Mini Review

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How Saturn could create dense rings after the emergence of its magnetic field. The Tchernyi-Kapranov effect: mechanism of magnetic anisotropic accretion

Abstract

The origin of Saturn's dense rings is still unclear. Here we propose a mechanism of the genesis of Saturn's dense rings from ice particles (chunks) of the protoplanetary cloud. It shows how Saturn could create rings after the emergency of its magnetic field. We take into account the force of diamagnetic expulsion and the Tchernyi-Kapranov effect: the process of magnetic anisotropic accretion. The force of diamagnetic expulsion acts on the particles together with the gravitational and centrifugal force. As a result, the orbits of ice particles of different sizes move into the plane of magnetic equator, where their energy is minimal. Ultimately, every particle acquires its stable orbit in magnetic equator plane, and the net force prevents its radial and vertical shift. The process described here is likely to contribute to the genesis of a stable disk-shaped structure of dense rings, formation of sharp edges of rings and gaps, and separation of particles (chunks) in rings. Previous theories are not questioned here, but they are complemented with the magnetic interaction, which accounts for the Tchernyi-Kapranov effect: mechanism of magnetic anisotropic accretion of diamagnetic ice particles of the protoplanetary cloud.

Keywords: origin of Saturn's rings, Tchernyi-Kapranov effect, magnetic anisotropic accretion, diamagnetism of cosmic ice, orthorhombic ice XI

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Introduction

Questions about the origin, evolution, and age of Saturn's dense rings remain unclear since G. Galilei first saw Saturn's rings in 1610. J. Maxwell proved that the rings consist of separate particles,[1,2] and G. Kuiper predicted (1947) that the particles of dense rings are made up of ice. The Cassini space probe (2004-2017) found particles radii from 1 cm to 10 m, they are composed of 90-95% water ice, and can take form of chunks.[3,4-9-19,51] There exist a number of hypotheses on the origin of planetary rings and physical causes of their existence. E.g.: the rings are the result of tidal disruption of a migrating moon within Saturn's circumplanetary disk; the structure of the rings is determined by orbital resonances with satellites; rings are debris maintained by the gravitational quadrupole moment of the planet; rings are a result of moon-moon collision disruption; rings are debris of the outer planet moons from collisions with comets or meteorites; rings originate from tidal disruption of a passing large comet; rings are a result of rapid viscous spread of the debris; the existence and evolution of rings 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; rings arise from volcanic activity on a moon of Saturn.[3-19] Unfortunately, none of these models provides a convincing explanation for many of the observed features of the dense rings, their stability and location in the equatorial plane.[3,4,12,16] In addition, there is no clear understanding of the fine structure of the rings, their extreme flatness and sharp edges, unusual separation of particles, etc.

There is an opinion that among the possible physical forces that maintain Saturn's dense rings stability, nongravitational ones can be significant.[3,4,6,7] Saturn's rings contain dense and diffuse matter. The origin of the diffuse rings was discussed in.[6,7] Also many authors have often mentioned that there must be another force that can help to understand the origin of dense rings.[3,4,12,16] 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 for the separation of particles, and several observed electromagnetic phenomena were explained from this standpoint.[20-32] However, to date there is no experimental evidence that cosmic 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 their ice particles superimposed on the gravitational field.

The Tchernyi-Kapranov effect: magnetic anisotropic accretion in the origin of Saturn's dense rings

The Cassini space probe measured that the ratio of the heavy and light hydrogen isotopes in the ice of dense rings is the same as in ice on the Earth.[33] Ice XI is stable below 73K.[34] And we have proposed that it may be the main polymorphic modification of ice in Saturn's rings, and it is diamagnetic.[35,36] This suggests that in the gravitational models of the rings origin, additional interaction of Saturn's magnetic field with diamagnetic ice particles (chunks) of the protoplanetary cloud should be taken into account.

Following V. Safronov's theory of the small nebula,[37] our concept[38-47] states that after the emergence of Saturn's magnetic field and diamagnetic expulsion force which start to act on ice particles together with gravitational and centrifugal force, all orbits of the particles inside the protoplanetary cloud started tilting towards the magnetic equator plane. The Cassini probe discovered that Saturn's magnetic equator coincides with its geographical one. Tchernyi-Kapranov effect means magnetic anisotropic accretion of the magnetized ice particles (chunks) in the process of the origin of Saturn's dense rings.[39-47] Eventually, the protoplanetary cloud collapsed into a disk of rings with particles (chunks). At the end of this process, all the particles were trapped inside a three-dimensional magnetic well in the plane of Saturn's magnetic equator and formed a disk-like system of rings. For an orbiting particle, the gravitational force is counterbalanced by the centrifugal force and the force of diamagnetic expulsion. It should be demonstrated how a protoplanetary cloud could collapse into a disk of rings (Figure 1).

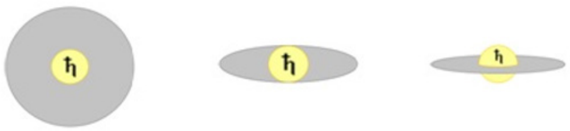

Figure 1 Transformation of Saturn's protoplanetary cloud into a disk of dense rings after the emergence of Saturn's magnetic field and its interaction with the ice particles: from a to b to c.

To this end, we need to solve the problem of how all orbits of diamagnetic ice particles in the Saturn's protoplanetary cloud, after the emergence of Saturn's magnetic field, end up in the plane of magnetic equator and create a system of rings with well-separated particles and fine structure of the rings. 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 in.[38-47]

First, the problem of a sole diamagnetic spherical particle in the gravitational and magnetic fields of the planet is formulated. Under an assumption of the constant orbital radius, the problem of the diamagnetic particle motion after the emergence of the planetary magnetic field is reduced to an equation for the azimuthal angle θ of the particle motion:[38,39]

$$\ddot{\theta}+\dot{\theta}^2\cot\theta-(A+Bcos^2\theta)\cot\theta=0 \quad (1)$$

where A and B are the constants related to the gravitational and magnetic forces, respectively. The analytical solution of this equation shows that all stable orbits of ice particles are locked in the magnetic equator plane. In the Saturn's gravitational field only (i.e., if the Saturn's magnetic field was zero), the ratio of the particle's angular velocity components is extremely unlikely, which apparently disproves the purely gravitational theory of stability of Saturn's rings. If the additional axisymmetric magnetic force is exerted on the particles, their circular orbits fall on the magnetic equator plane, as it follows from the equation solution and as established in several spacecraft missions to Saturn.

We then consider the model of Saturn's dense rings as spatially separated and uniformly magnetized spherical particles in a disk-shaped structure consisting of the identical spheres with uniform planar density. We find that the magnetization (M_d) and magnetic moment (m_d) 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. And the ratio of the corresponding parameters for the spherical particle in the disk and for the sole particle is

$$\frac{M_d}{M_0}=\frac{m_d}{m_0}=\left[1-\frac{\pi R^3\sigma(\mu+\mu_0)}{r_0(\mu+2\mu_0)}\right]^{-1} \quad (2)$$

Where μ and μ_0 are magnetic susceptibilities of the particle material and free space, respectively; R is the particle radius; σ is the planar density of the particles in the disk of rings, for tightly packed balls in hexagonal packaging $0<\sigma<\pi/2\sqrt{3}=0969$; and r_0 is the distance between the particle centers. 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.

Separation of particles, sharp edges, stability and age of the dense rings

The magnetic well of the disk of rings with ice particles disturbs the pattern of dipole magnetic field lines of Saturn (Figure 2).

Figure 2 Deformation of Saturn's dipole magnetic field lines by the disk of dense rings.

An earlier explanation for the sharp edges in the dense rings was based on the synchronization phenomenon due to which the epicyclic rotational phases of particles in the ring, under certain conditions, become synchronized with the phase of external satellites.[48] However, this only explains the irregularities at the edges of the rings. We propose a new explanation of both sharp edges of rings and separation of particles.[49,50] The structure of rings is a result of the 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, $F_z=-m_0\,\partial H/\partial z$ where m_0 is the magnetic moment of 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 $F_r=-m_0\,\partial H/\partial r$ where $\partial H/\partial r$ is the gradient of the magnetic field along the radius of the ring. The accidental break in the ring will be stabilized by the diamagnetic expulsion force component $F_\varphi=-m_0r^{-1}\,\partial H/\partial\varphi$ where $r^{-1}\,\partial H/\partial\varphi$ represents the gradient of the magnetic field in the tangential direction.

The magnetic field in the plane of dense rings is inhomogeneous. Magnetic field lines will tend to pass through the areas of the 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 the flux density will cause an inward magnetic pressure on each ring, so the rings will have sharp edges (Figure 3).[25,26]

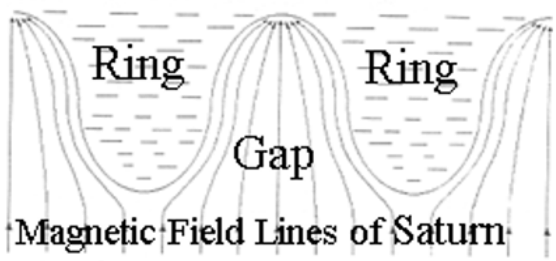

Figure 3 Dense and rarefied areas of particles as a system of dense rings.

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Features of the disk-shaped ring structure provide sufficient stability of the particle orbits and of the entire ring system. The resilience to the 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.

Conclusion

In this article, we emphasize the importance of the magnetic field of Saturn in the origin and evolution of its dense rings. It is demonstrated how Saturn could create stable dense rings by means of its dipole magnetic field together with gravitational field. The key role of the new mechanism plays the Tchernyi-Kapranov effect: magnetic anisotropic accretion of diamagnetic ice particles of the protoplanetary cloud in the origin of dense rings.

It follows from our consideration that the age of the dense rings is close to the age of Saturn's magnetic field, and the rings may be as old as the Solar System, which coincides with the opinion presented in [51]. James Clerk Maxwell, the founder of the electromagnetic theory, was close to solving the problem of the origin of dense rings when he proved in 1856 that Saturn's rings consist of separate particles,[1,2] but the information that the particles (chunks) are composed mainly of water ice,[3,4,11,12] which is likely diamagnetic,[34-36,38-47,49,50] was obtained by the outstanding Cassini space probe 150 years later, during orbiting Saturn in 2004-2017.

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Conflicts of interest

Authors declare there is no conflict of interest.

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