THE SOLAR SYSTEM BODIES: FROM OPTICS TO GEOLOGY (2008)

WEAK LOCALIZATION EXPLAINS RADAR OBSERVATIONS OF SATURN'S RINGS.

J. M. Dlugach[1] and M. I. Mishchenko[2], [1] Main Astronomical Observatory of the National Academy of Sciences of Ukraine, 27 Zabolotny Str., 03680, Kyiv, Ukraine; dl@mao.kiev.ua, [2] NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025; mmishchenko@giss.nasa.gov

In this work, we analyze average circular polarization ratios measured for the A and B rings of Saturn at a wavelength of 12.6 cm [1, 2]. For this purpose, we use a model which accounts for the effects of polarization, multiple scattering, weak localization of electromagnetic waves (WL), and ring particle nonsphericity. Also, we assume that the ring system is not strongly stratified in the vertical direction and adopt the model of a vertically and horizontally homogeneous plane-parallel layer of random particulate medium.

Radar observations have played a very important role in the study of the physical nature of Saturn's rings [2-4], and polarization radar measurements have always been expected to be especially indicative of the physical properties of the ring particles and the ring structure. Note that while the existing measurements of the radar cross sections published by different authors are somewhat inconsistent (cf. [2]), the measurements of the circular polarization ratio μ_C at a wavelength of 12.6 cm by Ostro et al. [1] and Nicholson et al. [2] appear to be quite consistent and show a systematic and nearly linear increase in μ_C with increasing ring opening angle *B*.

As monostatic radar observations involve measurements of the Stokes parameters in the exact backscattering direction (towards the source of illumination), the results of such observations of particulate media can be influenced by WL. The point is that the radiation reflected by a sparse disordered medium consists of two parts. The first part comes from the incoherent multiple scattering by particles and can be described by the solution of the vector radiative transfer equation (VRTE). The second part comes from the coherent interaction of particles and is equal to zero in most scattering directions except very close to the exact backscattering direction, and this case corresponds precisely to the case of monostatic radar observations.

Mishchenko [5] showed that in the exact backscattering direction all characteristics of weak localization can also be rigorously expressed in terms of the solution of the VRTE. This result is very useful since it allows one to calculate different characteristics of the polarized radiation scattered in the exact backscattering direction.

Thus the analysis of radar measurements of the polarization ratio involves the following:

1. the computation of the single-scattering properties of the ring particles;
2. the computation of the diffuse Stokes reflection matrix through the explicit numerical solution of the VRTE;
3. the computation of the requisite characteristics of WL in the exact backscattering direction from the diffuse Stokes reflection matrix;
4. the computation of the circular polarization ratio μ_C. The entire procedure is described in detail by Mishchenko [6], Mishchenko et al. [7, 8].

In this work, the ring particles are assumed to be randomly oriented, so-called Chebyshev particles whose shape with respect to the particle reference frame is given by

$$R(\theta) = r_0(1+\varsigma T_n(\theta)), \qquad (1)$$

where θ is the polar angle, r_0 is the radius of the unperturbed sphere, $T_n(\theta)$ is Chebyshev polynomial (we assume n=6), and ς is the deformation parameter [9], which can be either positive or negative. To analyze the effect of particle shape, we also use the model of oblate and prolate spheroids. Particle polydispersity is parameterized in terms of a simple power law distribution characterized by the effective radius r_{eff} and effective variance v_{eff}. Throughout this study, the effective variance is fixed at the value of 0.2, which corresponds to a size distribution that is neither very narrow nor very wide. The model refractive index of the ring particles corresponds to water ice [10] and is equal to 1.78+0.003i [11].

The single scattering characteristics of polydisperse Chebyshev particles are computed using the numerically exact T-matrix method [12, 7]. Afterwards the VRTE is solved for a homogeneous plane-parallel layer by use of a computational algorithm based on the invariant imbedding technique [13] or by means of the numerical solution of Ambartsumian's nonlinear integral equation [14]. The output of this procedure is the Stokes reflection matrix, which is then used to find the elements of the coherent reflection matrix for the exact backscattering direction according to equations (14.3.21)-(14.3.25) of [8]. The final step is to calculate the values of the circular polarization ratio using equation (14.5.15) of [8].

Some of the results of our extensive numerical computations are summarized in Figures 1 and 2, where we show only some of the data obtained for Chebyshev particles. Figure 1 depicts the values of the circular polarization ratio μ_C, while Figure 2 gives the values of the "diffuse" circular polarization ratio μ_C^{dif} obtained by neglecting the effect of WL and using equation (14.5.16) of [8].

In both figures, we present the average μ_C values measured for the A and B rings (dots) and the corresponding error bars. First of all, note that the strong dependence of μ_C on the ring opening angle is obviously an indicator of a significant effect of multiple scattering. Besides, the extrapolation of the observational data to $B \approx 0^0$ shows the ring particles to be weakly depolarizing. The results of our computations lead to the following conclusions.

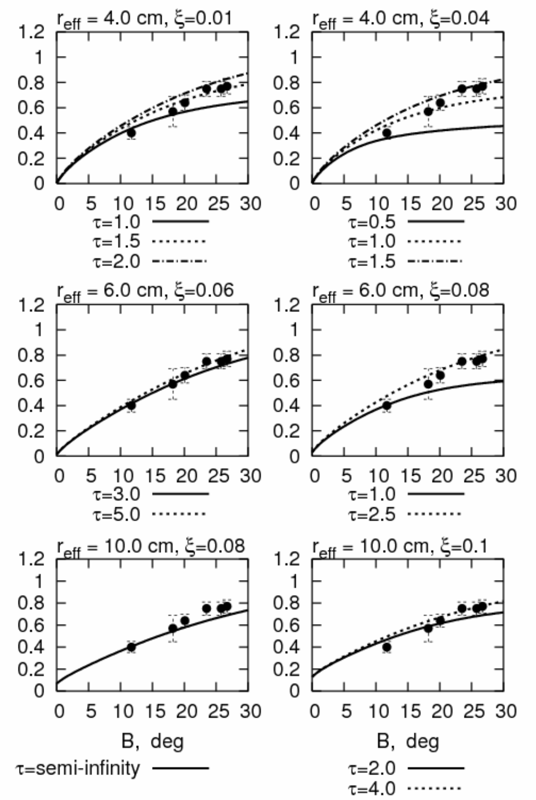

Fig. 1. Circular polarization ratio versus ring opening angle. Dots correspond to the results of observations [1, 2].

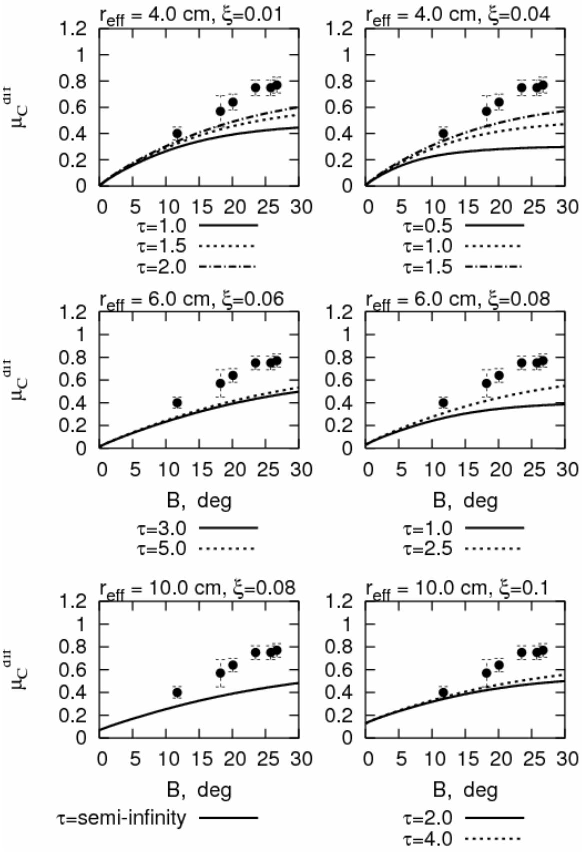

Fig. 2. As in Fig. 1, but for the diffuse circular polarization ratio

1. It is impossible to reproduce the results of radar observations without an explicit inclusion of the WL effect. This conclusion is well illustrated by Figure

2. Of course, the effect of WL should have been expected to be significant since the phase angle in monostatic radar observations is by definition equal to zero. However, it was important to establish this result by explicit numerical modeling.

3. We could not obtain a satisfactory theoretical fit using the model of spherical ring particles. This is not surprising as the particles forming Saturn's rings consist, in all likelihood, of solid water ice and cannot be expected to be spherical.

4. Our results favor the model of ring bodies in the form of particles with small-scale surface roughness (Chebyshev particles with $|\varsigma| < 0.15$). Our computations show the large observed circular polarization ratios to be mostly the result of multiple interparticle scattering rather than the result of particle nonsphericity.

5. We obtain average ring optical thickness values to be in the range 3 or even larger. However, it can be seen that the retrieval of the optical thickness depends rather strongly on the assumed size of the error bars in the radar observations.

6. Our results favor particles with effective radii in the range 10 cm and definitely rule out effective radii significantly smaller than 4 cm. This result does not imply that ring particles with radii much smaller than 4 cm do not exist. The point is that radar observations at 12.6 cm are completely insensitive to the presence of micrometer particles.

In conclusion, we believe that additional studies are required in order to analyze all available datasets (including the existing radar measurements of polarization ratio) and to develop a physically based model of Saturn's rings.

This research was sponsored by the NASA Radiation Sciences Program managed by Hal Maring.

References: [1] Ostro S. et al. (1980) *Icarus*, *41*, 381-388. [2] Nicholson P. et al. (2005) *Icarus 177*, 32-62. [3] Goldstein R. et al. (1977) *Icarus 30*, 104-110. [4] Ostro S. (1993) *Rev. Mod. Phys. 65*, 1235-1279. [5] Mishchenko M. (1991) *Phys. Rev. B, 44,* 12597-12600. [6] Mishhchenko M. (1996) *JQSRT 56*, 673-702. [7] Mishchenko M. et al. (2002) *Scattering, absorption, and emission of light by small particles. Cambridge University Press*. [8] Mishchenko M. et al. (2006) *Multiple Scattering of Light by Particles: Radiative Transfer and Coherent Backscattering. Cambridge University Press*. [9] Wiscombe W., and Mugnai (1986) *NASA Ref. Publ. 1157(Greenbelt: NASA/GSFC).* [10] Cuzzi J. et al. (2002) *Space Sci. Rev. 104*, 209-251. [11] Warren S. (1984) *Appl.Opt, 23,* 1206-1225. [12] Waterman P. (1971) *Phys. Rev. D , 3*, 825-839. [13] Mishchenko M. (1990) *JQSRT 43*, 163-171. [14] de Rooij W. (1985) *Reflection and transmission of polarized light by planetary atmospheres. PhD dissertation. Amsterdam: Vrije Universiteit.*