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Examining the wake structure in Saturn's rings from microwave observations over varying ring opening angles and wavelengths

David E. Dunn [a,b,*], Imke de Pater [b], Lawrence A. Molnar [c]

[a] *Astronomy Department, Sierra College, Rocklin, CA 95677, USA*
[b] *Astronomy Department, University of California, Berkeley, CA 94720, USA*
[c] *Department of Physics and Astronomy, Calvin College, Grand Rapids, MI 49546, USA*

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Abstract

Over the last 15 to 20 years several high quality, high resolution data have been taken with the very large array (VLA). These data exhibit a wide range of ring opening angles ($|B| = 0$ to $26°$) and wavelengths ($\lambda = 0.7$ to 20 cm). At these wavelengths the primary flux from the rings is scattered saturnian thermal emission, with a small contribution coming from the ring particles' own thermal emission. Much of the data do show signs of asymmetries due to wakes either on the ansae or the portion of the rings which occult the planet. As in previous work, we use our Monte Carlo radiative transfer code including idealized wakes [Dunn, D.E., Molnar, L.A., Fix, J.D., 2002. Icarus 160, 132–160; Dunn, D.E., Molnar, L.A., Niehof, J.T., de Pater, I., Lissauer, J.L., 2004. Icarus 171, 183–198] to model the relative contributions of the scattered and thermal radiation emanating from the rings and compare the results to that seen in the data. Although the models do give satisfactory fits to all of our data, we find that no single model can simulate the data at all different $|B|$ and λ. We find that one model works best for moderate and low $|B|$ and another one at higher $|B|$. The main difference between these models is the ratio of the wake width to their separation. We similarly find that the 2 cm data require higher density wakes than the longer wavelength data, perhaps caused by a preponderance of somewhat smaller ring material in the wakes. We further find evidence for an increase in the physical temperature of the rings with increasing $|B|$. Continuous observations are required to determine whether the above results regarding variations in wake parameters with $|B|$ and λ are indeed caused by these parameters, or instead by changes over time.

Keywords: Planetary rings; Radiative transfer; Radio observations

1. Introduction

Although the Voyager spacecraft flybys over two decades ago contributed a wealth of information to our general understanding of Saturn's rings, we still do not know much about the local spatial distribution of the ring particles. Even with the current Cassini Mission, neither individual particles nor their spatial correlation can be directly observed, but information about them may be extracted from scattering and transmission of light at different wavelengths (from the ultraviolet to radio) through large portions of the rings. In previous papers (Dunn et al., 2002, 2004), we have concentrated on observations at radio wavelengths, and have attempted to constrain such local particle distributions through comparison with model simulations.

Radio images of Saturn have been made with the very large array (VLA) over a wide range of wavelengths (0.7–90 cm) over the past 20 years. These observations have been made at a variety of ring inclinations ranging from nearly edge-on to its maximum of 27°. Radio measurements are well suited to probing details of the particle size distribution, as the wavelength range is similar to the range of particle sizes.

In 1979 and in the 1980s, several VLA data sets were obtained (de Pater and Dickel, 1982, 1983; de Pater, 1985; Grossman et al., 1989; Grossman, 1990; de Pater and Dickel, 1991). Specifically, de Pater and Dickel (1991) describe data taken at several VLA wavelengths (1.3, 2.0, 3.6, 6.0 cm) at

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[*] Corresponding author. Fax: +1 916 781 2433.
E-mail addresses: ddunn@sierracollege.edu (D.E. Dunn), imke@floris.berkeley.edu (I. de Pater), lmolnar@calvin.edu (L.A. Molnar).

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inclinations from $B = 5°–26°$, though no more than two wavelengths were measured for any individual epoch. These authors, as well as Grossman et al. (1989) and Grossman (1990) analyze some high $B \geqslant 25°$ VLA datasets, which were the first high resolution, high quality data at microwave wavelengths.

Van der Tak et al. (1999) present data taken in the 1990s at inclinations from 0.1° to 24.1° and at wavelengths between 2.0 and 90 cm. Again, no more than two wavelengths were measured for any individual epoch. Later, Dunn (1999) and Dunn et al. (2002) acquired two epochs of data at low inclinations ($|B| = 2.7°$ and 5.0°), measuring 4–6 wavelengths at a time.

Two more epochs of data were taken in 1998 (Molnar et al., 1999; Dunn et al., 2004) at moderate $|B| = 16°$ and 2002–2003 (Molnar et al., 2004) at very high $|B| = 26.4°$. Data were taken at multiple wavelengths again and had longer integration times than previous datasets. All major saturnian VLA data sets prior to 2000 were summarized in Table I in Dunn et al. (2004). Some of the 1998 data and all of the 2002 data are presented in detail in this paper.

Azimuthal asymmetry in visible sunlight backscattered from the A ring was first seen by Camichel (1958) and confirmed by others (Ferrin, 1974; Reitsema et al., 1976; Lumme and Irvine, 1976). Brightness minima were found at orbital phase angles of 70° and 250°. Nonaxisymmetric elongated particle conglomerations were first suggested to be the cause of this asymmetry by Colombo et al. (1976). Calculations by Franklin and Colombo (1978) and later by Lumme and Irvine (1979) showed that such wake-like structures with a pitch angle of $\phi_w \sim 20°$ would scatter light in a way that was consistent with the observed asymmetry.

Dones et al. (1993) used Voyager visible photometry to look at the A ring at a variety of phase and elevation angles. They found that the scattering properties from the A ring were similar to those of some jovian moons (significant backscatterers and moderate albedo). Furthermore, an examination of the forward scattering properties suggested a lack of submicron particles in the A ring. Additionally, the azimuthal asymmetry in the reflectivity of the A ring as seen with optical Earth-bound instruments, was also detected by the Voyager data. The general properties of the asymmetry, especially the narrow brightness minima some 20° from the ansae, are consistent with the presence of imbedded wakes.

Extensive 3-D simulations were done by Salo (1991, 1992a, 1992b, 1995) and Daisaka and Ida (1999) using a large number of particles. These works demonstrate how the A ring is the natural location for wakes: self-gravity allows assembly of small moons farther from the planet, while closer in tidal stress disrupts wakes completely. It remains beyond computational capacity to do completely realistic simulations, which would require to include simultaneously a sufficient number of particles to model a large portion of the rings in three-dimensional space and a broad range of particle sizes. Nonetheless, the general character of simulations with varying assumptions is similar; in particular, the average wake pitch angles are all alike.

Recently, Salo and Karjalinen (2003) and Salo et al. (2004) reconcile the (optical) photometric scattering to their previous dynamic simulations. The wakes produced by these simulations can account for several basic properties of the asymmetry, namely the inverse-tilt effect seen in ground-based observations, and the longitude dependence in Voyager observations in both reflected and transmitted optical light.

An east–west asymmetry in the radio emission from Saturn's ansae was first noted by de Pater and Dickel (1991) and again in van der Tak et al. (1999) with the west ansa favored in data with large ring opening angles ($|B| > 20°$). Unlike what is observed in the optical (from reflected sunlight), the radio ansae are primarily detected from the (side) scattered light originating from the planet. Dunn et al. (1996) found a similar asymmetry at a narrow opening angle ($|B| = 2.7°$), and suggested this may be due to asymmetric multiple scattering from wakes. Dunn (1999) and Dunn et al. (2002) showed the asymmetry seen at 2.7° was not visible at 5°. These latter papers also contained the first synthetic maps based on realistic radiative transfer calculations. Their calculations did not explicitly include wakes, and so they could not comment on the east–west asymmetry. However the scattering function needed for the A ring was suggestive of a geometrically thin ring, in agreement with the dynamic simulations. This conclusion assumed that all scattering is in the far-field and the close packing effects are not important which may not be the case in the wakes.

From observations taken in 1998 ($|B| = 15–16°$), Molnar et al. (1999) found a distinct east–west asymmetry in the Saturn light directly transmitted through the A ring at three different wavelengths. Dunn et al. (2004) extended the radiative transfer code to include wakes and showed this asymmetry could be modeled quantitatively. An optimum set of data of wake parameters was determined by simulating the high dynamic range of observations ($\lambda = 3.6$ cm) from 1998.

The most recent set of high resolution, high dynamic data was taken at a near maximum ring opening angle of $|B| = 26.4°$ (Molnar et al., 2004). In this geometry the A ring is no longer in front of the planet and cannot show the aforementioned asymmetry. However, the inner portion of the B ring shows the east–west asymmetry as it passes in front of the planet, as had been found in the A ring. (This was not seen well in previous images, where the B ring was too foreshortened to allow much direct transmission.) Furthermore, the A ring shows a strong east–west asymmetry on the far side of the rings, as predicted by the wake simulations of Dunn et al. (2004). [See Fig. 15b of Dunn et al. (2004) and this paper's Section 3.2.] Additionally, the inner portion of the B ring shows the same asymmetry signature, although with reduced amplitude. Taken together, this epoch shows the first clear evidence of wakes in the ansae portion of the A and inner B rings in the microwave regime.

Other data which detected wakes were Arecibo radar measurements of Saturn from Nicholson et al. (2005). These consisted of delay–Doppler measurements at a wavelength of 12.6 cm at $20.1° \leqslant |B| \leqslant 26.7°$ in which the A and B rings were clearly detected. While direct images were not obtained, both the delay and Doppler profiles detected the quadrupole asymmetry seen in the A ring from ground-based optical observations (cited above), with a hint of a similar asymmetry in the B ring.