The Spokes in Saturn's Rings: A Critical Evaluation of Possible Electrical Processes

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Abstract. Among the mechanisms proposed to explain the novel spoke phenomenon occurring in Saturn's B-ring, the alignment of particles by an electric field has been suggested. In this and related theories, the particles are assumed to be adequately conducting; or at least it is the case that electrical conductivity generally acts to enhance the feasibility of the proposed processes. These ideas are appraised in light of the fact that the particles are most likely composed of ice. We conclude that the electrical torque required to align the particles is many orders of magnitude larger than that which is likely to exist. Also, the conductivity of ice at ring temperatures is probably so small as to inhibit some of the proposed processes.

Introduction

The observations by Voyagers 1 and 2 of spoke-like features in the rings of Saturn and of the possibly related Saturn electrostatic discharges (SED's) have provoked great interest on the part of space scientists. As a result there has been some speculation as to the causes of these phenomena (Warwick et al., 1981; Hill and Mendis, 1981; Goertz et al., 1981; Carbary et al., 1982; Thomsen et al., 1982). Most of the ideas put forth invoke the involvement of micron-sized particles in electrical processes. However, certain relevant details have been neglected; first, the electrical properties of the particles involved, which are presumably water ice (Cruikshank, 1979), and, second, the magnitude and speed of the electrical and dynamical responses of these particles to the processes presumed to be operating. It is the purpose of this letter to address these neglected aspects of the problem and in turn to critically appraise the proposed ideas in light of what is found.

Ring Particle Alignment

Carbary et al. (1982) propose that a 16 kV potential across the 25,000 km wide B-ring acts to align the 1-10 μm ice particles radially or at least to produce a radially directed asymmetry in their alignments. The ability of this electric field, which is on the order of 1 mV/m, to produce the ice crystal alignment may be assessed by computing the electrical torque acting on the particles assuming, for the moment, that they are perfect conductors and that they are spheroidal. The torque is given by the cross product of the induced dipole p and the electric field E (see, e.g., Stratton, 1941). It may be expressed as

\[ T_E = T'_E \cos \theta \sin \theta \]

where

\[ T'_E = 4\pi \varepsilon_0 E^2 d^3 f(q) \]

and where \( d \) is the semi-major axis of the spheroidal ice particle, \( f \) is a function of its axis ratio \( q \) (or, for a dielectric, a function of \( q \) and the relative permittivity \( \varepsilon_r \)), and \( \theta \) is the angle between the spheroid's symmetry axis and the field direction. A graph of \( f(q) \) is shown in Figure 1 for values of \( q \) ranging from the very oblate \( q = 10^{-2} \) to the very prolate \( q = 10^{-2} \), for each of three cases: a perfect conductor, a dielectric with \( \varepsilon_r = 3.2 \), and a dielectric with \( \varepsilon_r = 100 \).

Taking an extreme case to overestimate the torque, we choose \( d = 10 \mu m \) and \( f(q) = 0.5 \). For \( E = 10 \text{ mV/m} \), \( T'_E \) then becomes \( 5.6 \times 10^{-30} \text{ N-m} \), or \( 3.5 \times 10^{-11} \text{ eV} \). The work done on an ice particle, as it rotates into alignment from an orientation perpendicular to the field, is half of this or \( 1.7 \times 10^{-11} \text{ eV} \). The electric field used here, 10 mV/m, is larger than that of Carbary et al. (1982), but it is representative of the corotational field in the B-ring. Since the ice particles may be expected to have rotational kinetic energy of at least the order of \( kT \) (more if collisions are frequent), and since \( kT \) is about \( 10^{-2} \text{ eV} \) for these particles (T is 50-80 K; Hanel et al., 1981), it is clear that the effects of the electrical torque will be small even in relation to thermal effects, provided that the electrical torque results from an induced dipole.

However, a much larger torque may exist if the dipole moment is produced by other means. For example, if the particles were ferroelectric, the dipole moment would be much larger than for the case of an induced dipole. A decade ago it was perhaps an open question as to whether or not a ferroelectric state exists in ice at temperatures below 100 K (Robert, 1974). However, the current consensus (Johari, personal communication) is that no such state exists, or at least that it has not been observed, as was once thought by some. In addition, even if ice undergoes a proton-ordering phase transition at low temperatures, it is not clear whether a ferroelectric state would result, or a dipole-less antiferroelectric state (Johari, personal communication); the latter being more often the case in the high-pressure forms of ice. Nevertheless, since the ring particles are at temperatures lower than those used in laboratory experiments and have likely been at such temperatures for long enough that dielectric relaxation may have occurred (see below), it is a useful exercise to compute the dynamical response of ferroelectric particles to see if, even then, electric field alignment is feasible. Assuming a dipole moment per molecule of \( 8.0 \times 10^{-30} \text{ C-m} \) and

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Properties of Low Temperature Ice

For the sake of the above induced-dipole calculations, the ice particles were assumed perfectly conducting. However, this is far from true for ice at these temperatures, and this brings up the fundamental question: What are the conduction and dielectric properties of ice at these temperatures and what are the constraints thereby imposed on the processes that may occur? Partial answers may be found in Hobbs (1974). At 0°C ice has significant surface and bulk conductivities. However, since the activation energies for these processes are roughly 1.3 eV and 0.4 eV, respectively, the exponential dependence of these conductivities on the negative of the ratio of the activation energy to kT will reduce them to negligible values at temperatures on the order of 10 to 80 K.

Similarly, the dielectric relaxation time for ice has an activation energy of about 0.57 eV, and this leads to absurdly long times required for dielectric polarization at low temperatures. This time is 20 µs at 0°C, but greater than 1000 years at 80 K (based on an extrapolation of the results of Johari and Jones, 1975). Actually this dielectric relaxation time applies only to the major component of ice’s static relative permittivity which at 0°C is of the order of 100, and is due to the motion of protons. However, even at lower temperatures, the electron component will be active, but this provides a relative permittivity of only about 3.2. (See Figure 1.) One additional consideration is the crystalline structure of the ice, or lack thereof, which depends on the temperature at which it is deposited. Measurements on cubic and hexagonal ice (Gough and Davidson, 1970) show no differences in the dielectric properties of these two polymorphs. Similarly, there is no obvious reason why amorphous ice, which is the third possible form at these temperatures, should be expected to be significantly more electrically active than the two crystalline states.

Discussion

What this means for Carbery et al. (1982) is that, ignoring the dynamical problems for a moment and assuming ice is not ferroelectric, there will be significantly less polarization than might otherwise be expected. For Warwick et al. (1981), who propose that charge may be exchanged by colliding particles, the low conductivities are a problem. It is thought that ice particles in terrestrial thunderstorms at temperatures of -20 to 0°C may be only marginally conductive enough to transfer charge during collisions (Pruppacher and Klett, 1978, p. 603). If
in fact we are dealing with ice in Saturn's rings, then low conductivity values will inhibit collisional charge transfer. It may be the case that conduction is not necessary for the charge transfer, even in thunderstorms. Nonetheless, it seems that it would help. The same also applies to the discharge process proposed by Goertz et al. (1981). In their calculation of emitted power and frequencies they assume no surface resistance. This is unlikely to be the case for ice at ring temperatures. However, since the discharge process may not in fact require surface conduction (Whipple, 1981), this may not be a serious problem; although the calculations of Goertz et al. (1981) may still be brought into question. Low conductivities are also a problem for the process proposed by Hill and Mendis (1981) and assumed by Thomsen et al. (1982), in which particles in contact with larger bodies are presumed to acquire at least some fraction of the potential of the larger bodies, apparently by conduction. If ice is as poor a conductor at these low temperatures as it appears it may be (no direct measurements have been made), then mechanisms using ice particles to explain spokes and SED's need to address this problem. An obvious way out is to suggest that even though ice may be the most prevalent substance in the rings, other materials may also be present and may participate in the production of spokes and SED's. Some particles may contain little or no ice, or there may be impurities or defects in the ice which enhance its conductivity. This may circumvent these conductivity problems, but not the dynamical problems faced by Carbery et al. (1982).

Summary

It has been the purpose of this letter to address quantitatively the electric field alignment of ice particles in Saturn's rings, and to introduce into discussions of the spokes and SED's the constraints imposed by the electrical properties of ice, assuming that ice is in fact involved. Considerable doubt has been cast on the feasibility of some of the ideas proposed on these topics. The difficulties raised for the mechanism proposed by Carbery et al. (1982), who require the electric field alignment of ice particles in mW/m fields, seem insurmountable unless ice is ferroelectric at ring temperatures, and this seems unlikely (Johari, 1981). Our calculations of representative alignment energies are summarized in Table 1. The difficulties raised for the other mechanisms in connection with the low conductivity of ice may be less severe. In any case, since it is widely conceded that the ring particles are composed of ice, the electrical properties of ice at low temperatures do require more attention than they have received up to this time.

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References

Warwick, J. W., J. B. Pearce, D. R. Evans, T. D.

Table 1. Representative alignment energies (~pE) for three different polarization mechanisms, for particles with semi-major axes of 1 μ and 10 μ, all for a field of 10mV/m. For purposes of comparison, the thermal energy is of the order of 10^-2 eV.

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>d = 1 μ</th>
<th>d = 10 μ</th>
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<tbody>
<tr>
<td>Conductor</td>
<td>10^-11 eV</td>
<td>10^-1 eV</td>
</tr>
<tr>
<td>Anisotropic Radiation</td>
<td>10^-5 eV</td>
<td>10^-2 eV</td>
</tr>
<tr>
<td>Ferroelectric</td>
<td>10^-1 eV</td>
<td>10^2 eV</td>
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