed below.

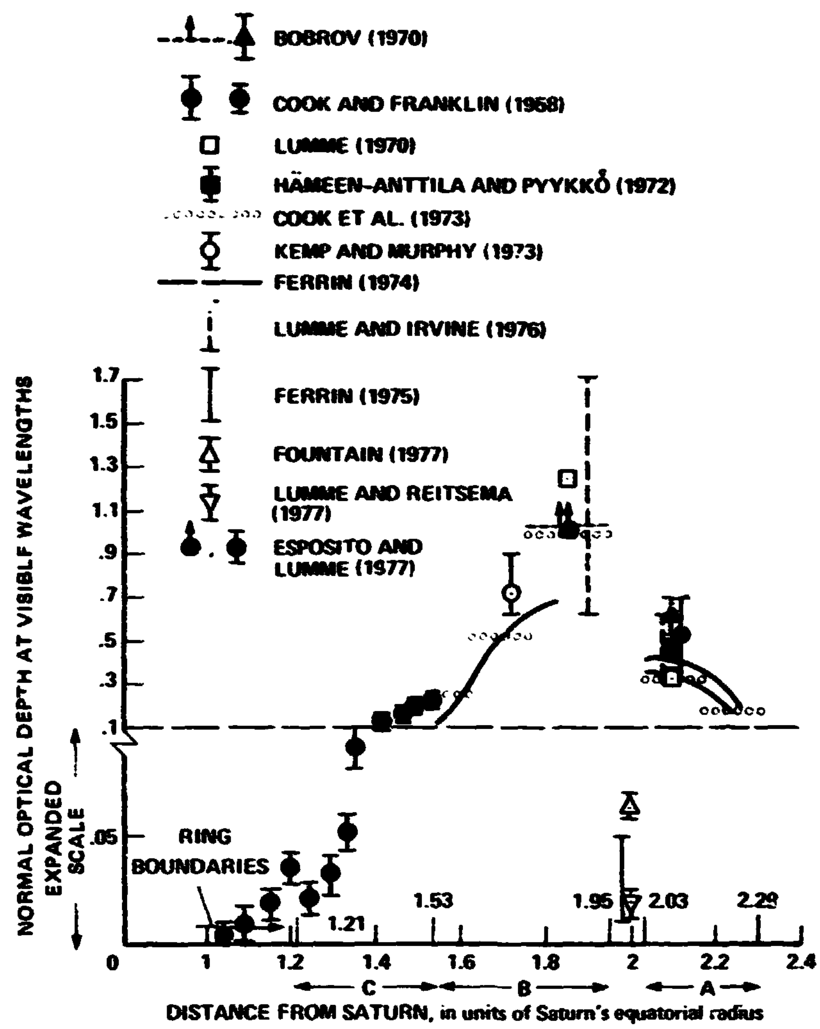

Figure 2. A comparison of several estimates of the optical thickness of the rings as a function of radial distance.

Vertical and Azimuthal Structure

The vertical and azimuthal structure are related in that they both deal with the local "internal" structure of the rings; that is, whether the rings are one particle thick (a "monolayer") or are many particles thick.

Perhaps the most significant observation constraining this question is the phase effect of the rings (see Figure 3). The net increase in brightness (about a factor of two) over 6° of observable phase is similar in magnitude to the lunar opposition brightening. Both arise from the fact that shadowing of particles in the lit surface by each other ceases rapidly as the directions to Sun and Earth become coincident at zero degrees phase angle. Detailed analyses of the effect for the rings (Irvine 1966, Bobrov 1970, Kawata and Irvine 1974) yield a volume density of particles $\sim 10^{-2}$ to 10^{-3} in a many-particle thick ring (see Figure 4), far lower than the lunar soil volume density (Hämeen-Anttila and Vaaraniemi 1975) and characterizing a layer containing particles which are separated by many times their own radius.

Until recently, dynamical arguments (Jeffreys 1947) indicated that inter-particle collisions would cause the rings to flatten and spread to a monolayer. This would require the opposition effect to arise from surface microstructure. However,

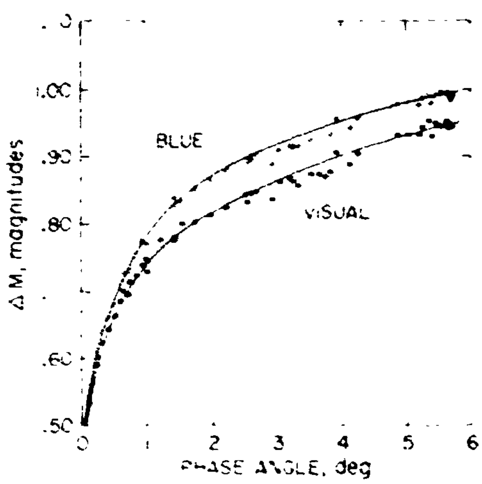

Figure 3. Phase curve for Saturn's B ring showing relative brightness, in magnitude units, as a function of phase angle, in degrees. From Franklin and Cook (1965).

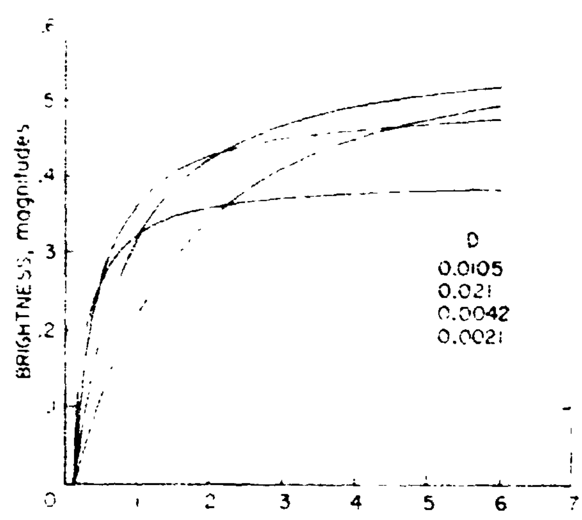

Figure 4. Theoretical curves for first-order scattering by a many-particle-thick ring with optical depth unity, and a ring tilt angle of 25°. The curves are labeled by the value of ring volume density. From Kawata and Irvine (1974).

recent studies of energy sources within the ring system (differential rotation, Mimas) indicate that a finite thickness may be maintained (Brahic, 1977; Goldreich and Tremaine, 1978a; Cuzzi *et al.*, 1978). The characteristic thickness is on the order of a few times the size of the largest particles. Should the rings also include a substantial number of much smaller particles, they would be "many particles thick." We return to this in Section III. In addition, other natural high-albedo surfaces (e.g., the Galilean satellites) show much less dramatic opposition effects (see Figure 5) than do the rings. The opposition effect for these objects, due to surface microstructure, is probably smaller due to particle transparency and multiple scattering. These, as well as other such observations, such as the color dependence of the opposition effect and of polarization, favor the many-particle-thick hypothesis slightly over the monolayer hypothesis (Pollack 1975).

The absolute thickness of the rings has not been observationally established. Observations at the time when the rings appeared edge on (Focas and Dollfus, 1969; Kiladze, 1969; Bobrov, 1970) have been recently re-analyzed (Lumme and Irvine, 1977) with the result that they appear to give only an upper limit of 3 km full thickness. The true thickness characterizing macroscopic particles is almost certainly two orders of magnitude smaller, if the rings are of the age of the solar system (Brahic, 1977; Goldreich & Tremaine, 1978a; Cuzzi *et al.*, 1978). However, radiation pressure could cause micron-sized particles to have vertical excursions as large as a kilometer (Vaaraniemi, 1973).

The rings present an interesting environment for horizontal structural variations as well. Gravitational perturbations by Saturn's satellites will theoretically produce a ripple, or wave, with largest components due to Titan, the Sun, Tethys and Mimas. Orbiting particles will attain vertical excursions as large as ~10 m or so, adjacent particles moving coherently in "roller-coaster" fashion (Burns *et al.*, 1978).

In addition it has been recently confirmed by several groups (Lumme and Irvine 1976; Reitsema, Beebe, and Smith, 1976) that Saturn's A ring exhibits azimuthal variations in brightness (see Figure 6). The amplitude of the effect is ~10% at maximum ring opening (26°) and increases slightly (to 15%) as the rings close to 16° (Lumme *et al.*, 1977). The "sign" of the effect (bright quadrants precede conjunctions) is not related to the position of the Sun or Earth, but the amplitude of the effect decreases at opposition (Lumme *et al.*, 1977). The effect is not shown by the B ring. Two classes of hypotheses have been advanced to account for the effect. One class invokes some use of large, synchronously rotating bodies which are either elongated or

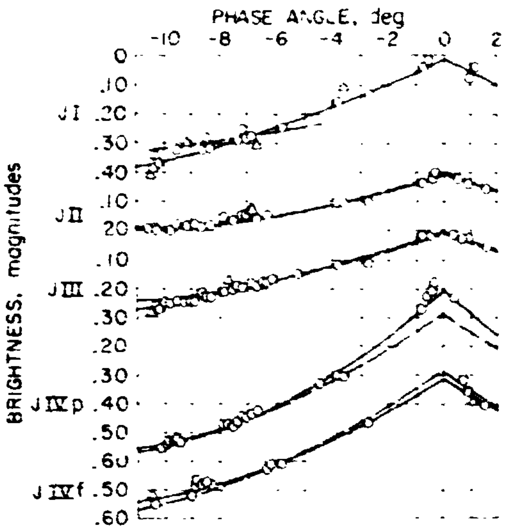

Figure 5. Phase curve for the Galilean satellites, JI, JII, JIII, and JIV From Stebbins and Jacobsen (1928).

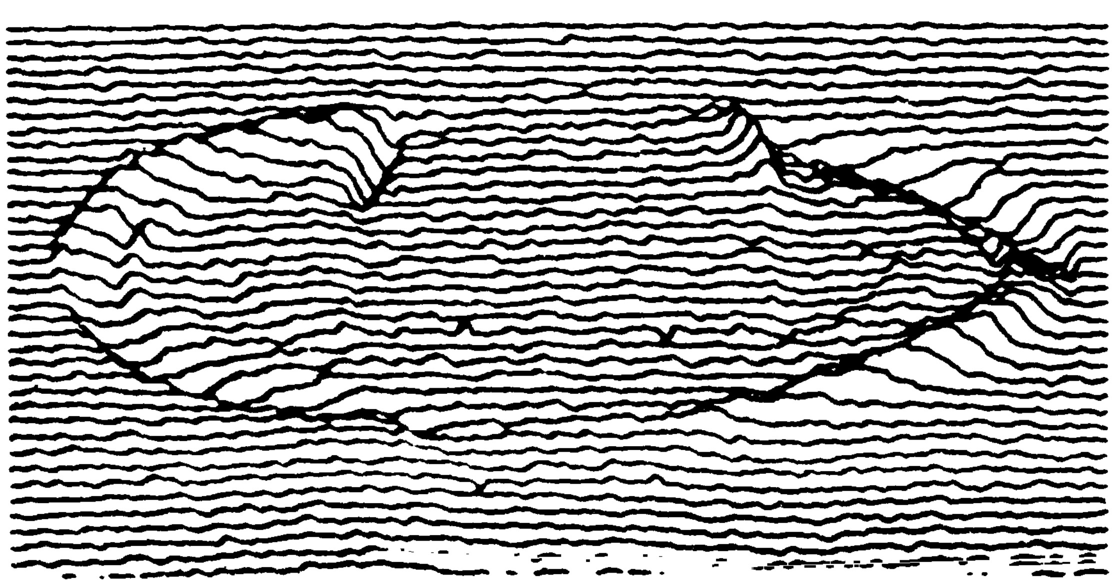

Figure 6. Quadrant asymmetry in the brightness of Saturn's A ring derived from a digitized Saturn image of 1977 January 26. Pseudo 3D plot shows the brightness when a mirrored image (left for right) is subtracted from the original Upper left and lower right quadrants of the A ring are maxima, while the upper right and lower left are minima (thus, East is to the right, and orbital phase angle increases clockwise). Shadow of planet on ring visible in upper portion. From Lumme et al 1977

asymmetrically reflective (Lumme and Irvine 1976, Reitsema *et al.*, 1976). The other class invokes transient, gravitationally induced, "clumping" of swarms of small particles in trailing "wakes" (e.g., Colombo, *et al.*, 1977). The predominance of very large (many-meter) particles in the rings is not in good agreement with microwave results discussed in Section III. Therefore some variant of the "clumping" hypothesis is favored.

Summary

The radial structure of the rings is determined primarily by orbital resonances with Mimas. The width of the Cassini Division is not completely understood, but may reflect the presence of a density wave driven by Mimas. The large opposition effect of the rings and other optical effects continue to favor the hypothesis that the rings are many particles thick, although some contribution from surface microstructure undoubtedly does exist. Dynamical arguments, including likely sources of particle random motions, are now apparently consistent with the many-particle-thick idea as well. However, the true "thickness" may in fact be no more than some tens of meters. A monolayer hypothesis would imply that the individual "particles" are many meters in size and, at least in the A ring, in synchronous rotation.

III. RING PARTICLE PROPERTIES

A full treatment of the great quantity of material dealing with particle properties such as narrowband and broadband geometric albedo, phase function, surface vs. bulk composition, and particle size is beyond the scope of this summary. In this article only a brief review of known or inferred particle properties is given. The reader is referred to review articles by Cook, Franklin, and Palluconi (1973), and Pollack (1975) for fuller details of the observations and their significance.

Particle Albedos and Temperatures

1. Albedos.

   The particle albedos ($\tilde{\omega}_o$) must be obtained simultaneously with ring optical depths by solving the multiple scattering problem and matching data such as the phase variation, tilt variation, and absolute value of the ring reflectivity. Many authors have approached this problem, usually by assuming isotropic scattering. The most sophisticated recent analyses, which include the use of both isotropic and anisotropic scattering phase functions, indicate that isotropic scattering is not consistent with the data (Kawata and Irvine, 1974, 1975; Esposito and Lumme, 1977). Particle albedos obtained in these analyses are shown for the brightest parts of the A and B rings in Table 2. The best-fit phase function is somewhat, but not strongly, backscattering, with derived values of the phase integral g ranging from ~ 0.9 to 1.6 (Lumme and Irvine, 1976; Esposito and Lumme, 1977). This value represents a surface intermediate between a Lambert surface and the lunar surface in degree of backscattering, similar to the characteristics of typical snowbanks (Veverka, 1970). The large range of allowed values of g and $\tilde{\omega}_0$ is due in part to the very small range of observable phase angles.

2. Particle temperatures.

Thermal balance calculations giving the physical temperature of the ring particles are quite complex in the case of the rings because of: (a) The gradient in insolation with optical depth in the rings and the associated diffuse radiation; (b) Heating of particles by the infrared emission of other particles; and (c) Heating of particles by emission from Saturn. In addition, the variation of (a) with ring tilt angle must be considered. These calculations have been carried out by Kawata and Irvine (1975), for likely upper and lower limits of bolometric Bond albedo $A_B = 0.54$ and 0.38 respectively. In addition to the uncertainties in Bond albedos at blue and visual wavelengths mentioned above, the large uncertainty in albedo from 0.7-1.1 μm wavelengths leaves the bolometric Bond albedo quite uncertain. The results (see Figure 7) are grossly consistent with thermal infrared observations (see Table 3 and Morrison, 1976) but, for the more realistic case $A_B \sim 0.5$, calculated temperatures are somewhat lower than recent observations. More study and better observations of the rings over a wider range of wavelengths and phase angles (i.e. from an orbiter) could help greatly to resolve this apparent discrepancy.

Table 2. Albedos at the Brightest Part of Each Ring Element

Ring Element	Mean Radius/R_E	λ	p	q	$\tilde{\omega}_o$	Source
A	2.10	V	1.1	0.57*	0.63	Cook *et al.*, 1973
		V	0.48-0.61	1.57	0.75-0.95	Esposito & Lumme, 1977
		V	0.72 ± 0.05	1.0-1.5	0.5-1.0	Lumme & Irvine, 1976
		V	---	---	0.75	Kawata & Irvine, 1976
		V	0.64 ± 0.04	1.0-1.5	0.8-1.0	Lumme & Irvine, 1976
B	1.85	V	1.1	0.57*	0.63	Cook *et al.*, 1973
		V	0.51-0.61	1.57	80-0.95	Esposito & Lumme, 1977
		B	0.86	0.57*	0.49	Cook *et al.*, 1973
		B	---	---	0.48	Kawata & Irvine, 1975

*Assumed value

Spectral Observations and Compositional Implications

Water ice was first identified in the rings by Pilcher *et al.* (1970), and Kuiper *et al.* (1970) using 1-3 μm spectroscopy (see Figure 8). The shapes of the spectral features in this region vary both with temperature (Kieffer 1974, Fink and Larson 1975) and particle size (Pollack *et al.* , 1973). Pollack *et al.*. 1973, used this effect to infer the grain size of the ice particles doing the absorbing to be ~ 30-40 μm (see Figure 9). As discussed in section C below, this is probably the size of individual grains on the surfaces of much larger particles. The variation of ring reflectivity over the entire visible-near IR range, however, (Lebofsky *et al.*, 1970), is not consistent with a pure water ice composition, which would have constant reflectivity in the 0.3-1.0 μm region. In fact, the spectral reflectivity of the rings (see Figure 10) closely resembles that of Jupite 's innermost (and highly reddened) satellite Io (Johnson and McCord, 1970) in overall behavior. The spectra of the A and B rings are quite similar. This

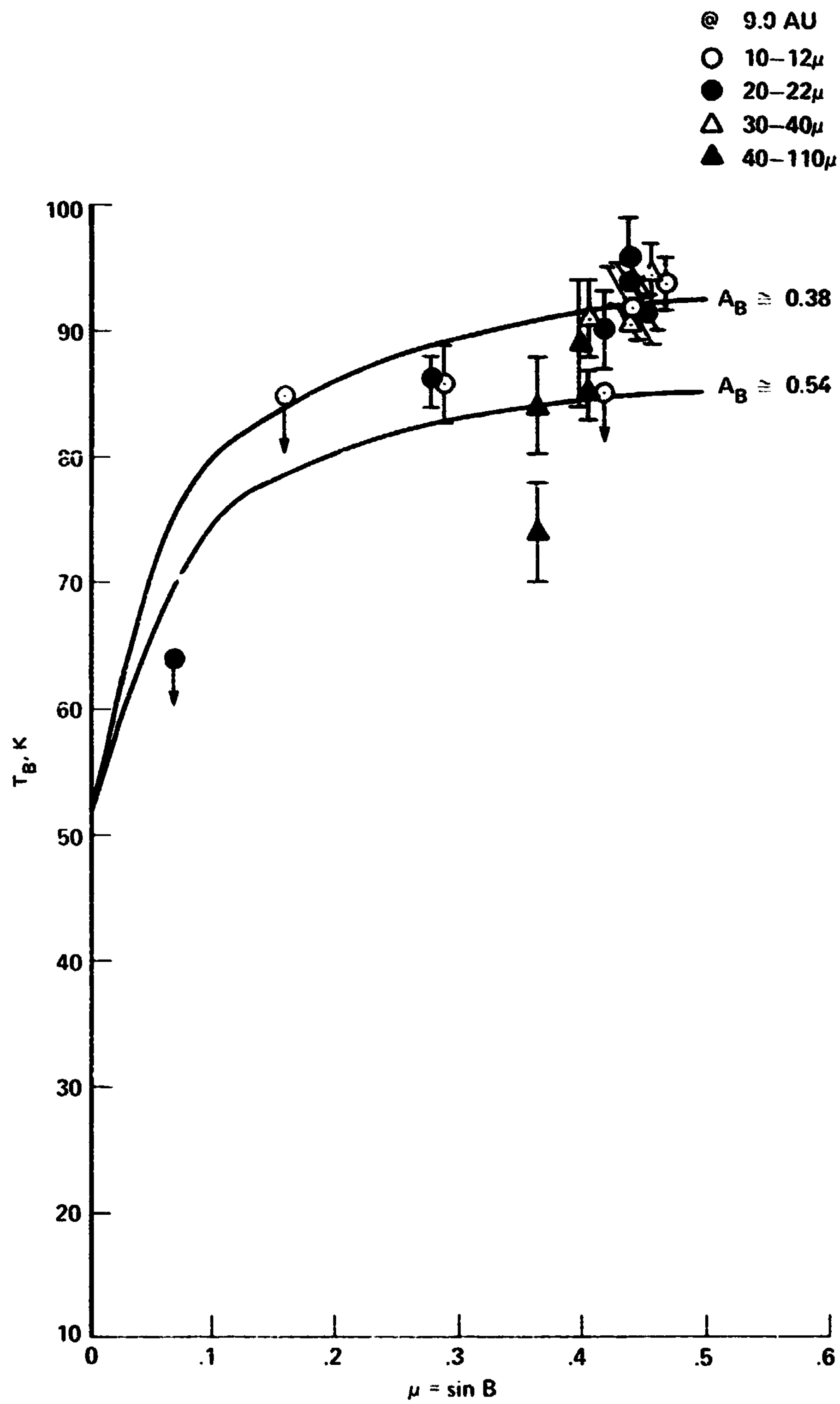

Figure 7. Calculated infrared brightness of Saturn's B ring as a function of ring tilt angle for two choices of particle Bolometric albedo, from Kawata and Irvine (1975). Observations from Table 3 are plotted, normalized to a heliocentric distance of 9.0 AU.

Table 3. Observations of the Brightness Temperature of the B Ring in the Thermal Infrared*

Year	λ, μm	T_B (B ring), K	Tilt Angle, B	Observers
1964	10	<85	~9°	Low (1965)
1965	20	<64	~4° ± 1°	Low (unpublished)
1969	12	86 ± 3	17°	Allen & Murdock (1971)
1971	20	90 ± 3	25°	Murphy *et al.* (1972)
1971	11	<85	11	Armstrong *et al.* (1972)
1971-72	45-80 65-110	85 ± 7 89 ± 5	255° 255°	Armstrong *et al.* (1972) Wright (1976) recalib.
1972	20	94 ± 2	26°	Murphy (1973)
1973	20	96 ± 3	26°	Morrison (1974)
1973	11	92 ± 3	26°	Morrison (1974)
1973	35	92-97	26°	Nolt et al (1974)
1973	~33	91 ± 2	26°	Rieke (1975)
1974	~11	94 ± 2	26°	Rieke (1975)
1974	~22	91.5 ± 1	26°	Rieke (1975)
1975	39	91 ± 3	24.5°	Nolt *et al.* (1977)
1976	45-80 65-110	84 ± 4 74 ± 4	21.8°	Ward (1978)
1977	22.7	86 ± 2	16°	Nolt *et al.* (1978)

*Corrected to heliocentric distance of 9.0 AU

reddening effect is not understood, but could be due to trace impurities (sulfur? phosphorus? Axel dust?) and/or the effect of charged particle bombardment on the ice lattice (Pollack, 1975). An even stronger reddening is seen in the spectrum of Titan (see Figure 11). The existence of water ice comes as no surprise due to its abundance and stability compared to methane and ammonia ice in the outer solar system. Hydrate clathrates of methane or ammonia with water ice are also possible (Miller, 1961). Their existence has not yet been established observationally, as near-IR spectra (Smythe, 1975) do not distinguish water ice from clathrates. Spectra at longer wavelengths, however, (Bertie *et al.*, 1973) could be quite useful.

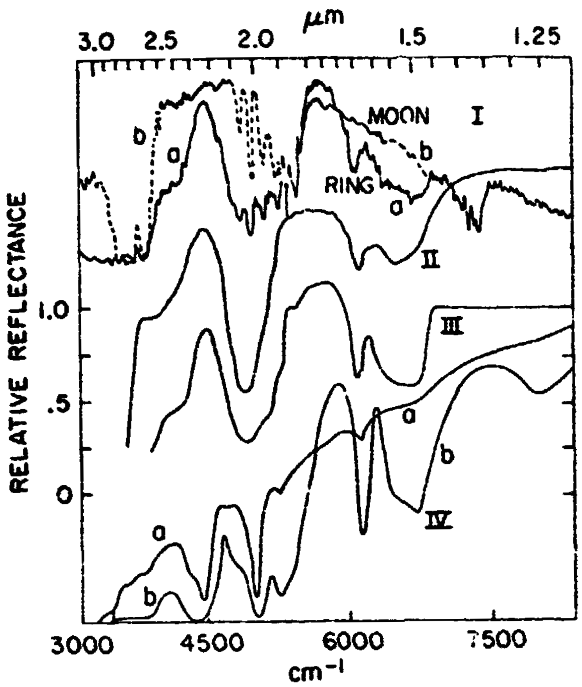

Figure 8. Comparison of the reflectance spectra for H_2O and NH_3 frosts and Saturn's rings. (Ia): The Saturn ring spectrum of Kuiper et al. *(1970) (Ib): Lunar comparison spectra; (II): Fine-grained H_2O frost spectrum; (III): Spectrum of the rings divided by that of the moon; (IV): NH_3 frost, fine grained, a; coarse grained, b. From Pilcher* et al. *(1970).*

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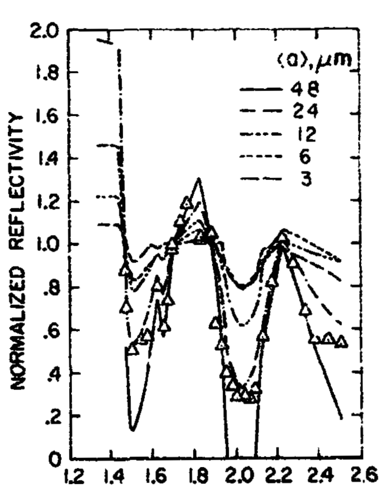

Figure 9. Comparison of the reflectivity spectrum of the rings (triangles) with theoretical curves for the reflectivity behavior of a water frost surface characterized by a mean given radius (a). The observed values were obtained from Kuiper et al. *(1970). From Pollack* et al. *(1973).*

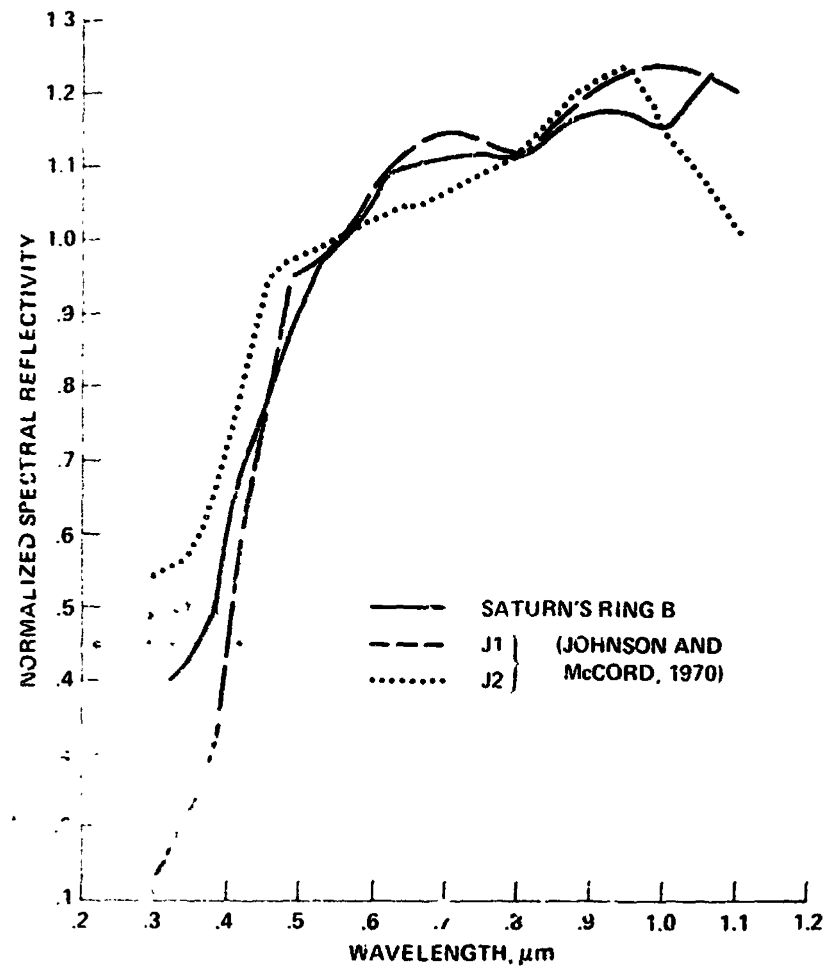

Figure 16. The normalized spectral reflectivity of Saturn's B ring is shown, compared with spectra of J1 and J2. From Lebofsky et al. (1970).

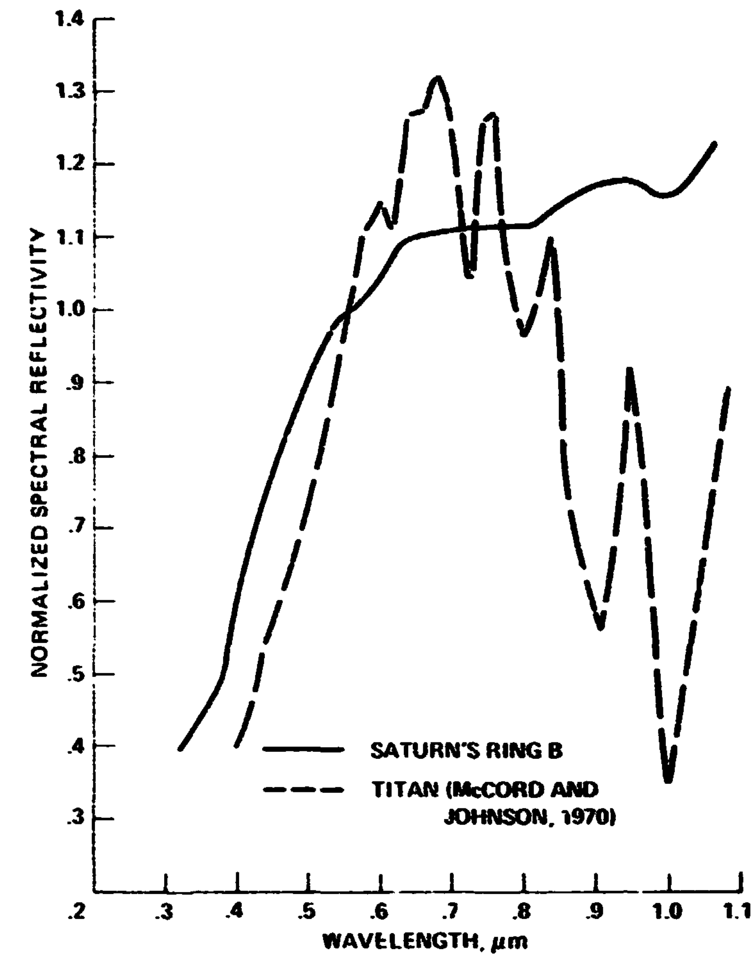

Figure 11. The spectral reflectivity of Saturn's B ring is shown along with the spectral reflectivity of Titan. From Lebofsky et al. (1970).

The above observations sample only the surface layers of the ring particles, and do not constrain the bulk particle composition. Observations at microwave wavelengths sample depths of centimeters to meters, giving a better idea of the bulk composition. However, particle size effects may be significant at these longer wavelengths. Therefore, we discuss these two aspects simultaneously below.

Particle Size Distribution and Composition as Constrained by Microwave Observations

The brightness temperature of the rings at wavelengths $\gtrsim 0.86$ cm is $\lesssim 10 \pm 3$ K, significantly lower than their physical temperature of 95 K or so. This result comes from current model analysis (Cuzzi and Pollack, 1978) of published interferometric (high resolution) observations (Briggs, 1974; Cuzzi and Dent, 1975; Janssen and Olsen, 1974). Recent interferometer maps of the rings (Muhleman *et al.*, 1976, Schloerb, 1977) are in agreement with this low, but non-zero, ring brightness. The low temperature is due to an emissivity effect, as the optical depth of the rings at centimeter-decimeter wavelengths is comparable to its value at visible wavelengths based both on the above observations and on the high radar reflectivity of the rings (Goldstein and Morris, 1973; Goldstein et al., 1977). In fact, for the high reflectivity implied by the radar observations, it is not difficult to show that most, if not all, of the microwave brightness of the rings is scattered radiation from the planet, and not "emission" at all. At longer wavelengths, the rings seem colder (Berge and Muhleman, 1973; Briggs, 1974; Jaffee. 1977) and perhaps less optically thick.

Two possibilities exist for the low emissivities. First, the bulk material of the particles could have an intrinsically low emissivity. To match the observations by this "compositional" means alone for particles much larger than the wavelength in size, nearly pure metallic particles or particles possessing dielectric loss orders of magnitude lower than the least lossy of naturally occurring materials (ices) would be required. Second, as pointed out by Pollack *et al.* (1973) particles of size comparable to a wavelength may have extremely low emissivity, and yet high scattering efficiency, in the presence of a realistic value of dielectric loss such as possessed by ices. Using radio brightness limits and the observed radar reflectivity at two wavelengths, 3.5 and 12.6 cm, Pollack (1975) and Cuzzi and Pollack (1978a, 1978b) have set constraints on the possible particle size distribution and composition using realistic scattering models. First, silicates are excluded except possibly as a minor (<10% by mass) constituent of the particles. Second, water ice (or clathrate) particles with radii distributed following a power law distribution $n(r) = n_o r^{-3}$ for $1 \text{ cm} \lesssim r \lesssim$ several meters could satisfy the observations if distributed in a many-particle-thick layer (see Section II). The upper limit on r here depends on the value of dielectric loss for the ice at 100 K and is not known to better than a factor of three or so (Whalley and Labbé, 1969). Third, an optical depth $\gtrsim 1.5$ at visible wavelengths in the thickest part of the B ring is indicated. Fourth, metallic particles larger than a centimeter in radius are still a possibility. Fifth, very large (many-meter) particles of very low density ($\lesssim 10^{-1}$ g cm^{-3}) with subsurface scatterers of the composition and sizes discussed above could also satisfy the existing observations based on analogy with the high radar reflectivity and depolarization characterizing the Galilean satellites (Campbell *et al.*, 1977; Ostro and Pettengill, 1977). Some of the results leading to these constraints are shown in Figures 12-14, and these results are summarized in Table 4. The important aspects of the radar observations are their high absolute value and depolarization, and apparent wavelength independence.

Another point of interest is that the radial variation of radar reflectivity is in fairly good agreement with the radial variation of visible depth (Pettengill *et al.*, 1977). A corollary of the microwave results is that the fraction of the rings (by surface area) composed of particles smaller than a centimeter or so must be quite small. This result is in good agreement with the results of analysis of eclipse cooling of the particles by Aumann and Kieffer (1973) and observations by Morrison (1974) that the particle size is greater than about 1.5 cm. These results are also in agreement with the likely structure of the ring as discussed in Section II and with the expected lifetime of small particles against Poynting-Robertson drag. However, one should not be surprised to find some small particles (<< 1 cm in size) in the rings, possibly being continually produced in collisions.

The rings are largely unobserved in the interesting transition wavelength range between 100 μm and 1 cm within which the temperature drops from ~ 90 K to ~10 K. Far-infrared observations (about 10-400 μm) over the last ten years appeared to show a clear contribution from the rings at their physical temperature (see Table 5). In addition, observations of Saturn relative to Jupiter at ~ 1 mm wavelength (Low. 1966; Rather *et al.*, 1975) appeared to show some ring contribution at a brightness temperature of 30-40 K. However, recent observations are not in agreement with these results. From a scan of Saturn at 400 micrometers, it appears that the brightness of the rings is less than 0.35 of the disk brightness (Werner, private communication). Also Werner *et al.* (1978) see no evidence for excess flux due to the rings (in an unresolved observation comparing total flux with Jupiter) at 1 mm wavelength. These important short wavelength observations will become more difficult as the solid angle of the rings decreases further in coming years, but will be essential to understanding the composition and size distribution of the ring particles.

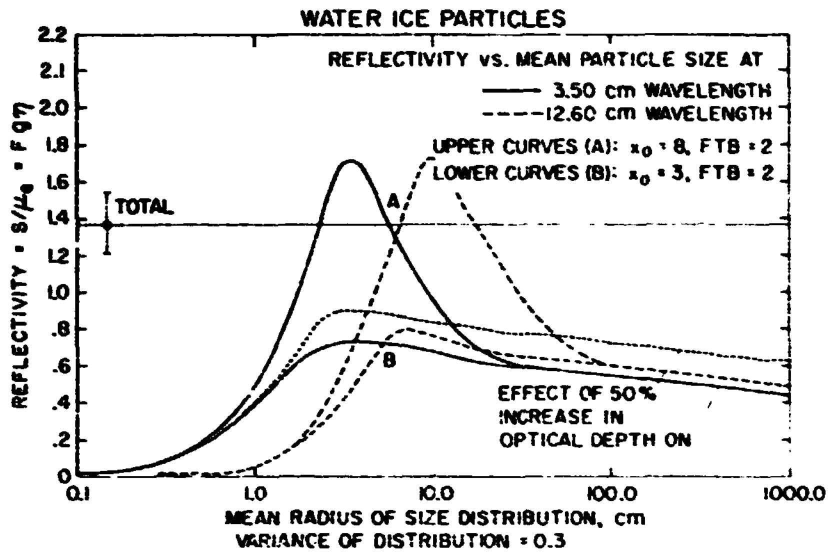

Figure 12. Comparison of observed radar reflectivity with the calculated reflectivity of a many-particle-thick layer with a relatively narrow size distribution. The parameters x_0 and FTB characterize scattering by nonspherical particles and are fairly typical values for rough (x_0 = 3) and smooth (x_0 = 8) particles respectively. From Cuzzi and Pollack (1978).

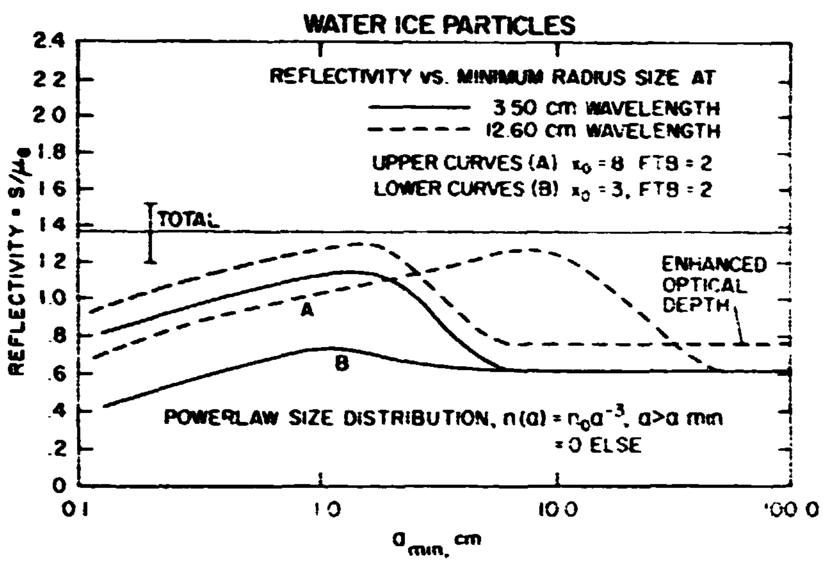

Figure 13. Comparison of observed radar reflectivity with the calculated reflectivity of a many-particle-thick ring layer composed of ice particles with a broad (power law) size distribution. From Cuzzi and Pollack (1978).

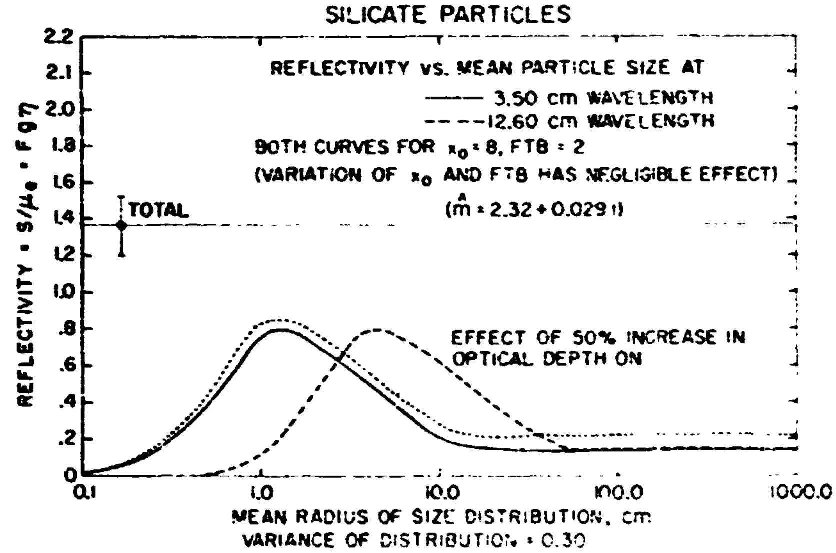

Figure 14. Comparison of observed radar reflectivity with the calculated reflectivity of a many-particle-thick ring layer composed of silicate particles. From Cuzzi and Pollack (1978).

Table 4. Acceptability of Ring Models of Different Structure, Composition, and Particle Size

	Particle Composition		
Model Structure	Ice	Rock	Metal
Extended layer:			
A: $a \ll \lambda$ ($a < 1$ cm)	No, due to low net reflectivity and strong λ-dependence	No, due to low net reflectivity and strong λ-dependence	No, due to strong λ-dependence
B: $a \gtrsim \lambda$ (narrow size distribution)	Possible ($\bar{a} = 6 \pm 1$ cm only)	No, due to low net reflectivity	Possible
C: $a \gg \lambda$ ($a > 1$ m) (narrow size distribution)	No, due to low net reflectivity	No, due to low net reflectivity	Possible
D: Power law ($a > 1$ cm) $n(a) = n_o a^{-3}$	Possible	No, due to low net reflectivity	Possible
Monolayer:			
A: $a \ll \lambda$ ($a < 1$ cm)	No, due to low net reflectivity and strong λ-dependence	No, due to low net reflectivity and strong λ-dependence	No, due to strong λ-dependence
B: $a \gtrsim \lambda$ ($a > 1$ cm)	Unlikely, due to low depolarization	Unlikely, due to low depolarization	Unlikely, due to low depolarization
C: $a \gg \lambda$ ($a > 1$ m) (narrow size distribution)	Possible (multiple internal scattering)	No, due to low net reflectivity	Unlikely, due to low expected depolarization
D: Power law ($a > 1$ cm) $n(a) = n_o a^{-3}$	Unlikely, due to low depolarization	No, due to low net reflectivity	No, due to low net reflectivity

Table 5. Far Infrared Observations of Saturn and Its Rings: Variation of Net Flux Coming from Disk Using Values of Disk T_B Derived on Two Different Assumptions

F1: T_B obtained assuming no flux from rings.

F2: T_B obtained assuming rings & disk of equal temperature

Date	Tilt Angle	Area (Disk + Rings)/Area (Disk)	$\left(\frac{F_1\ (\text{date})}{F_1\ (1968)}\right)$	$\left(\frac{F_2\ (\text{date})}{F_2\ (1968)}\right)$	Source
Dec. 1968 (1-350 μm)	-11°	1.0	1.0	1.0	Aumann *et al.* (1969)
Winter 1975-76	-21°	1.6			
(40-300 μm)			1.5 ± 0.3	1.0 ± 0.1	Loewenstein *et al.*
(100-400 μm)[b]			1.8 ± 0.1[b]	0.93 ± 0.03	(1977)
Oct. 1971 (30-300 μm)	-24°	1.8	1.7 ± 0.1	1.0 ± 0.1	Armstrong *et al.* (1972) and
(125-300 μm)[b]			2.0 ± 0.1[b]	0.97 ± 0.03	Wright (1976)
Winter 1973-74 (300-500 μm)[b]	-26°	1.9	1.9 ± 1[b]	0.9 ± 0.1	Hudson *et al.* (1974)

a) approximate correction for ring blockage by planet included.
b) Rayleigh-Jeans limit assumed in scaling temperature to flux.

Summary

The albedos of the ring particles are somewhat uncertain, but quite high ($\tilde{\omega}_o \gtrsim 0.8$) at blue and visible wavelengths. The scattering phase function is fairly backscattering, but not as highly backscattering as that of the lunar surface. These properties are similar to those of typical snowbanks. Particle temperatures calculated for a range of values for the bolometric albedo consistent with the above results decrease with ring tilt angle as observed, but seem slightly low (5-10 K) with respect to observations in the thermal IR. Water ice (and possibly clathrate hydrates) apparently constitutes the major part of the ring material, although ice-coated metal may not be ruled out on the basis of existing infrared, radio, or radar observations.

Metal may, however, be regarded as unlikely both on grounds of cosmic abundance and on grounds of its high density. If the ring particles were of metal, the Roche limit would lie well within the rings and accretion could proceed. Also, the

net ring mass based on the observed volume density would very likely be so large as to cause a noticeable discrepancy in the location of Cassini's division (see Section II).

It appears that the particles must be larger than a centimeter or so in size. A very broad size distribution, possibly $n(r) = n_o r^{-3}$, is consistent with all existing data if the largest particles are several meters in radius. Such a situation would explain the probable ring "many-particle" thickness and azimuthal variations (Section II) as well, in terms of dispersion of the numerous small particles by the few large ones. Another possibility is that the "particles" are much larger, with internal scatterers of centimeter-to-meter size fixed in a low-density matrix.

IV. NEAR-TERM INFORMATION EXPECTED (1978 – 1984)

Earth-based Studies

1. Further investigations of the opposition effect and the azimuthal brightness variations with decreasing ring tilt angle and at longer (red, IR) wavelengths. These will hopefully constrain the particle albedo more closely, impacting the question of the "infrared discrepancy."

2. An interferometric observation of the ring brightness at 3 mm wavelength may be possible in the near future, but in general critical short microwave-wavelength observations (100 μm - 1 cm) will become more difficult as the rings close up. Hopefully, laboratory measurements of the microwave (and infrared) dielectric properties of ices and clathrates at low temperatures will be obtained, as these will eventually be critical for final analyses of ring particle size and composition.

3. Continuation of radar backscatter observations of the rings as they close up may allow us to discriminate between monolayer and many-particle-thick models.

Pioneer and Voyager

1. Pioneer 11 will "probe" the region exterior to ring A for particles, but due to the low value of ring tilt angle, may not provide much other information.
2. Voyager will encounter Saturn at a ring tilt angle of 5 degrees. The Voyager Radio Science experiments (Eshleman *et al.*, 1978; Tyler, 1978) will obtain high-quality information on ring optical depths for regions with low (τ_o < 1) optical depths. Parts of the B ring may still be opaque. Good radial resolution will be obtained (~100 km) giving new information on dynamics and radial structure. Proper use of the two Voyager spacecraft in different modes (one in direct occultation, one in large-angle bistatic reflection) will provide information on particle sizes spanning the whole range of interest. Oblique scattering angles are desirable both in studying particles between 1 cm and several meters in size, and in obtaining interesting polarization results, which bear directly on particle shape.
3. Voyager IRIS experiments will obtain independent "mean" size information from observations of eclipse cooling of the particles. Spectral observations from 0.3-50 μm will provide useful information on composition and temperature of the particles observed. Photography may reveal the existence of extremely large "parent" bodies with sizes on the order of a kilometer or more.
4. Determination of the ring mass with an accuracy of $\sim 10^{-6}$ M_s will be possible. This measurement will probably discriminate between ices and metal as major material constituents. However, if the rings are of ice, their mass may very well be less than the above detection limit.

V. POTENTIAL USES OF SOP^2 FOR STUDY OF THE RINGS

Composition Determinations and Relevance to Studies of Solar System Formation

As mentioned in Section 1, the origin of the rings is still not well-established. However, indications are that very large (> 1 km) particles are, at best, a rarity in the rings. As internal strength would limit the size of fragments produced by Roche breakup of a larger satellite to a value at least this large (Harris, 1975; Greenberg *et al.*, 1977), this may be taken as at least an indication that the ring material is a direct condensate from the proto-planetary nebula. Because the ring particles have not been chemically or thermally altered by atmospheric or tectonic processes, they provide a valuable boundary condition on conditions in the protoplanetary nebula.

For instance, Lewis (1973) and Miller (1973) have suggested that methane and ammonia hydrates are stable at temperatures around or below 90 K. Thus, one would expect them to exist currently, if they ever formed. Pollack *et al.* (1977) have shown that the early high-luminosity phase of proto-Saturn may have kept the region of the rings too warm for anything but pure water ice to form there, and then only very close to the end of the accretion period. Thus, determination of the clathrate *vs* ice composition will provide an important constraint on the formation history of Saturn and the outer solar system in general. This may well be accomplished by an IRIS-type experiment operating out to long wavelengths (~1-100 μm) where spectral discrimination of clathrates appears to be possible (Bertie *et al.*, 1973). Some evidence for spectral structure in the 10 and 20 μm region has been inferred in observations by Morrison (1974). Laboratory work is needed to determine critical wavelength intervals and sensitivity required. In addition, trace silicate impurities which may be admixed in the ice may be representative of the composition of the original interstellar grains, and may be present in sufficient amounts to be detectable by an IRIS experiment. Hydrated silicates appear to be likely constituents of the Galilean satellites (Pollack *et al.*, 1978) and observable even from the ground. High-resolution spectra at visible wavelengths would help resolve the source of the "reddening" which seems to characterize all outer solar system objects. Organic photo-products have been suggested for this "Axel dust" on Titan, but the rings have no atmosphere in which to form such products.

Both in ice vs clathrates and ice vs silicate, compositional gradients may exist with distance from Saturn at a level which might be detectable only with substantial integration time, requiring repeated observations from an orbiter.

Particle Size Distribution and the Evolution of the Rings

A detailed knowledge of the particle size distribution, possibly a function of distance from the planet, may tell us a good deal about the evolution of rings. Smaller particles will be affected more by drag effects and will drift inwards. Also particles undergoing the most collisions (the smaller, more numerous particles) will diffuse inwards and outwards the most rapidly. Thus, information may be gained as to whether the rings originated in one place and diffused radially, or remain in much the same location in which they were formed. The exact form of the size distribution may be compared with distributions characterizing meteorites and with theoretical studies of accretion/comminution processes (Greenberg *et al.*, 1978) to give us a greater understanding of the accretion process itself.

These studies would be best accomplished using bistatic radar reflectivity and polarization studies over as large a range of view angles as possible. This implies observations from a fairly inclined orbit ($\sim$10-20°) with respect to the ring plane. Such an inclined orbit would also improve our chances of obtaining a ring mass as separable from the higher gravitational harmonics of Saturn itself. A full knowledge of the diffuse scattering properties of the rings (see Figure 15) would provide an excellent constraint on the distribution of particle sizes from less than one centimeter to several meters radius. Studies of the polarization would allow inferences as to particle shape and irregularity to be made, giving qualitative information on the collisional processes shaping the particles. Repeated ring occultations at a time when the rings are fairly open ($\sim$20 degrees in 1984) will give us full knowledge of the optical depth in the thickest regions of the rings which will be necessary for understanding of the intensity and polarization results. Coherent radio occultations also provide a good means of detecting small ($\ll$1 cm radius) particles, by the phase shift of the coherent signal.

Radiometry at short microwave wavelengths (100 μm-1 mm) would be of great value in establishing limits on the size of the largest particles. These maximum sizes might also vary with radial distance. Current values of ring brightness temperature at millimeter wavelengths are not in agreement; however, model calculations (Cuzzi and Pollack 1978) indicate that brightness temperatures of 30-50 K could be expected, if the particles are composed of ice. Better knowledge of the critical transition zone between 100 μm and several millimeters wavelength will be essential to better knowledge of the particle sizes and compositions. Improved knowledge of the phase effect at visible wavelengths would lead to good determination of the volume density of the rings critical for proper analysis of the microwave scattering behavior. The volume density may vary with radial distance, especially near the resonances, providing indirect information on the dynamics of resonances and ring thickness.

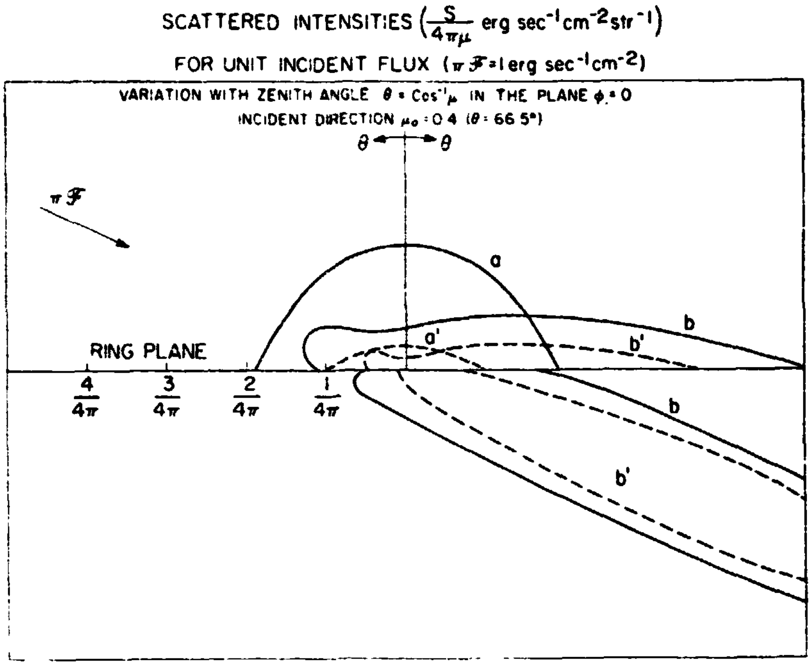

Figure 15. The angular distribution of diffusely scattered and transmitted radiation in the plane of incidence. The incident plane wave has unit flux normal to itself. Curves a and a': total and singly scattered intensities reflected by a semi-infinite layer of isotropic scatterers with $\tilde{\omega}_0 = 1$. Curves b and b': total and singly scattered intensities diffusely reflected and transmitted by a typical ring model composed of centimeter-to-meter-sized particles in a many-particle-thick ring layer. From Cuzzi and Pollack (1978).

The ring system as a dynamics laboratory: The recent discovery of the rings of Uranus shows that ring systems are more common than had been thought, and vary greatly in nature. These two systems afford us a great opportunity to study large-scale gravitational perturbations which could lead to a better knowledge of the accretion processes forming resonant pairs of satellites, and even planets themselves (Goldreich and Nicholson, 1978), as well as large-scale dynamical effects influencing galactic structure. For instance, the exact shape and optical depth of the gaps in the rings will allow tests to be made of density wave theory in differentially rotating disks (Goldreich and Tremaine, 1978). Knowledge of the "strengths" of the Mimas resonances as barriers to mass motion (from theory), studies of the optical depth variations across the resonances, and the "spreading rate" of the rings as determined by velocity dispersion (thickness) may be compared with observations of radial diffusion of particles as evidenced by radial variations in composition on particle size distribution. More detailed study of local ring irregularities such as the non-axisymmetric disturbances in ring A and the physical thickness of the rings, even from $3R_S$ orbital distance, appears to be difficult as these are probably tens of meters in size, requiring angular resolution less than 0.1 arc sec.

Summary

Several points of interest are noted vis-a-vis use of SOP^2 to study the rings and the relevance of these studies to solar system formation. Studies of particle composition and size distribution, and their variations with distance from the planet, could provide several useful constraints on conditions prevailing in the proto-planetary nebula. These are best accomplished from inclined orbit (10-20°) with visible photometry at several wavelengths (or spectroscopy), an IRIS experiment operating from 1-50 μm (100 μm?) wavelength, a multiband radiometer operating from ~100 μm to several millimeters wavelength, and extensive bistatic radar mapping. Studies of the dynamics of particles in the rings will greatly improve our theoretical understanding of the gravitational processes that influenced, and might have initiated, planetary accretion and evolution. These will arise from extensive photography of the rings and repeated radio occultations of an orbiter by the rings.

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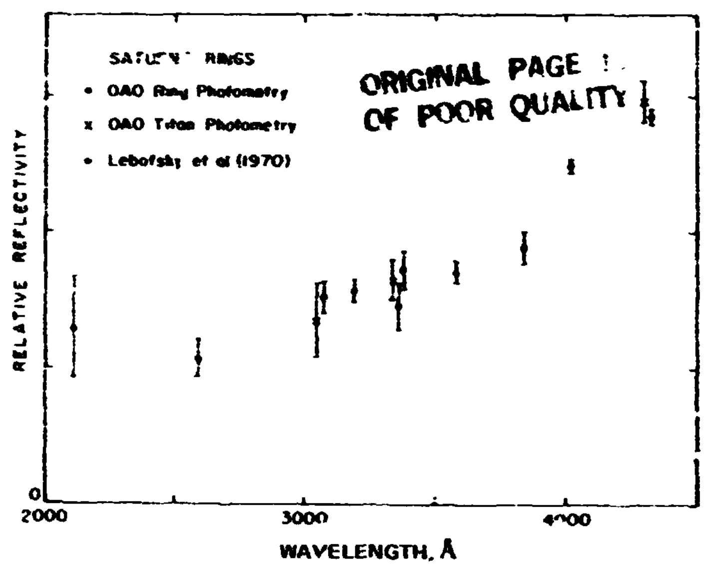
DISCUSSION

J. CALDWELL: I would like to show a Figure A taken from Caldwell, J. (1975) Ultraviolet observations of small bodies in the Solar System (Icarus 25, 384-396) and compare it with one of Jeff's (see Figure 9)



This figure shows OAO data that extend the reflectivity measurements of the rings below 3000 Å to practically 2000 Å. The precipitous drop in reflectivity implied by McCord and his colleagues stops around 3000 Å.

The reflectivity in the 2000-3000 Å region is flat and is consistent with water frost. It also appears to me that the total spectrum would be consistent with two components. I don't know whether they are spatially separated or mixed together.

The ultraviolet reflectivity of the rings does not look like that of the Galilean satellites, which continue to decrease noticeably all the way down to 2000 Å, at least for those for which measurements are possible (Callisto, Ganymede, and Europa).

L. TRAFTON: Although the rings are brighter than Titan, the relative reflectivities from 5000 Å down to at least 3000 Å are very similar. So whatever makes up the dust on Titan, may be the same stuff which helps to color the rings.

B. SMITH: During the recent Iapetus eclipse we did confirm the existence of the Encke division or minimum, so we have a little more than Dollfus's visual observation to go on.

Also, with regard to ring thickness seen at the time the Earth goes through the ring plane, its true that the rings never completely disappear, but the model that Cook has developed has turned up edges near the resonance divisions. Thus the rings can be very thin and still appear thicker when seen edge on.

J. CUZZI: Yes, however it is uncertain whether Cook's inclination resonance, which produces the "turned-up" edges, lies in a region containing particles, or in fact within an empty region near the ring edge.

D. MORRISON: In your upper limit on the amount of silicates that can be included in the particles and still be consistent with the radar measurements, I presume that it refers to the centimeter or perhaps the 10-cm particles. If you had a silicate core in some of the large objects, could you tell the difference?

J. CUZZI: Probably not. The meter-sized and larger objects in the power law distribution contribute relatively little to the radar signal, so their properties do not constrain the model.

D. MORRISON: So, in fact, a component of a relatively small number of meter-sized objects made of anything would be consistent with existing data.

J. CUZZI: Yes, as long as their total surface area, or optical depth, is less than a few percent of that of the entire ring system.