atmosphere of Saturn is an open question which is being examined separately. Thus, the measurements in the LSB are much more reliable than those in the USB. The results for P1334-127 are shown in the first three rows of Table 2 and the best estimate of the flux density at $\lambda = 2.661$ mm is 3.35 ± 0.11 jansky. The resulting "continuum" brightness temperature of Titan is 69.0 ± 10 K. Results for the USB are shown for completeness. Clearly, the ratio of the two Titan temperatures from Table 2 is far less accurate than that from Table 1.

We show the entire microwave spectral models of Titan for three surface dielectrics in Fig. 2. Also shown are our measurement at 112.6 GHz, the three Very Large Array (VLA) measurements of Jaffe *et al.* (*10*) at 5, 15, and 23 GHz, and the 1-mm bolometer measurement from Roellig *et al.* (*11*). The last measurement was corrected from the published value of 86 ± 12 K to 90 ± 12.5 K, using an effective radius at 1 mm of 2650 km computed from our model. This measurement included the (2–1) CO emission line in the instrument bandpass. We estimate a +3 K contribution to the measured brightness temperature with our value of the CO mixing ratio. The effect of the surface dielectric constants of 2 (nonpolar liquids), 3 (ices), and 4 (compacted soils and rock) are evident below 80 GHz. The current VLA measurements are not accurate enough to distinguish the surface effects. Future measurements at the VLA should have an accuracy as good as ± 5 percent or ± 4 K.

Conclusions. The Titan emission line for the lowest rotational transition of CO (115.3 GHz) has been measured. Assuming constant mixing of CO for the entire atmosphere, we estimate a mole fraction of 6×10^{-5}, in excellent agreement with Lutz *et al.* (*2*). This is a factor of 2 smaller than the value predicted by Samuelson *et al.* (*3*), based on their interpretation of the 667-cm^{-1} CO_2 emission line in the Voyager 1 IRIS spectrum and photochemical modeling.

Collision-induced absorption due to N_2-N_2 interactions causes the atmosphere to be opaque at 2.6 mm somewhat below the tropopause. The microwave CO line is formed in the relatively hot atmosphere above this level. Models of the complete microwave spectrum must be regarded as tentative until laboratory measurements of the N_2 collision-induced absorption coefficient at the relevant Titan temperatures and pressures are carried out. Nevertheless, it is apparent that careful measurements in the frequency range 5 to 80 GHz could resolve the question of a liquid surface (*12*). High-resolution VLA measurements may be sufficiently accurate to directly yield the polarization of the surface emission, from which the dielectric constant can be estimated. Future spacecraft microwave measurements to an accuracy of about ± 1 K will ultimately be important in resolving the Titan surface structure.

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5. Provided by E. M. Standish, based on work by G. Null, both at Jet Propulsion Laboratory.
6. The SIS receivers were built by D. P. Woody. For the development see T. Phillips *et al.*, *IEEE Trans. Magn.* **MAG-17**, 684 (1981). C. Masson and A. Moffet were primarily responsible for the phase-locked coherent reference system, interferometry, and cross-correlator systems. S. Scott and L. Murdock developed the interferometer software.
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Thickness of Saturn's Rings Inferred from Voyager 1 Observations of Microwave Scatter

Abstract. *Earth-based telescopic observations indicate that Saturn's rings are about 1 kilometer thick, while spacecraft measurements and theoretical considerations give an upper bound of about 100 meters. Analysis of a shielding effect present in radio occultation provides a sensitive new measure of the ring thickness. On the basis of this effect, Voyager 1 microwave measurements of near-forward scatter imply a thickness ranging from less than 10 meters in ring C to about 20 and 50 meters in the Cassini division and ring A, respectively. Monolayer models do not fit the observations in the latter two regions. The discrepancy between the Earth-based and spacecraft measurements may be due to warps in the ring plane or effects of tenuous material outside the primary ring system.*

The thickness of Saturn's rings as observed from Earth is estimated to be about 1 km (*1*). Voyager spacecraft observations of edges in the ring system give upper bounds to the thickness of 100 to 200 m (*2*). Estimates based on the observation of density wave phenomena in the rings and theoretical considerations give values of 10 to 50 m (*3*).

We present new evidence from microwave scatter in the near-forward direction indicating that the rings are, at most, a few tens of meters thick and, with the possible exception of ring C, are dispersed vertically so that they are thicker than an ideal monolayer of particles. These results, which apply to several broad areas in rings A and C and the Cassini division, are independent of dynamical modeling. No results for ring B are available since the combination of large radio depth and a small ring opening precluded observation of microwave scattering from that region.

The data were obtained during the occultation of Voyager 1 by the rings when radio transmissions from the spacecraft passed through the rings to be received on Earth (*4*). These data have been reduced to the differential scattering cross section $\sigma_d(\alpha)$ (square meter per square meter per steradian) of 3.6-cm-wavelength (λ) radiation over the range $0 \leq \alpha \leq 0.012$ rad, where α is the scattering angle (*5–7*). These cross sections have been obtained for eight locations in the ring. Simultaneous measurement of the unscattered, or "direct," signal extinction yields the microwave opacity (τ) at λ = 3.6 and 13 cm.

The combination of the $\sigma_d(\alpha)$ and τ measurements is sensitive to thickness as a result of a shielding effect which is present in the case of a thick ring but absent in a monolayer. Consider Fig. 1, which represents the edge view of a collection of particles slightly dispersed relative to a reference plane. Incident radiation is from the left, with the observer to the right. If, for example, the particles were all confined to the mean plane, then any photon passing through the plane would be intercepted by the center of a particle once at most. For a photon passing through a slightly dispersed medium, however, it is possible for one particle to shield another from incident radiation and thereby modify the relation between the magnitude (and to a lesser extent the form) of the differential cross section and the observed total opacity. The likelihood of such a shielding event increases with the dispersion of the particle centers from the reference plane. In the case of the Voyager radio occultation experiment, the sensitivity to this shielding effect is magnified by the small (5.92°) opening of the rings at the time of observation.

We quantified the relation between the shielding effect and the observations by using Monte Carlo techniques to trace the average behavior of photons through ring models of varying thickness, where thickness was defined by the limits of a uniform distribution of the particle centers relative to the mean plane. In the model we employed particle size distributions obtained from reduction of the singly scattered differential cross sections (*6, 8*) and used the Voyager geometry. In the calculations a photon initially passing through the ring encountered a particle with probability determined from the observed extinction of the direct signal. The location of the encounter along the path was obtained by modeling the interactions as a Poisson process, scaled by the assumed apparent thickness. If an interaction occurred in the ring, then a new direction of travel for the photon was chosen approximately in accordance with the Mie scattering phase function for a particle of random size drawn from the actual particle size distribution. The photon was then moved in the new direction until either it encountered another particle and the procedure just described was repeated or it emerged from the populated region. There were ~10^6 trials in each Monte Carlo experiment.

It was also necessary to consider that particles that happen to be in close proximity to one another behave as a single scattering center; general solutions for this effect have not been obtained, however. We accounted for close interparticle coupling by considering two extreme cases. First, we required that particle centers be separated by more than twice the radius of the first particle encountered before a second interaction could occur. Second, we required that the photon travel at least to the far field of a scattering particle (given by R^2/λ, where R is the particle radius) before a second interaction could occur. These two cases provided likely bounds in distance for exclusion of high-order interactive effects between particles.

Results of these calculations for one location in the rings are illustrated in Fig. 2, which compares the Monte Carlo calculations with observed data for ring A. The two panels in Fig. 2 correspond to the two extremes in considering near-field effects. The best match between model and data occurs at thicknesses near 1 and 50 m for the first and second cases, respectively. We interpret these results as indicating that the thickness at this location lies between these extremes, and is likely to be on the order of 5 to 20 m. Recall that these values apply

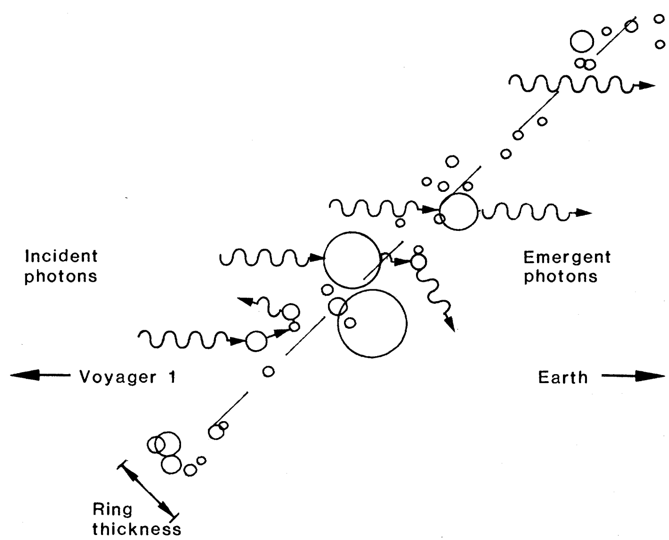

Fig. 1. Schematic illustration of particle geometry. In this edge view, particles are dispersed perpendicularly to the mean plane of location. Large particles, which scatter predominantly in the near-forward direction and thus are detectable in the scattered signal, are more likely to be shielded from incident radiation by the more isotropically scattering smaller particles in a dispersed configuration than for the case of a coplanar particle ensemble. Note that dispersed small particles also effectively shield the receiver from forward-scattered signal by scattering photons that have previously interacted with the large particles.

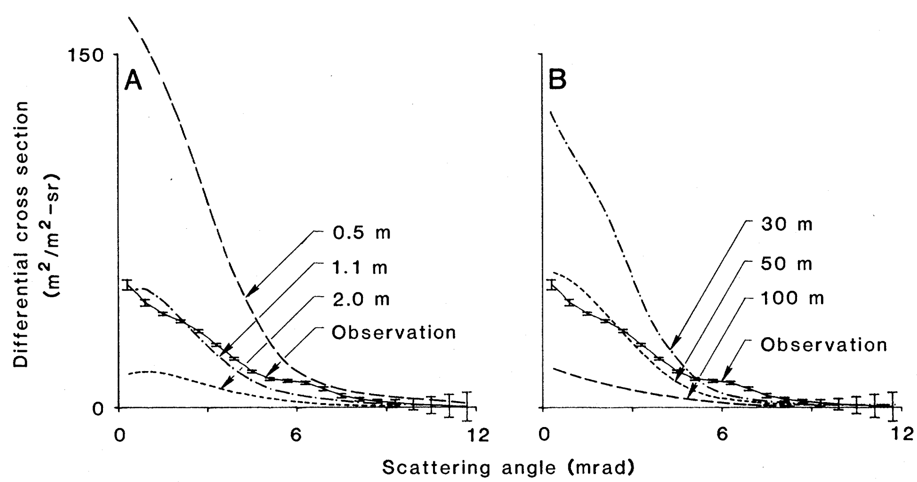

Fig. 2. Comparison of differential scattering cross sections as a function of ring thickness. Curves show Monte Carlo results and observed scattering cross section for ring A for two extreme assumptions. In the close spacing model (A) it is assumed that each multiply scattering particle is separated from successive scattering particles by at least twice its radius; the far-field spacing model (B) requires separation proportional to the radius of the scattering particle squared. The curve labeled *Observation* is the solution from analysis of near-forward scatter of 3.6-cm radiation from rings between 2.08 and 2.16 Saturn radii (*6*). Neither classical many-particle-thick nor monolayer models provide a close match to measured values. Small-scale structure in observation, such as the "bump" at 3 mrad, may be an artifact of systematic biases in the measurements not accounted for by statistical uncertainties.

to the uniform dispersion of the particle centers with respect to the mean plane. The actual thickness would be somewhat larger since the largest particles have diameters of about 10 m (*9*).

The thickness in the simulation that results in an accurate fit to the observations of differential cross section depends on the parameters of the particle size distribution function assumed for a specific region in the rings. Preliminary calculations indicate, for example, that a 10 percent change in the upper size cutoff of the distribution results in a 10 percent change in the thickness estimate (*8*). As discussed above, we adopted the distributions derived from Voyager 1 radio occultation measurements for the models.

Two additional assumptions also affect the thickness estimate. First, we assume that the particles are composed entirely of water ice with an index of refraction equal to 1.78. Although measurements of the scattered portion of the signal are dominated by diffracted energy and are insensitive to the composition of the scatterers, the extinction efficiencies of the particles depend somewhat on the index of refraction. Consequently, the inferred thickness is weakly dependent on this assumption. Second, for the simulation calculations, we assume that the particles are equally likely to exist anywhere in a slab of limited thickness. Many other configurations are possible; for example, it has been suggested that large particles are essentially confined to the mean ring plane, while small particles make up a dispersed cloud on both sides of the ring plane. However, the best match to observation in these simulations occurs when the particles have a dispersion on the order of the diameter of the largest particles, and we feel that assuming different configurations in the vertical structure of the rings will produce relatively minor changes in the estimated thickness.

Table 1 summarizes the results from the two extreme models for several locations in the rings. The apparent thickness of ring C is significantly less than that for locations in ring A, while the Cassini division thickness is intermediate between the values for rings A and C. We caution that, because the total opacity is small in ring C, the effects of shielding are somewhat less important as a result of the reduced multiple scatter, and the result is weaker. Thus the model results for far-field spacing in ring C were insensitive to thickness values less than about 10 m, so only an upper bound is shown for this case in Table 1. We are unable to give quantitative estimates of the modeling uncertainties.

Table 1. Thickness of Saturn's rings, as inferred from microwave scatter.

Approximate location (Saturn radii*)	Thickness (m)	
	Close spacing	Far-field spacing
	Ring C	
1.30 to 1.40	0.1	< 10
1.50 to 1.52	0.1	< 10
	Cassini division	
2.00 to 2.02	1	20
	Ring A	
2.08 to 2.16	1.1	50
2.08 to 2.12	1.5	50
2.12 to 2.16	1.3	50
2.17 to 2.21	1.5	60
2.22 to 2.26	1.3	40

*One Saturn radius equals 60,330 km.

Earth-based observations of the ring thickness are sensitive to warps in the surface of the rings and to very small values of normal opacity at the location of the principal rings or in the extended ring system. Either of these could readily account for the large values of thickness inferred from telescopic observations (*10*). Similarly, ring B could be significantly thicker than other regions, although this seems unlikely to us (*11*).

Other determinations are consistent with the results given here. Observations of ring edges give upper bounds for the thickness at the edges that are greater than the present results. Determinations based on density wave phenomena apply locally at the positions of these waves, and are generally in agreement with the present results, which apply to much larger areas of rings A and C and the Cassini division. Theoretical calculations also indicate that the thickness could be on the order of 10 m or less (*12*).

Both the density wave determinations and the microwave scatter results here depend on theoretical models, one of wave formation in a particulate gravitational disk and the other on the theory of scatter by particulate ensembles. It is difficult to assess the uncertainties in either of these, but the agreement obtained by two such diverse methods is encouraging. Altogether, the results of four different methods of investigation—analysis of edge sharpness, analysis of density waves, theoretical modeling of energy loss and transfer in the ring system, and analysis of microwave scatter—lead to bounds on the thickness that are on the order of 100 m, or thickness values that are on the order of tens of meters. At the same time, the microwave scatter results are inconsistent with a strict monolayer model. It appears that the ring thickness is a few times the diameter of the largest particles.

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7. Differential scattering cross section $\sigma_d(\alpha,\beta)$ is the effective area of a particle for scattering in the α,β direction, given in units of scattering area per unit area of ring surface per steradian. For circular symmetry, σ_d depends only on the scattering angle α; then the relation between differential cross section and the more familiar total scattering cross section C_{sca} is
$$C_{sca} = \int_0^{\pi} 2\pi\, \sigma_d(\alpha) \sin(\alpha)\, d\alpha$$
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10. Telescopic observations from Earth yield a ring thickness on the order of 1 km. Bending waves or gravitational warping of the ring plane could make a thin ring appear much thicker when viewed edgewise; a bending wave with 1.4-km peak-to-peak amplitude has been identified in Saturn's ring A [F. H. Shu, J. N. Cuzzi, J. J. Lissauer, *Icarus* **53**, 185 (1983)], while the warp in the Laplace plane is estimated to be about 400 m as a result of gravitational forces from exterior bodies [J. Burns, P. Hamill, J. N. Cuzzi, R. H. Durisen, *Astron. J.* **84**, 1783 (1979)]. Burns *et al.* also suggested that if the rings are surrounded by a tenuous halo, the edgewise geometry again could lead to appreciable optical depth and the impression of thick rings. Similar effects might arise from the extended ring E outside the classical ring system.
11. C. Porco *et al.* (in preparation) inferred an upper limit of 10 m for the thickness of the outermost region of ring B from measurement of the angular separation between the direction to Mimas and the radial minimum of the noncircular edge of ring B at 1.95 Saturn radii.
12. P. Goldreich and S. Tremaine [*Icarus* **34**, 227 (1978)] obtained 10 m as an upper bound for "identical, indestructable, imperfectly elastic, smooth spheres" for which mutual gravitational interactions are ignored. J. N. Cuzzi, R. H. Durisen, J. A. Burns, P. Hamill [*ibid.* **38**, 54 (1979)] obtained a "ring thickness of several times the radius of the largest particles, or many times the radius of the smallest particles" for the case of a broad, inverse cubed power law–type particle size distribution, where mutual gravitational effects are considered. J. N. Cuzzi, J. A. Burns, R. H. Durisen, P. M. Hamill [*Nature (London)* **281**, 202 (1979)] showed that the estimate of tens of meters for local vertical thickness is not overly sensitive to variations in the power law index of a broad size distribution.
13. The observations used here are the result of the efforts of persons associated with many aspects of the Voyager program. We are especially indebted to E. A. Marouf for many helpful discussions about radiowave scattering theory and aspects of practical computation. We also thank J. Burns, J. Holberg, and two anonymous reviewers for many helpful suggestions. This work was supported by NASA and the Voyager project.

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