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Dust grains in planetary magnetospheres

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Abstract

Micrometeoroid impacts on small moons or ring particles generate dusty debris of all sizes. Grains launched from parent bodies on Kepler orbits become electrically charged due to interactions with the plasma environment and solar photons. The tenuous dusty rings are essentially collisionless systems and hence sub-micron grains, released and charged in the rotating magnetic field of their host planet, follow trajectories under the combined forces of electromagnetism and gravity. Depending on their launch distance and charge-to-mass ratio, some grains can be unstable to either radial perturbations (positively-charged grains only), or vertical perturbations (both positive and negative charges). These instabilities act on short timescales and cause grains to collide with the planet or escape in less than an orbit. [5] compiled numerical data and analytical solutions to the boundaries between stable and unstable trajectories, for the idealized case of a planet with an aligned dipolar magnetic field. The effect of a vertically offset or moderately tilted dipolar magnetic field configuration increases the class of grains that are vertically unstable, but has little effect on the short-term radial instability. We present numerical stability maps for each of the giant planets.

1. Introduction

Many authors have studied the motion of highly-charged dust grains in the idealized case of an aligned dipolar magnetic field. In this configuration, the ring systems that generate the dust are also in the magnetic equator, and many aspects of the motion are analytically tractable. Radial instabilities excite large radial excursions [7][8] which can even lead to escape [1][2][3][6] across magnetic field lines in the equatorial plane. This can be distinguished from vertical instability, whereby grains climb out of the equator plane moving along magnetic field lines to either crash into the planet at high latitude [9], or be reflected by high latitude mirror points [4]. In the absence of instability, expressions can be derived for the radial epicyclic motion [7][8][10] and the vertical bounce motion [9][5]. As a function of charge-to-mass ratio and launch distance, [5] systematically explored the boundaries between stable and unstable trajectories.

As a measure of the relative strengths of the EM force and gravity acting on a dust-grain, we take the ratio of the corotational electric force to gravity, L_*, a parameter that is both independent of distance and dimensionless:

$$L_* = \frac{q g_{10} R_p^3 \Omega_p}{G M_p m c} \quad (1)$$

where q and m are the charge and mass of the grain, M_p, R_p, Ω_p and g_{10} are the mass, radius, spin frequency and equatorial magnetic field strength of the host planet, and G and c are the gravitational constant and speed of light, respectively. L_* allows similar dynamics to be compared between planets with differing magnetic field strength. Corresponding grain sizes depend on the circumplanetary plasma environment and photo-electric yields.

In reality, no planet has a perfectly aligned and centered dipolar magnetic field, and we aim to test under which circumstances the idealized configuration behaves as a robust approximation to the planets in our Solar System. Saturn for example, has a dipolar magnetic field that is only slightly offset northward along its rotation axis. Next, in ascending order of magnetic field complexity, Jupiter's magnetic field is dominated by the tilted dipolar component. We plot, for a broad range of grain sizes and launch distances at Jupiter, the fate of grains in an aligned dipolar magnetic field (Fig. 1a), and in a tilted dipolar geometry (Fig. 1b).

2. More complicated magnetic fields

The ice giants, Uranus and Neptune, have higher-order magnetic field components which are substantial compared to the dipolar component. As might be expected, this greatly enhances the size of the instability regions. In this talk, we will shows plots for each of the giant planets and discuss our key findings.

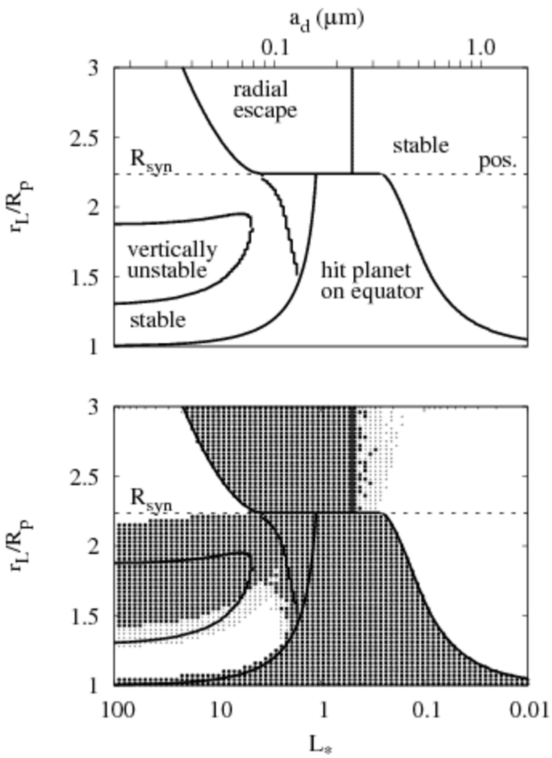

Figure 1: The stability boundaries for positively-charged grains in a centered and aligned dipole magnetic field configuration for Jupiter (top), compared to a tilted dipole magnetic field model (bottom). Grain sizes along the top axis correspond to a 5 volt potential and a grain density of 1 g cm^{-3}. The vertical axis denotes launch distance in Jupiter radii. The dark grey scale (bottom) marks grain trajectories that either collided with Jupiter or escaped, the light grey indicates grains that were vertically bound between high latitude mirror points, and the white area signifies locally stable orbits. Tilting the magnetic dipole has the effect of increasing the vertically unstable region, but the radial stability boundaries are largely unaffected.

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