Mini Review

The role of Saturn's magnetism in the equilibrium separation of particles of dense rings

Abstract

For the first time we have demonstrated that, taking into account the interaction of Saturn's magnetic field with the diamagnetic ice particles of the rings, it is possible to explain the separation of particles. It is shown that there is an equilibrium distance between the particles when the force of gravitational attraction between them is compensated by the force of magnetic repulsion. An expression for calculating the equilibrium distance is obtained. It also becomes clear why the ring particles do not stick together.

Keywords: origin of Saturn's rings, magnetic anisotropic accretion, separation of ring particles, equilibrium distance between ring particles, diamagnetism of space ice

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Introduction

After G. Galileo observed the dense rings of Saturn in 1610, for 400 years their origin and observed features still remain a problem of understanding.[1-3] To date, there is not a single gravitational hypothesis of the origin of Saturn's dense rings that would provide a convincing explanation of their origin, the separation of particles and the equilibrium distance between the particles, as well as why the particles do not stick together.[4-7] At the same time, it has recently been demonstrated that Saturn can create rings by itself due to the additional process of magnetic anisotropic accretion (the Tchernyi-Kapranov efrfect) of diamagnetic ice particles of Saturn's protoplanetary cloud if its magnetic field is taken into account.[8-22] Here we try to emphasize the important role of action of the non-gravitational magnetic force of diamagnetic expulsion to explain separation of particles, existence of the equilibrium distance between particles, and why particles do not stick together.[23-26] All these features were observed by the Cassini probe (2004-2017).

The Cassini probe found that particles of dense rings consist of 90-95% water ice[27,28] and the ratio of the heavy and light hydrogen isotopes of the ice of dense rings is the same as for ice on Earth.[29] The ice XI is stable below 73K,[30] and it is diamagnetic.[31,32] Saturn has a spherically symmetric gravitational field and axisymmetric magnetic field with magnetic equator. The Cassini found the plane of magnetic equator of Saturn almost coincides with geographical one.[33] Dense rings located in the magnetic equator plane. Saturn's magnetic field has a dipole structure in the region of dense rings.[34]

The fact that the rings along the orbit are not continuous, but consist of separated particles has already been proved by J. K. Maxwell.[35,36] The study of the separation of ice particles by radius in rings due to their diamagnetism can also make an additional contribution to Maxwell's outstanding analysis. In the magnetic field of the planet, ice particles acquire magnetization and magnetic moment. These are the quantities characterizing the force of interaction with the magnetic field needed to formulate the Newtonian dynamics of the particles, and these quantities for a sole particle differ from those for particles congregated in the rings. For particles located along the radius, this leads to their repulsion due to the magnetic force. At the same time, the particles are attracted to each other due to the gravitational force. From the balance of the forces of gravitational attraction and magnetic repulsion, an expression can be obtained for the equilibrium and stable distance between the particles in the rings. It is assumed that an ice particle is spherical and uniformly magnetized, which allows solving the magnetization problem in spherical coordinates. To solve the problem of interaction of two identical diamagnetic spheres in an external magnetic field, we use the expression of the magnetization and magnetic moment of one diamagnetic sphere obtained in.[10]

Separation of particles and the equilibrium distance between them in the Saturn's dense rings

The force acting on a point magnetic dipole with a moment $\mathbf{m}_2$ in the magnetic field of another point magnetic dipole $\mathbf{m}_1$ at a distance $\mathbf{r}_0$ is[37]

$$\mathbf{F}_m = \frac{3\mu_0}{4\pi r_0^5}\left[\mathbf{m}_2(\mathbf{m}_1\cdot\mathbf{r}_0)+\mathbf{m}_1(\mathbf{m}_2\cdot\mathbf{r}_0)+\mathbf{r}_0(\mathbf{m}_1\cdot\mathbf{m}_2)-5\mathbf{r}_0(\mathbf{m}_1\cdot\mathbf{r}_0)(\mathbf{m}_2\cdot\mathbf{r}_0)\right] \quad (1)$$

where $\mathbf{r}_0$ is the vector pointing from dipole 1 to dipole 2 (Figure 1).

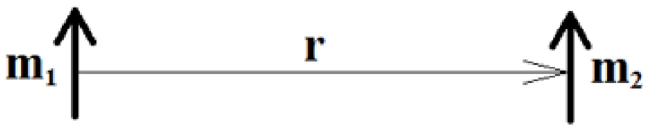

Figure 1 Parallel magnetic dipoles $\mathbf{m}_1$ and $\mathbf{m}_2$ at a distance *r* from each other.

Under an assumption that the dipole moments are parallel and equal in magnitude (m),

$$\mathbf{F}_m = \frac{3\mu_0 m^2}{4\pi r_0^5}\mathbf{r}_0 \quad (2)$$

Substituting the relationship (29) for the induced magnetic dipole moment *m* obtained in[10]

$$\mathbf{m} = \frac{4\pi R^3 \mathbf{B}_0}{\mu_0}\frac{\mu-\mu_0}{\mu+2\mu_0} \quad (3)$$

F*m* of (2) arrives at

$$\mathbf{F}_m = \frac{12\pi R^6 B_0^2}{\mu_0 r_0^5}\left(\frac{\mu-\mu_0}{\mu+2\mu_0}\right)^2 \mathbf{r}_0 \quad (4)$$

where B_0 is the magnitude of Saturn's magnetic field that magnetizes the particles.

Magnetic field of Saturn's magnetic dipole in the infinitesimal approximation[37] is

$$\mathbf{B}_0\left(\mathbf{r_{Sp}},\mathbf{m_S}\right)=\frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r_{Sp}}\left(\mathbf{r_{Sp}}\cdot\mathbf{m_S}\right)}{r_{Sp}^5}-\frac{\mathbf{m_S}}{r_{Sp}^3}\right) \quad (5)$$

where $\mathbf{r_{Sp}}$ is the radius vector from Saturn's magnetic dipole.

In the magnetic equator plane,

$$\mathbf{B}_0\left(\mathbf{r_{Sp}}\perp\mathbf{m_S}\right)=-\frac{\mu_0}{4\pi r_{Sp}^3}\mathbf{m_S}\,, \quad (6)$$

and thus, from (4), the force acting on particle 2 in the equatorial plane is

$$\mathbf{F}_m\left(\mathbf{r_{Sp}}\perp\mathbf{m_S}\right)=\frac{3\mu_0 R^6 m_S^2}{4\pi r_0^5 r_{Sp}^6}\left(\frac{\mu-\mu_0}{\mu+2\mu_0}\right)^2\mathbf{r_0}\,. \quad (7)$$

If distance between the particles is proportional to their radius, which is the case when the particles are uniformly distributed, the repulsive magnetic force will increase proportionally to the particle volume.

The gravitational attractive force acting on particle 2 with the mass M_{p2} induced by particle 1 with the mass M_{p1} is

$$\mathbf{F}_g=-\frac{GM_{p1}M_{p2}}{r_0^3}\mathbf{r_0} \quad (8)$$

As we can see from (7) and (8) there is a distance between particles when repulsion is prevail on attraction, Figure 2.

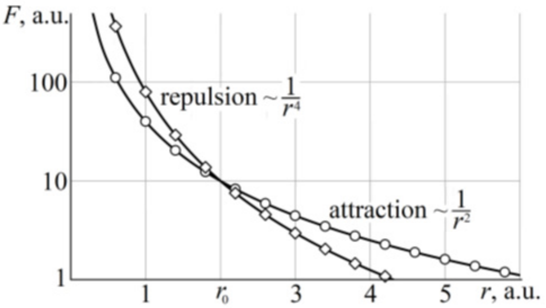

Figure 2 The dependence of the repulsion force and the attractive force on the distance between the particles. At a certain distance ro there is an equilibrium balance in the separation distance between the particles.

If the masses are equal ($M_{p1}=M_{p2}=M_p$), the balance of the gravitational and magnetic forces $\mathbf{F}_g+\mathbf{F}_m=\mathbf{0}$ occurs when

$$r_0=\left(\frac{R}{r_{Sp}}\right)^3\frac{m_S}{M_p}\left|\frac{\mu-\mu_0}{\mu+2\mu_0}\right|\sqrt{\frac{3\mu_0}{4\pi G}}=\left(r_{Sp}\sqrt{\frac{4\pi}{3}}\right)^{-3}\frac{m_S}{\rho_p}\left|\frac{\mu-\mu_0}{\mu+2\mu_0}\right|\sqrt{\frac{\mu_0}{G}}\,. \quad (9)$$

Thus, the equilibrium balanced distance between particles varies inversely with the particle density ρ_p and decreases as the third power of distance from the planet. To calculate the equilibrium distance between particles correctly, it is necessary to know the physical characteristics of dense rings, such as their composition, ice density, magnetic permeability, and others. Certainly, in addition to these forces, centrifugal forces also act on the particles of the ring. However, with a small distance between the particles compared to the radius of the rings, they have almost the same magnitude and do not contribute to a change in the balance of forces.

Conclusion

We have demonstrated that, taking into account the interaction of Saturn's magnetic field with the diamagnetic ice particles of the rings, it is possible to explain the separation of particles. It is shown that there is an equilibrium distance between the particles when the force of gravitational attraction between them is compensated by the force of magnetic repulsion. An expression for calculating the equilibrium distance is obtained. It also becomes clear why the ring particles do not stick together.

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Conflicts of interest

Authors declare there is no conflict of interest.

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