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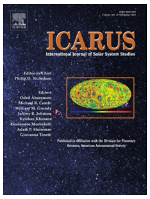

Cassini microwave observations provide clues to the origin of Saturn's C ring

Z. Zhang[a,*], A.G. Hayes[a], M.A. Janssen[b], P.D. Nicholson[a], J.N. Cuzzi[c], I. de Pater[d], D.E. Dunn[e], P.R. Estrada[c,f], M.M. Hedman[g]

[a] *Astronomy Department, Cornell University, Ithaca, NY 14850, USA*
[b] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109, USA*
[c] *Space Science Division, Ames Research Center, NASA, Moffett Field, CA 94035, USA*
[d] *Astronomy Department, University of California, Berkeley, California 94720, USA*
[e] *Astronomy Department, Sierra College, Rocklin, CA 95677, USA*
[f] *SETI Institute, Moffett Field, CA 94035, USA*
[g] *Physics Department, University of Idaho, Moscow, ID, 83844, USA*

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ABSTRACT

Despite considerable study, Saturn's rings continue to challenge current theories for their provenance. Water ice comprises the bulk of Saturn's rings, yet it is the small fraction of non-icy material that is arguably more valuable in revealing clues about the system's origin and age. Herein, we present new measurements of the non-icy material fraction in Saturn's C ring, determined from microwave radiometry observations acquired by the Cassini spacecraft. Our observations show an exceptionally high brightness at near-zero azimuthal angles, suggesting a high porosity of 70–75% for the C ring particles. Furthermore, our results show that most regions in the C ring contain about 1–2% silicates. These results are consistent with an initially nearly pure-ice ring system that has been continuously contaminated by in-falling micrometeoroids over ∼15–90 million years, using the currently accepted value of the micrometeoroid flux at infinity of $\sim 4.5 \times 10^{-17}$ g cm^{-2} s^{-1}, and assuming that the C ring optical depth and surface density has not changed significantly during that time. This absolute time scale is inversely proportional not only to the flux at infinity, but also to the amount of gravitational focusing by Saturn the micrometeoroids experience before encountering the rings. We also find an enhanced abundance of non-icy material concentrated in the middle C ring. When assumed to be mixed volumetrically ("intramixed") with water ice, this enhanced contamination reaches a maximum concentration of 6–11% silicates by volume around a ring radius of 83,000 km, depending on the volume mixing model used. This is significantly higher than the inner and outer C ring. As opposed to an intramixing model, we also consider a silicate-core, icy-mantle model to address the fact that silicates may be present in chunks instead of fine powder in the ring particles. Such a model naturally helps to account for the observed opacity distribution. We propose several models to explain the radially varied non-icy material contamination. Our preferred model is that the C ring has been continuously polluted by meteoroid bombardment since it first formed, while the middle C ring was further contaminated by an incoming Centaur, a rocky object torn apart by tides and ultimately broken into pieces that currently reside in the middle C ring. If correct, the spatial extent of the enhanced non-icy material fraction suggests that the Centaur was likely to be captured and integrated into the rings perhaps as recently as ∼10–20 million years ago.

1. Introduction

Saturn's rings are the most massive, extensive and diverse ring system in the Solar System, yet despite decades of ground and spacecraft-based observations (Dougherty et al., 2009; Grossman, 1990; de Pater and Dickel, 1991; van der Tak et al., 1999; Dunn et al., 2002; 2005; Poulet et al., 2003; Nicholson et al., 2008), their origin and age remains a subject of debate. In particular, the small non-icy material fraction, which is related to their origin through source composition and exposure age (Cuzzi and Estrada, 1998), is poorly understood. At first, astronomers predominantly agreed Saturn's rings were primordial (Harris et al., 1984) until

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[*] Corresponding author:.
E-mail address: zz246@cornell.edu (Z. Zhang).

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observations from the Voyager spacecraft suggested that dynamical considerations necessitated a short ($\sim 10^8$ yrs) lifetime (Harris et al., 1984; Dones et al., 1991; Goldreich and Tremaine, 1982). A more recent post-Cassini view returns to an ancient origin (Esposito, 2008), but invokes a much more massive pure-ice primordial ring formed via tidal disruption of a Titan-sized, differentiated satellite (Canup, 2010). Yet another recently revisited scenario (Charnoz et al., 2009a) suggests that the cometary flux was so high during the Late Heavy Bombardment (LHB) that several tens of Mimas masses of cometary material may have been brought into Saturn's Hill sphere, and that a fraction of it could have ended in Saturn's Roche zone. In this 'destroyed satellite scenario', it has been recently shown (Charnoz et al., 2009b) that a Mimas-mass moon located 10^5 km from Saturn can be disrupted during a LHB type event (Tsiganis et al., 2005) about 700 Myr after the planet's birth (though possibly even later, see Sec. 5.2). The probability for disruption is model dependent, but can be $> 95\%$ (see Table 3, Charnoz et al., 2009b, and references therein). The abundance and character of non-icy material in Saturn's present-day ring system can help distinguish between these origin scenarios by constraining the composition of source material and, for a given initial composition, estimate the rings' exposure age due to micrometeoroid bombardment (Cuzzi and Estrada, 1998).

The exact composition of Saturn's ring particles remains unclear. Though water ice has long been known as the most prominent component (Cuzzi et al., 1984; Esposito et al., 1984), the single scattering albedos of ring particles are much too low for them to be pure water ice. The rings' spectrum in the visible and near-IR shows strong absorption at near-UV and blue wavelengths leading to a decrease in reflectivity at wavelengths shorter than 0.6 μm. Yet, little is known about the specific makeup of the non-icy, absorbing material that accounts for this observation, the presence of which apparently gives the rings their slightly non-gray, very pale tan or salmon color (Estrada and Cuzzi, 1996). Several investigators have considered a variety of potential UV absorber candidates such as tholins, PAHs, nanophase iron and nanophase hematite in order to match the observed color. Despite the range of materials considered, all of these studies have generally constrained the non-icy fraction to be less than a few percent by mass (Cuzzi and Estrada, 1998; Cruikshank et al., 2005; Morris et al., 1985; Clark et al., 2008). Furthermore, ring photometry has shown that the optically thin C ring and Cassini Division have darker and less red particles than the optically thick A and B rings (Estrada and Cuzzi, 1996), which indicates the presence of varying amounts of unidentified darkening non-icy material with a spectrally neutral color (Smith et al., 1982; Cuzzi et al., 1984; Dones et al., 1993; Poulet et al., 2003; Nicholson et al., 2008). We will later show that the very small amount of reddening material required to give the rings their apparent color in the visible and near IR wouldn't contribute significantly to the microwave observation (Sec. 5.4), and thus it is the presence of some other non-icy material, besides these reddening materials, that determines the intrinsic thermal emission at the wavelength of our interest.

The Cassini RADAR radiometer (Elachi et al., 2004) provides an ideal window through which to study the non-icy material fraction in Saturn's main rings, as it operates at a wavelength where the absorptivity of water ice is negligible compared to that of most non-icy material, and thus the intrinsic thermal radiation from the ring layer is dominated by the non-icy components. Moreover, whereas visible and near-IR spectra are only sensitive to the top millimeter or less of ring particle surfaces, microwave observations are able to sample the bulk of the ring mass. For solid pure water ice particles, microwave radiation from Saturn at 2.2 cm can penetrate as deep as almost 100 m, while the largest particles in the rings are no larger than 10 m (Marouf et al., 2008).

The C ring lies close to Saturn, situated between the D and B rings, and is the darkest of all the main rings. Since first formed, the rings have been continuously darkened by incoming micrometeoroids. In optically thin rings like the C ring, ring particles are sparse and only a fraction of incoming meteoroids actually hit the rings as opposed to merely passing through them. As the rings become optically thicker, a larger fraction of the meteoroids are absorbed by the ring particles until reaching a level of saturation, where none of the incoming meteoroids can pass through. Saturation is reached for an optical depth $\tau \gtrsim 1$, while the mass of material to be darkened continues to increase with τ. Thus, the optically thin C ring is easier to darken than the optically thicker A and B rings.

It should be noted that many of the structures we see in the C ring lack a satisfactory explanation. Apart from having a profound darkening effect on the rings, micrometeoroid bombardment and transport of their impact ejecta has been shown to explain many aspects of C ring structure (see Estrada et al., 2015), but much of the structure, especially the plateaus, remain enigmatic. A great deal of the mystery of the C ring revolves around the measured ring opacity (see Sec. 5) which can be associated with the particle size distribution. A complete radial profile of the C ring opacity is lacking, but observations suggest that the particle size distribution in the C ring differs across the ring and within different ring regions (e.g., Marouf et al., 2008; Cuzzi et al., 2009; Colwell et al., 2011, 2012) which further complicates efforts to explain the observed structure. Though our analyses in this paper are not meant to address the specifics of C ring structure, we do advance a compelling model to explain the anomalously low opacity (and thus structure) in the middle C ring (Sec. 5.2).

Despite the complexities associated with the particle size distribution across the C ring, the C ring has a lower optical depth and smaller particle albedo than the A and B rings, so one would expect the C ring to have the highest abundance of non-icy material and hence be the ideal place for studying the rings' contamination history. It had been noted as early as Voyager that the presence of some then as-of-yet unknown non-icy component is required to account for the regional and local color variations in ring color (e.g., Smith et al., 1982); however, because previous radio-wave observations have been limited by resolution and sensitivity, no detailed C ring non-icy material fraction has been reported until now. In this work, we determine the non-icy fraction and attempt to constrain candidate materials from the brightness temperature profile of the C ring obtained from analysis of Cassini RADAR observations with resolutions as high as $\sim$2000 km. The observed flux is composed of scattered Saturn radiation and intrinsic thermal emission, the latter being directly related to the non-icy material fraction.

In Section 2 we give an overview of Cassini Radiometry observations of the rings and describe the calibration process and the resulting brightness temperature map. In Section 3, we present the method we use to model the microwave scattering and emission in the rings. We also list the ring parameters that determine the simulated brightness temperature. In Section 4, we compare simulated brightness temperatures from the model with Cassini observations, vary the ring properties, and search for the best-fit parameters. In section 5, we discuss the implication of our results and suggest possible ring origin scenarios that could explain our findings. In Section 6, we summarize our conclusions on the C ring particle porosity, the radially varied non-icy material fraction profile and their implications for the rings' origin and age.

2. Observations & deconvolution

The Cassini RADAR instrument (Elachi et al., 2004) scanned Saturn and its rings at 2.2 cm wavelength on twelve occasions