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Energy Gap in Saturn's Rings

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Abstract

In this article, we consider, based on the super-diamagnetic model, the new problems of Saturn's rings discovered by Cassini, such as: 1) anomalous purity of water ice; 2) Saturn's magnetic field alignment with the planet's rotation axis; 3) "ring rain" of the submicron particles; 4) the deviation in the qualitative composition of the "rain" from the composition of the rings; 5) "dirt" concentrated in the ring gaps; 6) "plateaus" in Saturn's C ring; 7) age of the rings; 8) roll-off in the spectrum of Saturn's rings, and 9) "propellers" in Saturn's A ring. Interpretation of Cassini's observations of spectral roll-off in Saturn's rings in the wavelength range from 100 micrometers to 0.5 mm is given. It was concluded that the substance of the rings could be in the superconducting state. An explanation of the Cassini spectral data is given using the hypothesis of the existence of a superconducting energy gap in the substance of rings.

Keywords

Saturn Rings, Cassini CIRS Interpretation, Super-Diamagnetic Model, Superconducting Energy Gap, Ring Rain, Plateaus and Propellers in Saturn's Rings

1. Introduction

Cassini's research added new puzzles [1] [2] [3] to long-standing problems [4] [5] [6] [7] [8] and, at the same time, reinforced the super-diamagnetic model of Saturn's rings (**Table 1**). Due to the fact that each problem of Saturn's rings was explained by a few separate models or hadn't explanation at all [9], we chose an approach that would set a single reason for a dozen known problems. We assumed that such a common cause could be the superconducting state of matter in the rings of Saturn. Then, the numerous phenomena, properties, and effects of superconductors entered into battle with the problems and puzzles of Saturn's

Table 1. Possible solutions of the problems of Saturn's rings based on a super-diamagnetic model.

Problems regarding Saturn's rings	Saturn's ring problems explained through superconducting effects
1) Anomalous purity of water ice (99.9 %)	Superconductivity of ice in Saturn's rings [13], Meissner-Ochsenfeld effect [14]
2) The existence of a temperature boundary beyond the asteroid belt, where the planets may have rings	Superconducting transition temperature (T_c)
3) Great flattening of the rings system. Sharp edges and rings discontinuities. Arcs	The phenomenon of expulsion of the superconductors out of the areas with greater density of magnetic flow [15]
4) Fine periodical structure of the Saturn's rings, density waves	The phenomenon of the formation of a periodic structure in a super-diamagnetic liquid film under the influence of normally oriented magnetic field
5) "Ring rain" of the submicron particles	Disappearance of the super-diamagnetic properties of superconducting particles at a greater depth than London's penetration depth of the magnetic field (50 - 500 nm)
6) Forming and development of the "spokes" of Saturn's B ring	Loss of superconductivity due to the critical magnetic field H_c
7) High reflection and low brightness of the ring particles in the radiofrequency range	Critical frequency for the superconductor, above which electromagnetic waves are absorbed, and below which they are completely reflected (10^{11} Hz)
8) The wide band pulse radiation of the rings (20 kHz - 40.2 MHz)	Non-stationary Josephson phenomenon: generation of electromagnetic waves by Josephson's weak links with the parameter 4.83594×10^{14} Hz/V [16]
9) Existence of Kilometric radiation of the Saturn rings ($\nu < 1.2$ MHz)	The electric field appears due to the movement of the superconducting fluid within the magnetic field
10) Color differentiation of Saturn's rings in a small scale	Dependence of the force of magnetic levitation from the volume of superconducting phase in the bulk matter (observed in experiment)
11) Phenomenon of anomalous inversion of reflection of the radio waves with the circular polarization ($\lambda \geq 1$ cm)	Positive charge of the superconducting carriers (protons) [17]
12) Possible distribution of particles by size in Saturn's rings in the radial direction	Dependence of magnetic separation of the superconducting particles by size, and also, strength, extension, and the range of the applied magnetic field [18]
13) The existence of an atmosphere of molecular oxygen around the rings of Saturn	Magnetic levitation of gas molecules due to diamagnetic expulsion forces induced in superconducting particles by molecular magnetic moments (observed in experiment). Flux pinning [19]
14) Saturn's magnetic field alignment with the planet's rotation axis (<0.06˚)	London moment [20]
15) Increasing the purity of the ice in the radial direction from Saturn	The dependence of the force of expulsion of a superconductor from a magnetic field on the volume of the super conducting phase (observed in experiment)
16) "Dirt" concentrated in the ring's gaps	The phenomenon of expulsion of the superconductors out of the areas with greater density of magnetic flow
17) Deviation in the qualitative composition of the "rain" from the composition of the rings [21]	London's penetration depth , flux pinning, super-diamagnetic expulsion
18) "Plateaus" in Saturn's C ring	Tao effect: Electric-field induced formation of superconducting granular balls [22]
19) Age of the rings	London moment, super-diamagnetic expulsion, flux pinning
20) Roll-off in the spectrum (100 μm - 0.5 mm) [23] [24]	Superconducting energy gap (10^{-4} eV - 10^{-3} eV)
21) "Propellers" in Saturn's A ring [25]	Gyromagnetic effect [26], London moment, super-diamagnetic expulsion
22) Origin, dynamics and evolution of the rings	All phenomena above

rings. Moreover, a deeper analysis using spectral studies indicates that the mystery of the nature of rings is hidden in the physical state of the particles of the rings. In our approach, we proceeded on the basis of one hypothesis about the nature of rings to find a solution to as many problems as possible, no matter how fantastic this hypothesis seemed. In the case of Saturn's icy rings, this required overcoming a psychological barrier, since it seems to everyone that everything is known about the ice that we deal with in everyday life. But the nature of cosmic ice, which was formed under weightless conditions at very low temperatures (~10 K) for a very long time (~1 billion years), has hitherto been unknown.

2. Super-Diamagnetic Model of Saturn's Rings

We have compiled a list of problems for Saturn's rings and a list of effects, properties, and phenomena for superconductors, and then found a match between each of them. This resulted in the super-diamagnetic model of Saturn's rings (**Table 1**).

The problems of Saturn's rings with numbers 2 - 13, 22 of **Table 1** were considered by us in a previous article [10]. The problems with numbers 1, 14 - 21 will be discussed in this article.

3. Discussion of the New Problems Discovered by Cassini

The rings of Saturn, with rotation at a speed of 20 km/s, with a thickness of 10 m, and a total width of the main rings of 2.82×10^8 m can be considered as a flow of super-diamagnetic thin film fluid (with suspended superconducting particles).

Colloidal systems based on superconducting materials may possess a number of unusual properties. These include an anomalously high initial diamagnetic susceptibility, a non-analytical magnetization curve that is capable (in the case of composite suspension) of changing the sign, and dynamic Josephson contacts [11].

3.1. Anomalous Purity of Water Ice in Saturn's rings

The fact that the rings are extremely pure ice (99.9%) remains the number one mystery. According to popular opinion, the reason for such purity may be that they are very young; otherwise they should darken with age due to accumulated dust. The speed of darkening may depend on the influx of dust, and on the total mass and internal dynamics of the rings [12]. The super-diamagnetic model adds a new factor: self-cleaning of the rings due to the Meissner-Ochsenfeld effect and the London penetration depth of the magnetic field. Due to the fact that icy particles are possibly superconducting, they exhibit super-diamagnetism and the Meissner-Ochsenfeld effect. This allows them to remain in their Kepler orbits, while impurities, as well as ice particles with sizes smaller than 1 micron, cease to interact with the magnetic field of the planet and rush to the planet. Such a mechanism may explain the predominance of water ice in the rings of Saturn.

3.2. Saturn's Magnetic Field Alignment with the Planet's Rotation Axis

Based on data collected by Cassini's magnetometer instrument, Saturn's magnetic field appears to be surprisingly well-aligned with the planet's rotation axis. The tilt is much smaller than 0.06 degrees—which is the lower limit of the spacecraft's magnetometer. The core of Saturn probably consists of metallic hydrogen and is superconducting. In accordance with the London moment, a rotating superconductor generates a magnetic field whose axis exactly coincides with the axis of rotation.

3.3. "Rain" of the Submicron Particles

The ring rain that Cassini's Ion Neutral Mass Spectrometer caught falling from Saturn's rings into its atmosphere is only about 24 percent water. This is—a major surprise—given that Saturn's ring system is almost entirely water ice. The rest of the ring rain is composed of organic material and other molecules.

The explanation for this is the loss of super-diamagnetism by superconducting ice particles with a size of less than 1 micron, which corresponds to the doubled London depth of penetration of the magnetic field into the superconductor. Ice particles that have lost super-diamagnetism, nevertheless, retain their diamagnetism, which causes them to move along magnetic field lines.

3.4. The Deviation in the Qualitative Composition of the Rain from the Composition of the Rings

Ring rain is highly contaminated with organic matter and other molecules. Water constituted only about 24 percent of the material tumbling from Saturn's ring system into its atmosphere; the rest is methane, carbon monoxide, dinitrogen, ammonia, carbon dioxide and fragments of organic nanoparticles. Remote observations show that Saturn's ring system, on the whole, is almost entirely water ice. Why is ring rain so deprived of water? It turns out that the rain that falls out of rings consisting of 99.9% water ice contains 76% of pollutants. What kind of mechanism is responsible for this filtration? We believe it to be the simultaneous action of three quantum effects: the Meissner-Ochsenfeld effect, flux pinning for icy particles larger than 1 micron, and the penetration of a magnetic field into a superconductor to the London depth for icy particles smaller or equal to 1 micron. At the same time, the above-mentioned effects do not affect the pollutants.

3.5. "Dirt" Concentrated in the Rings Gaps

The presence of dirt in the gaps of the rings is explained within the framework of the super-diamagnetic model by the magnetic field condensing in the gaps due to expulsion of the magnetic field from the rings, where superconducting ice particles are located, and also, due to the paramagnetic properties of cosmic dust, which tend to the concentrations of the magnetic field.

3.6. "Plateaus" in Saturn's C Ring

The bright areas inside the rings, where a large number of particles are concentrated are called plateaus. The plateaus have a fancy striped structure, while the neighboring regions seem lumpy or have no obvious structure at all. These textures provide information about different ways in which the ring particles are interacting with each other. Cassini data indicates that the plateaus do not necessarily contain more ring material than the C ring at large, but the ring particles in the plateaus may be smaller, enhancing their brightness. The task of how plateaus are created and maintained has not been solved. The super-diamagnetic model offers a possible solution. When a strong electric field (0.8 kV/mm) is applied to a suspension of micron-sized superconducting particles, the particles quickly aggregate together, to form millimeter-sized balls. The balls contain more than 10^6 particles each. This phenomenon is the result of the interaction between Cooper pairs and a strong electric field. The strong electric field induces surface charges on the particle surface. When the applied electric field is strong enough, Cooper pairs near the surface are depleted, leading to positive surface energy. The minimization of this surface energy leads to aggregation of particles with the formation of balls. If superconducting particles are in a strong electric field and a moderate magnetic field, the electric-field induced balls align in the magnetic-field direction to form ball chains [27].

3.7. Age of the Rings

Estimation of the age of Saturn's rings using a super-diamagnetic model does not depend on the mass of the rings and the extent of their contamination. The estimation is based on the assumption of the origin of the rings from the proto-planetary cloud and the proto-ring disc at occurrence of a magnetic field. Superconducting particles, which were present in the proto-planetary cloud, under the influence of a rotating planetary magnetic field, were involved in a circular rotation. Then they formed into a proto-ring disk due to the effect of super-diamagnetic expulsion and drift into the plane of the magnetic equator, where the magnetic flux density is the smallest. Here, the superconducting particles finally became fixed due to the effect of flux pinning. Flux pinning is the phenomenon where a superconductor is pinned in space by a magnetic field. The flux tubes are pinned in place and cannot move. This pinning is what holds the superconductor in place thereby allowing it to levitate. Time became powerless in destroying the rings. The super-diamagnetic model estimates the age of the rings to be equal to the age of Saturn. Rings began to form with the advent of Saturn's magnetic field.

3.8. Cassini CIRS Data Interpretation

Cassini Composite Infrared Spectrometer (CIRS) spatially resolved Saturn's main rings in the far-infrared, measuring the spectrum from 20 to 400 wavenumbers (cm^{-1}) (between 100 microns and 0.5 mm). A spectral roll-off below 50 cm^{-1} (200 μm) for each of the A, B and C rings was found (**Figure 1**). From these data temperatures and emissivities for each ring were derived. Interpretation of Cassini CIRS spectral roll-off in Saturn's rings has encountered difficulties. The

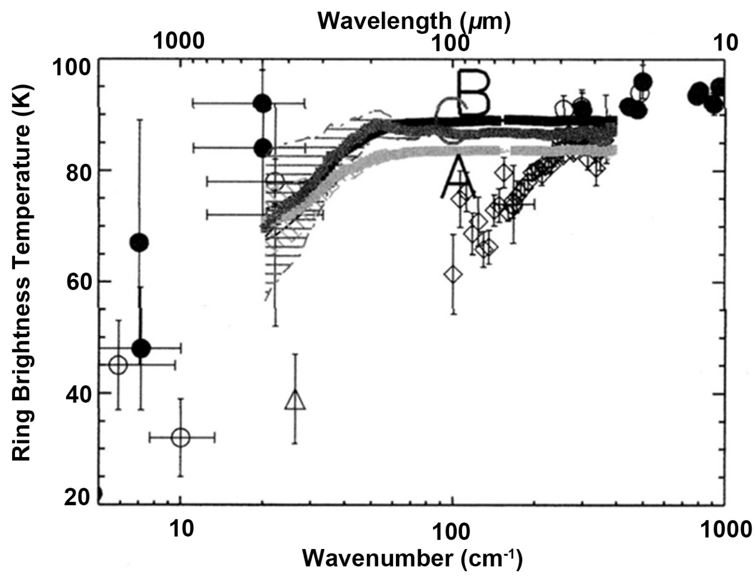

Figure 1. Brightness temperatures of the A, B and C rings as a function of wavenumber (and wavelength).

roll-off in temperature measured by CIRS is principally due to material properties of the ring particles that change dramatically in this region [28]. Lack of laboratory data in the far infrared region below 100 cm^{-1} for water ice analogs of Saturn's rings still hamper the interpretation and understanding of the spectral roll-off observed by the Cassini CIRS instrument [29].

3.8.1. Superconducting Energy Gap

To prove that a substance is a superconductor, it is necessary to measure its energy gap. Cassini CIRS received data in a submillimeter range could be used for the purpose of measuring an energy gap.

If the energy of the infrared radiation is above a certain threshold value, the superconductors absorb radiation very effectively, but if it is below the threshold value then they do not. This is very good evidence that the carriers in a superconductor behave as if they do have an energy gap. The idea of a Cooper pair offers a way of understanding this. Since the pairs are bound, it takes a certain amount of energy, called binding energy, to break the pairs up and this leads to what is known as the superconducting gap. In a superconductor, nothing will happen until an amount of energy equal to the binding energy is supplied. And, once that gap has been bridged, then that energy can be absorbed. This effect can be measured by looking at the way in which superconductors reflect electromagnetic waves; if the waves have an energy (determined by their frequency) which is smaller than the gap energy, the waves are not absorbed and reflect straight back from the superconductor; however, as soon as the energy is large enough, superconducting pairs can be broken apart and energy is absorbed [30].

Ice provides a good example of electrical conduction by proton transfer [31]. Protons, and not just electrons, can travel unobstructed through superconductors. As protons are much heavier than electrons, the pairing of protons is less likely to be destroyed by high temperatures than the pairing of electrons.

3.8.2. Interpretation of Cassini CIRS Spectral Roll-Off

The super-diamagnetic model of Saturn's rings offers an interpretation for Cassini CIRS observations of a roll-off in Saturn's ring spectra at submillimeter wavelengths. The observed roll-off in the spectrum of the rings is possibly related to the superconducting state of ice. In this case, the thermal conductivity of ice decreases, because charge carriers no longer interact with the lattice and cannot exchange energy, and therefore, they cannot transfer heat from one part of ice to another [32]. The steepness in the curve in **Figure 1** can be interpreted using the two-fluid model of a superconductor, where fewer and fewer normal protons participate in heat transfer with increasing ring radiation wavelengths and more and more superconducting protons do not participate in heat transfer.

It can be assumed that the ice of the Saturn ring is a high-temperature proton superconductor with an energy gap of $2\Delta = 6.2 \times 10^{-3}$ eV (which corresponds to 200 μm) and a superconducting transition temperature T_c of at least 100 K. With such values of 2Δ and T_c, the **Equation 1** for the width of the superconducting energy gap for ice in the rings of Saturn takes the form:

$$2\Delta = 3/5\, k_B T_c. \tag{1}$$

where k_B is Boltzmann constant.

3.9. "Propellers" in Saturn's a Ring

The propellers are gaps in the ring material which were created by a moonlets. These moonlets are smaller than known moons but larger than the particles making up Saturn's rings. It is estimated that these moonlets could number in the millions.

The reason for this phenomenon may be a gyromagnetic effect which takes place when a magnetic field is applied to a superconducting body (moonlet). Then superconductor acquires an angular moment in direction opposite to the applied field and it starts to spin spontaneously. Due to the London moment, a rotating superconductor (moonlet) generates its own magnetic field, which in turn, moves superconducting particles apart, forming double-armed propeller structures.

4. Conclusions

The interpretation of Cassini data is particularly relevant now after the recent completion of the mission (2017). Especially important is the analysis of the physical characteristics of the particles of the rings because behind them there lies the nature of the substance of the rings. Such information is contained in an unexpected drop in the spectral range of sub-millimeter waves. Classical approaches to the problem do not give satisfactory results. Our approach to using the super-diamagnetic model of Saturn's rings, based on the assumption of the superconducting nature of the substance of the rings, is new, timely, and leading to far reaching consequences.

For example, conclusions from the presented work can be extended to the rings of other objects of the Solar System such as the rings of Jupiter, Uranus, Neptune, minor planets and centaurs Chariklo and Charon, and possible ring system around Rhea, which at least partially composed of water ice and possibly other superconducting substances. As a result, it can also be argued that Chariklo, Charon and Rhea have their own magnetic fields.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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