

Role of Electromagnetism in the Origin of Saturn's Rings Due to Diamagnetism of Their Ice Particles: J. C. Maxwell Had Almost Solved the Rings Origin Problem

Vladimir V. Tchernyi (Cherny), Sergey V. Kapranov, and Andrey Yu. Pospelov

Abstract – For the first time, we take account of the interaction of Saturn's magnetic field with diamagnetic ice particles of the protoplanetary cloud (the Saturn nebula), a force that is likely to contribute to the genesis of a stable disk-shaped structure of rings, formation of sharp ring edges, and separation of particles in rings.

1. Introduction

G. Galilei first saw Saturn's rings in 1610. J. Maxwell proved that the rings consist of particles [1, 2], and G. Kuiper predicted (1947) that the particles are made up of ice. The Cassini probe found (2004–2017) that ring particles are composed of >90%–95% water ice [3, 4].

There exist a number of hypotheses on the origin of planetary rings and physical causes of their existence—for example, the rings are a result of tidal disruption of a migrating moon within Saturn's circumplanetary disk; their structure is determined by orbital resonances with satellites; they are debris maintained by the gravitational quadrupole moment of the planet; they are a result of moon–moon collision disruption; they are debris of the outer planetary moons from collisions with comets or meteorites; they originate from tidal disruption of a passing large comet; they are a result of rapid viscous spread of the debris; their existence and evolution are explained with a gravitational viscous turbulent model of differential orbiting of colliding debris; the ring system is a product of cosmogonic implications of gravito-electrodynamic and magneto-gravitational interactions of the charge grains of dusty plasma or condensation from a partially corotating plasma; rings are the relic of the protosatellite disk; or they arise from volcanic activity on a moon of Saturn [3–19].

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Vladimir V. Tchernyi (Cherny) is with the Modern Science Institute, Science And International Business Research, Osennii Boulevard, 20-2-702, Moscow, 121614, Russia; e-mail: chernyv@bk.ru.

Sergey V. Kapranov is with the A.O. Kovalevsky Institute of Biology of the Southern Seas, Russian Academy of Sciences, Leninskiy Avenue 38/3, Moscow, 119991, Russia; e-mail: sergey.v.kapranov@yandex.ru.

Andrey Yu. Pospelov is an independent researcher, 3940 Grand View Boulevard, #256, Los Angeles, California 90066, USA; e-mail: apospelov@hotmail.com.

Unfortunately, none of these models provides a convincing explanation for many of the observed features of the rings, their stability, and their location in the equatorial plane [4, 12, 16]. In addition, there is no clear understanding of the fine structure of the rings, their extreme flatness and sharp edges, unusual separation of particles, and so on.

There is an opinion that among the possible physical forces that maintain Saturn's rings stability, nongravitational ones can be influential [3].

Previously, we assumed that the superconductivity of particles is responsible for the location of Saturn's rings in the plane of its magnetic equator and the separation of particles, and several observed electromagnetic phenomena were explained [20–32]. However, to date there is no experimental evidence that space ice may be superconductive.

In this article, we try to take into account the influence of Saturn's magnetic field due to the diamagnetism of ice particles superimposed on the gravitational field. This article benefits from a previous one (2020) by V. Tchernyi and S. Kapranov [33].

2. Concept of Magnetic Anisotropic Accretion

The Cassini probe measured that the ratio of heavy and light hydrogen isotopes in the ice of rings is the same as in ice on Earth [34]. Ice XI that is stable below 73 K can be the main polymorph modification of ice in Saturn's rings [35], and it is diamagnetic [36, 37]. This suggests that in the gravitational models of ring origin, additional interaction of Saturn's magnetic field with diamagnetic ice particles of the protoplanetary cloud should be taken into account.

Following V. Safronov's theory of the small nebula [38], our concept [33, 39–42] states that after the emergence of Saturn's magnetic field and diamagnetic expulsion force acting on ice particles, all chaotic orbits of the particles inside the protoplanetary cloud started tilting toward the magnetic equator plane. Eventually, the protoplanetary cloud collapsed into a disk of rings with particles in the plane of the magnetic equator. At the end of this process, all the particles are trapped inside a three-dimensional magnetic well in the plane of Saturn's magnetic equator and form a disklike system of rings. For an orbiting particle, the gravitational force is counterbalanced by centrifugal force and the force of diamagnetic expulsion. Cassini discovered that for

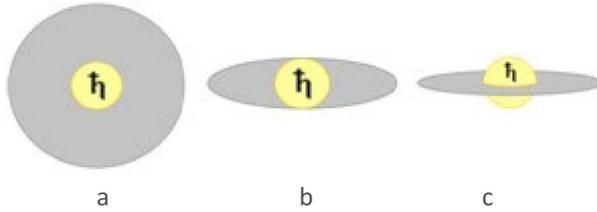


Figure 1. Transformation of Saturn's protoplanetary cloud into a disk of rings after the emergence of Saturn's magnetic field and its interaction with the ice particles.

Saturn, the magnetic equator coincides with the geographical one.

3. Solution of the Problem of the Origin of Saturn's Rings With the Contribution of Magnetic Anisotropic Accretion

It should be demonstrated how a protoplanetary cloud can collapse into a disk of rings (Figure 1).

To this end, we need to solve the problem of how all chaotic orbits of diamagnetic ice particles in Saturn's protoplanetary cloud, after the emergence of Saturn's magnetic field, end up in the plane of the magnetic equator and create a system of rings with well-separated particles and fine structure. It is important to note that Saturn has a spherically symmetric gravitational field and an axisymmetric magnetic field. The solution of the problem is based on the fundamental electromagnetic approach proposed by V. Tchernyi and S. Kapranov [33, 43–46]. First, the problem of a sole diamagnetic spherical particle in the gravitational and magnetic fields of the planet is formulated. Under the assumption of a constant orbital radius, the problem of diamagnetic particle motion after the emergence of the planetary magnetic field is reduced to an equation for the azimuthal angle of the particle motion. The analytical solution of this equation shows that all stable orbits of ice particles are locked in the magnetic equator plane. In Saturn's gravitational field only (that is, if Saturn's magnetic field is zero), the ratio of the particle's angular velocity components has proven to be extremely unlikely, which apparently disproves the purely gravitational theory of the stability of Saturn's rings. If the additional axially symmetric magnetic force is exerted on the particles, their circular orbits fall on the magnetic equator plane, as follows from the equation solution and established in several spacecraft missions to Saturn.

We then consider the model of Saturn's rings as spatially separated and uniformly magnetized spherical particles in a disk-shaped structure consisting of identical spheres with uniform planar density. We find that the magnetization and magnetic moment of a particle in the disk-shaped structure is much higher than that of a sole sphere, due to the alignment of many magnetic dipoles with the field. In the disk structure, the force of diamagnetic expulsion into the weak-field region is stronger, and the magnetic well in the magnetic equator is deeper.



Figure 2. Deformation of magnetic field lines of Saturn by the disk of rings.

4. Stability, Separation of Particles, and Sharp Edges of the Rings

Features of the disk-shaped ring structure provide sufficient stability of the particle orbits and of the entire ring system. The resilience to vertical shift is due to the minimum energy of the particles at the equator, and the horizontal orbit stability is ensured by the inhomogeneity of the magnetic field along the radius. The magnetic well of the disk of rings with ice particles disturbs the pattern of Saturn's magnetic field lines (Figure 2).

An earlier explanation for the sharp edges in the rings was based on the synchronization phenomenon, in which the epicyclic rotational phases of particles in the ring, under certain conditions, become synchronized with the phase of external satellites [47]. However, this explains only regularity in the ring edges. We propose a new explanation of sharp edges and separation of particles [48, 49]. The structure of the rings is a result of particle redistribution in the areas of magnetic field gradient variations within the magnetic equator plane due to the different magnetic force components. The force components are as follows. In the vertical direction, $F_z = -\mu \partial H / \partial z$, where μ is the magnetic moment of a particle and $\partial H / \partial z$ is the gradient of the magnetic field along the axis of the magnetic dipole. The force of the diamagnetic expulsion that forms sharp edges of the ring is $F_r = -\mu \partial H / \partial r$, where $\partial H / \partial r$ is the gradient of the magnetic field along the radius of the ring. An accidental break in the ring will be stabilized by the diamagnetic expulsion force component $F_\phi = -\mu r^{-1} \partial H / \partial \phi$, where $r^{-1} \partial H / \partial \phi$ is the gradient of the magnetic field in the tangential direction.

The magnetic field in the plane of the rings is inhomogeneous. Magnetic field lines will tend to pass through areas of highest magnetic flux density, and particles will be accumulated in areas with low magnetic flux density. The magnetic flux density gradient repels particles from each other and also clears gaps inside the ring system, forming a stiff, fine structure of separated rings. The magnetic flux density inside each ring will be lower than in the surrounding space. The difference in flux density will cause an inward magnetic pressure on each ring, so the rings have sharp edges (Figure 3).

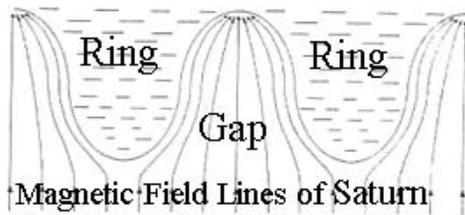


Figure 3. Dense and rarefied areas of the particles look like a system of rings.

5. Conclusion

In this article, we envision the importance of the electromagnetic effects of Saturn's magnetic field in the origin and evolution of its rings. This, however, needs to be proved in future numerical simulations. It follows from our consideration that the age of the rings is close to the age of Saturn's magnetic field, and the rings may be as old as the solar system [50]. James Clerk Maxwell, the founder of electromagnetic theory, almost solved the problem of the origin of rings when he proved in 1859 that Saturn's rings consist of separate particles [1, 2], but the information that the particles are made up mainly of ice was only obtained in the Cassini mission 150 years later.

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