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Changing electrical nature of Saturn's rings: Implications for spoke formation

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[1] During Cassini's orbit insertion at Saturn, the trajectory took the spacecraft overtop the planet's famed ring system. At this time, the Cassini Radio and Plasma Wave Science (RPWS) instrument obtained unprecedented observations of electron density in the vicinity of the rings. Using this information and a model of photoemission anticipated from the rings, we demonstrate that the ring surface potential undergoes a seasonal change in electrical configuration, being primarily unipolar (of one charge polarity/potential) during the Voyager era and now bipolar (two separate polarities/potentials) during the Cassini era. We calculate the approximate ring/sun opening angle required for the transition from unipolar to bipolar configuration. Using electron density profiles, we explicitly examine the conditions for current balance on the B ring and show which regions are most likely to charge to positive potentials and those that may remain negative as a function of ring opening angle relative to the sun. Finally, we demonstrate that the current body of observations of Saturn ring spokes is consistent with their formation only on negatively-charged surfaces, and suggest future times and locations to look for spoke activity based upon the model.
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1. Introduction

[2] On 1 July 2004, Cassini flew into the inner magnetosphere of Saturn as part of its orbit insertion burn. During that period, the spacecraft flew through the planetary ring plane from southern latitudes, overtop the rings at northern latitudes, and then crossed back through the plane to fly outbound at southern latitudes. The spacecraft flew inward to a radial distance of 1.41 R_s of the planet itself. During this close approach, new and unique magnetoplasma observations were obtained of the inner magnetosphere and ring system including electron and ion densities [*Gurnett et al.*, 2005; *Young et al.*, 2005; *Sittler et al.*, 2005; *Coates et al.*, 2005, *Tokar et al.*, 2005]. Specifically, *Gurnett et al.* [2005] used the identification of the local plasma and upper hybrid frequencies as detected by the RPWS instrument to derive an electron density profile over the rings (see their Figure 5) which was found to have peak values near 100 el/cm^3 at the outer edge of the A ring, but decreased to <0.1 el/cm^3 in the center of the B ring. Note that this electron density change is associated with a steep gradient that ranged over three orders of magnitude in about ½ a planetary radii. We now use this new electron density information to demonstrate that the more opaque rings may undergo a seasonal change in electrical configuration, and this change may influence the development of ring spoke formation.

[3] The spokes on the B-ring were initially detected by the Voyager 1 Imaging Subsystem (ISS) during the planetary encounter [*Smith et al.*, 1981]. The complementary Voyager 2 ISS also detected the spokes during its flyby [*Smith et al.*, 1982]. These spokes, shown in Figure 1, appear as slightly dark (for backscattered light), translucent features generally finger-shaped and oriented in the radial direction. The typical width of a spoke was several thousands of kilometers and their radial extent was typically $\sim$10000 km [*Esposito et al.*, 1984; *Mendis et al.*, 1984]. In many cases, multiple spokes were present on the rings at any given time. These features tended to form on the dawn side of the rings just following the ring's emersion into sunlight. Based on the occurrence of a large number of spokes, a variation in spoke activity was found at a periodicity of 646.6 ± 3.5 minutes [*Porco*, 1983] and they showed a longitude preference of that associated with Saturnian kilometric radiation [*Porco and Danielson*, 1982].

[4] There are many explanations for spoke formation (e.g., see review of *Mendis et al.* [1984]) and most invoke some presumed electrical property of the rings. One particular theory involving electrostatic levitation has been elaborated in great detail in the literature. In this case, the spokes are the result of enhanced dusty plasmas that form at- and transport from - the site of micrometeoroid impacts [*Goertz and Morfill*, 1983; *Goertz*, 1989]. As describe by *Goertz* [1989], at impact sites, large amounts of both dust and plasma (10^{15} el/cm^3 [*Mendis et al.*, 1984]) are ejected from the rings. Because of the dense plasma, the local ring surface tends to charge to a negative potential. The dust is also immersed in this high-density plasma at the impact site and thus is charged negative as well. Repulsive electrical forces then lift the grains from the ring surface. Once lifted, the negative levitating grains proceed along Keplerian orbits while electrons and ions in the enhanced plasma region proceed to get picked-up by the corotating magnetic field creating an azimuthally-directed electric field, E_ϕ and associated current systems.

[5] *Goertz and Morfill* [1983] were unsure whether the ring surface away from the impact site was of positive or negative potential. As described therein (see their Figure 1) it depended upon the detailed estimates of the photoelectric versus ambient plasma flux in the inner ring vicinity, which were not available in the 1980s. Because of Cassini's close passage over the rings, new ambient plasma density mea-

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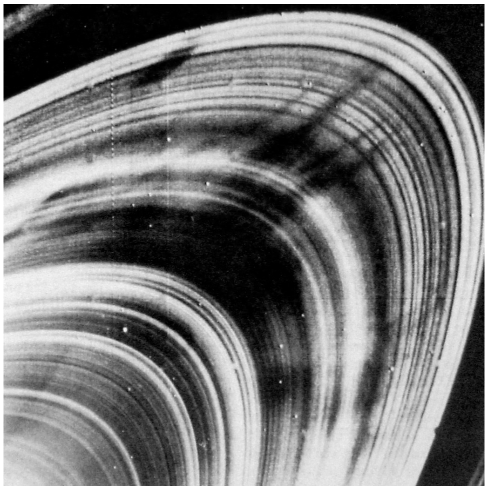

Figure 1. A Voyager image showing the radial spokes (dark streaks) along the rings.

surements can be used to quantify and compare these fluxes. Based on these new observations and simple modeling, we present evidence that the ring top and bottom surfaces change from a negative unipolar electrical configuration at small opening angles to a bipolar (negative-topside/positive-bottomside) configuration at large opening angles. Further, we demonstrate that the observed spoke activity by Voyager, HST, and Cassini is consistent with their formation only on the negatively-charged portions of the ring surfaces.

2. Ring Charging

[6] The more opaque A and B rings consist of particles ranging from small (centimeter-sized) to large (most likely meter-sized ice) [*Esposito et al.*, 1984] in size. One key point regarding the opaque portion of the rings is that the particle density is very high, such that particles lie within each other's Debye sheath (interparticle spacing less than Debye sheath length) [*Mendis et al.*, 1984; *Goertz*, 1989]. The rings, while granular in material nature, can be considered quasi-continuous in electrical nature, where adjoining grain Debye sheaths interlace to form a uniformly-charged disk. As illustrated in Figure 10 of *Goertz* [1989], we can thus envision ring equipotential surfaces to run quasi-parallel to the ring surface, rather than forming spherically about isolated individual particles.

[7] There are basically three currents that determine the potential of this ring-shaped disk: The photoemission current leaving the object from photon energy deposition, inflowing plasma electron currents and inflowing ion currents. *Goertz* [1989] and *Manka* [1973] indicate that the photoemission flux from an object at distance D (in AU from the Sun) is

$$J_p = \eta\left(4 \times 10^{-5}\right) D^{-2} \cos\theta \qquad (1)$$

in A/m^2 with η being the photoemission efficiency ($\eta \sim 0.1$ for insulators like ice, $\eta \sim 1$ for conductors) and θ being the angle of incidence of the photons relative to the surface normal. Note that θ is the geometric complement of ring opening angle as viewed from the sun, t. For direct solar incidence on an icy surface at Saturn, this photoemission current is about 4×10^{-8} A/m^2. The magnetospheric electron currents are slightly more complex and are the new element associated with this work. *Gurnett et al.* [2005] showed that the region near the outer edge of the A ring had a plasma density of >100 el/cm^3 at 2.2 R_s, but this progressively and steeply decreased to $\sim$0.03 el/cm^3 near 1.71 R_s near the central region of the B ring. It is believed the high densities reported outside the A ring are associated with a plasma torus created by icy moon sputtering [*Richardson and Jurac*, 2004]. For thermal electrons near 1 eV [*Coates et al.*, 2005], electron currents range from $J_e \sim 10^{-5}$ A/m^2 at the outer A ring region to $J_e < 10^{-8}$ A/m^2 in the central region of the B ring. We assume the ion currents would show a similar trend but be a factor of $\sim$40 smaller.

[8] Figure 2 illustrates our fundamental concept. During the Voyager era, the rings were only slightly tilted relative to the sun (small opening angle), and hence photoemission currents were minimal (θ close to 90°). Consequently, the rings are immersed in plasma electron currents and hence charged the disk to a negative potential. Note that both sides of the ring gets little sunlight and hence both surfaces (top and bottom) are of negative potential. In this case, the rings are considered unipolar.

[9] However, when the rings become increasingly open toward the sun, the sunlit side of the rings obtains an increasing photon flux in association with the decreasing value of θ (or increasing opening angle). During the Cassini era, in southern summer, we define herein the ring surface obtaining increasing solar flux as the "bottom" side of the rings. This flux increases photoemission such that J_p will exceed J_e at some threshold opening angle, T, with the low plasma density portion of the rings (near 1.7 R_s) initially obtaining a positive potential. As opening angle progressively increases over a season, the region of positive potential on the ring's bottom sunlit side also increases radially both inward and outward along the B ring.

[10] Consider now the top side of the ring shown in Figure 2: it is assumed to be unlit and that solar photon emissions cannot propagate through the ring to the other surface (most likely for the opaque B ring). This unlit side of the ring is still immersed in a dominate plasma electron current and remains at some negative potential. Thus, when the opening angle of the rings exceed the threshold opening angle, t > T, the rings are considered bipolar, with the sunlit bottomside having a large region of positive potential and the unlit topside of negative potential. Half a Saturnian year

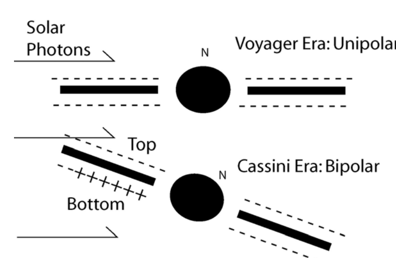

Figure 2. An illustration of the change in ring electrical configuration from Voyager in the early 1980s to Cassini. The opening of the rings allows more photoemission from the bottom side ring, thereby charging it positive.

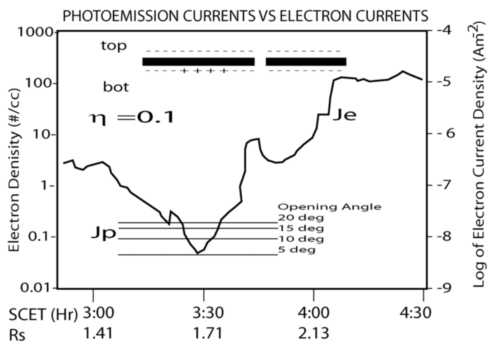

Figure 3. A comparison of the plasma electron currents to the photoemission current. The photoemission currents are presented as a function of opening angle. At locations where $J_p > J_e$, the sunlit bottom side of the B ring should charge to a positive potential.

later, the same situation occurs, only now the topside ring is charged positive and the bottomside remains negative. Note that there is still a portion of the ring in Saturn's shadow, and this will be of negative potential both on the top and bottom sides.

[11] As applied to the Cassini era (i.e., southern summer), along the sunlit bottomside ring where the potential is positive, the electrostatic levitation of the dusty plasma would be disrupted since the negatively-charged dust would eventually be drawn back to the strongly attractive positive surface as the grains migrate in their Keplerian orbits. In essence, when the surrounding surface is positive, attractive electrical forces dominate over weak gravitational forces that make the Keplerian orbital motion. The attractive electrical forces exceed the very weak gravitational forces even for grains at many 10's of Debye lengths from the ring surfaces (i.e., grains do not have to be within one Debye length to be dynamically-altered via the attractive E-field). The bipolar aspect of the rings, including the positive surface, which is seasonal and occurs for relatively large opening angles, may explain why Cassini, to date, has not observed spokes on the sunlit side of the ring.

[12] One can estimate the approximate threshold opening angle, T, where the sunlit surface starts to obtain a positive potential using the electron density profile in the work by *Gurnett et al.* [2005] and applying a 1 eV (6×10^5 m/s) electron thermal velocity, v_{the}. Basically, this critical opening angle occurs when $J_p = J_e$ in the region where the electron density is at a minimum (near 1.7 R_s) and is

$$\mathrm{Sin\,T} = n_e e v_{the} D^2/\eta\left(4 \times 10^{-5}\right) \quad (2)$$

making T $\sim$ 11° for the low densities found in the central B ring region ($n_e \sim 0.1$ el/cm^3). For opening angle, t < T, the rings are considered unipolar, but for t > T, they become bipolar in nature and the sunlit bottom side has a relatively large region of positive potential (and hence a propensity to disrupt spoke formation).

[13] The positive potential in these sunlit regions can be quantified by placing the condition that the ring surface requires current balance. For positive potentials, *Manka* [1973] and *Goertz* [1989] find that the photoelectric currents go as $\eta(4 \times 10^{-5})D^{-2}$ Sin t $\exp(-e\Phi/kT_p)$ where Φ is the surface potential and T_p is the photoemission temperature usually of 1–2 eV (see discussion by *Manka* [1973]). Given current balance it is straightforward to show that the potential in these positive regions is approximately

$$e\Phi = -kT_p \ln\left(n_e e v_{the} D^2/\eta\left(4 \times 10^{-5}\right) \mathrm{Sin\,t}\right) \quad (3)$$

and that these regions will have potentials exceeding +4V. Such a positive potential will disrupt the levitation of negative grains particularly as the grains move in Kepler orbits relative to the initial impact site.

[14] Figure 3 shows the evolution of the region of positive potential on the (bottomside of the) B ring as a function of opening angle. Figure 3 contains the electron density profile measured by the Cassini Radio and Plasma Wave (RPWS) instrument [*Gurnett et al.*, 2005] during its close overflight of the rings. As the Cassini Plasma Spectrometer (CAPS) instrument demonstrates, plasma in this region is relatively cold with a temperature very near 1 eV [see *Coates et al.*, 2005, Figure 3]. With the n_e profile shown in Figure 3 and an estimate of v_{the}, we can derive an estimate for the electron current (labeled on the right side of Figure 3). Note that the profile of J_e as a function of radial distance has a minimum in the center of the B-ring. This current can be compared to the expected (modeled) photoemission current, J_p, which is shown as a function of opening angle as a set of lines. Figure 3 shows J_p for insulating material where the photoemission efficiency in equation (1) is $\eta \sim 0.1$ (appropriate range for icy rings).

[15] In considering Figure 3, we note that for small opening angles, $J_e > J_p$, and hence the B and A rings charge primarily to negative potentials. The inset contains an illustration of the rings and the approximate region of charging on the ring top and bottom. However, there is a region of positive potential that can develop on the ring bottomside if the ring's opening extends above 5°, thereby allowing J_p to exceed J_e in the lowest density region centered in the middle of the B ring (near 1.7 R_s). As the opening angle increases, the region of positive potential on the B ring bottomside progressively increases in radial extent, such that by an opening angle of 15° over 1/3 of the bottomside ring is positive. This region of positive potential in the outer portion of the B ring is also co-located to the region where spokes tend to exist [*Mendis et al.*, 1984]. Using HST observations, *McGhee et al.* [2005] noted that the spokes were fainter and less abundant with increasing opening angle, with a complete absence of spokes for opening angles >15°. In their Table 1, they show that the number of spokes per observation progressively decreased from 7 events for opening angles <5°, to 3 events for openings between 6°–10°, to 0.5 events between 11°–15°, and no events observed for openings >15°. Our model is consistent with their observations, with an initially small region of positive potential near 1.7 R_s at an opening angle of 5° that could partially disrupt event formation. This region progressively expands to larger sizes, such that near opening of $\sim$15° the events disappear (assuming that negative grains require an extended negative surface to remain lifted). In Figure 3, we apply 1 eV electron temperatures for both the B and A ring, but CAPS observations indicate that the A ring is slightly hotter (3–6 eV temperature)

[*Coates et al.*, 2005] making J_e even larger than that modeled. The 1 eV application for the B ring is consistent with the CAPS observations.

[16] Given J_p, J_e, and equation (3), an estimate of the peak positive potential along the bottomside B-ring (near 1.7 R_s) can be made. Specifically, for $\eta \sim 0.1$, the peak positive potentials are 0.8 V, 2.2 V, 3.0 V, 3.6 V, and 4 V for 5°, 10°, 15°, 20° and 25° opening angles respectively.

[17] The profile shown in Figure 3 was obtained from a single Cassini overflight. While the broadest structures of the J_e profile are most likely well-represented in Figure 3, including the electron density "well" forming at 1.7 R_s, at any other time the detailed structure may vary from that shown due to intrinsic temporal variability. Also, using auroral hiss generated at the rings as a remote diagnostic tool, L. Xin et al. (Whistler mode auroral hiss emissions observed near Saturn's B ring, submitted to *Journal of Geophysical Research*, 2005) demonstrated that a slight plasma density gradient should exist between the spacecraft and ring tops that increases the electron density by an e-fold (factor of 3) at the rings as compared to spacecraft values. As such, the J_e curves in Figure 3 might be shifted upward by ½ of a decade compared to those currently shown (but overall concept remains the same).

3. Conclusions

[18] This work focuses on the charging of the ring surfaces and the unipolar/bipolar ring configuration, but the results have direct implications for spoke formation. Specifically, the Goertz/Morfill model would be facilitated by a negative ring surface to allow negative grain levitation and easy migration from the micrometeoroid site. Consequently, locations where the spokes have (and have not) been observed can be used as a proxy to indicate regions of negative (and positive) potential on the B-ring. There are three prominent examples: First, during the Voyager flybys, spokes were copiously observed on both ring sides and our calculations here indicate that both sides of the rings should be negative. Second, as viewed from Earth (via HST), the bottomside ring spokes were found to progressively become fewer in number and more difficult to detect at opening angles >5° finally to disappear in late 1998 when the rings had opening angles exceeding ~15° [*McGhee et al.*, 2005]. Our calculations suggest that the bottomside B ring was correspondingly developing a progressively larger region of positive potential as the opening exceeded 5°, consistent with the decreasing spoke number and eventual disappearance. Third, Cassini has not observed spokes on the ring bottomside since SOI (from mid 2004). Our calculations suggest the existence of a relatively large region of positive potential on the bottomside B ring during that same 2004–2005 time frame, again consistent with this lack of spoke activity.

[19] Finally, the Cassini imager recently reported the first spoke detection in the rings made during prime mission (http://ciclops.org/view.php?id = 1435). However, these spokes were found during a relatively rare viewing of the B ring topside surface, which is modeled to be of negative potential. The bottom side B-ring (presumably of positive potential) continues to remain devoid of spokes.

[20] In 2008, as the opening angle drops below 13°, the bottom side B-ring will become increasingly charged negative, and spokes will reappear. However, spoke development at this time should be strongly influenced by solar photon emissions, particularly given increased solar activity with the 2011 solar maximum (i.e., greater variability in solar UV and x-rays). Specifically, weak spokes that might develop during this transition period when J_e is just becoming slightly greater than J_p could completely disappear during a Saturn-directed solar flare with increased photonic energy on the ring surface (that would temporarily increase J_p at the rings). This transition period may be the most complex test of the Goertz/Morfill model, and may be a potentially illuminating period in the understanding of the electrodynamics of Saturn's rings.

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