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Dust-plasma interaction through magnetosphere-ionosphere coupling in Saturn's plasma disk

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Abstract

The ion bulk speeds in the equatorial region of Saturn's inner magnetosphere, according to data from the Langmuir Probe (LP) on board the Cassini spacecraft, are about 60% of the ideal co-rotation speed. These findings suggest that sub-micrometer negatively charged E ring dust contributes to the plasma dynamics in the plasma disk.
We calculated the ion speeds by using multi-component MHD equations, taking into account dust interactions to investigate the effects of ion–dust coulomb collision, mass loading, as well as taking into account magnetosphere–ionosphere coupling to investigate the effect of the magnetospheric electric field. The results show that the ion speeds can be significantly reduced by the electric fields generated by the ion-dust collisions when the dust density is high and the thickness of dust distribution is large. We also show that the ion speeds from our model are consistent with the LP observations when the maximum density of dust is larger than ~10^5 m^{-3}.

1. Introduction

Observations using the Langmuir Probe (LP) on board the Cassini spacecraft showed that part of the ion bulk speeds are close to the Keplerian speed in Saturn's E ring (*Wahlund et al.*, 2009), which is consistent with the presence of small (micro- and nano-sized) dust particles. These dust particles are negatively charged inside 7 R_S and are expected to contribute to the electrodynamics of the plasma disk structure (e.g. *Horányi et al.*, 2004). Near Enceladus, which is a major source of the E ring dust, the electron density is significantly less than the ion density and the ion speeds are near Keplerian within a large region (*Morooka et al.*, 2011). In the latest observations by the LP, data collected from February 2005 to June 2010 (Rev 003–133) were used (*Holmberg et al.*, 2012). They showed the ion speeds are much less than the ideal co-rotation speed in the inner magnetosphere. The speeds were 50–70% of the ideal co-rotation speed. As suggested by *Wahlund et al*. (2009), the charged dust particles in the E ring were related to the lower ion speeds.

2. Ion modelling and results

We calculate the ion and dust velocities by using multi-component MHD equations (i.e. protons, water groups ions, charged dusts and electrons) to investigate the effect of dust on ion speed. We consider the ion-dust collision, mass loadings, including the charge exchanges and the ion pickup, and magnetospheric electric fields through the magnetosphere-ionosphere coupling. An inner magnetospheric total current generated by the collisions and the mass loadings flows along a magnetic field line and weaken the dynamo electrinc field in Saturn's ionosphere. As a result, the magnetospheric electric field is smaller than the ideal co-rotational electric field and the ion speeds are slowing from the co-rotational speeds. We calculate the ion speeds in two cases about densities. The thickness of the dust distribution, *D*, is also used in three cases: *D* = 1, 2 and 3 R_S.
Ion speeds start to decrease from the ideal co-rotation speed around 3 R_S. The ion speeds are 50–90% of the ideal co-rotation speed less than about 5 R_S (top panel in Figure 1). The thickness of dust distribution is important parameter for a total current flowing in the magnetosphere. The generated magnetospheric electric field is smaller when *D* is large. The green lines in Figure 1 are about 80% of the orange lines around 5 R_S (top panel in Figure 1). For the generated magetospheric electric field, the green line is larger than the orange line (third panel in Figure 1).

Therefore, the ion speeds depend on D and they are smaller when D is large. The dust density is important for the electric field. The ion speeds in Figure 1b are less than those in Figure 1a. Therefore, the ion speeds are smaller when the dust density is larger. On the other hand, the collisions between ions and dust particles do not have a direct effect on ion speed because an ion-dust collision frequency is much smaller than the ion cyclotron frequency (red line of bottom panel in Figure 1).

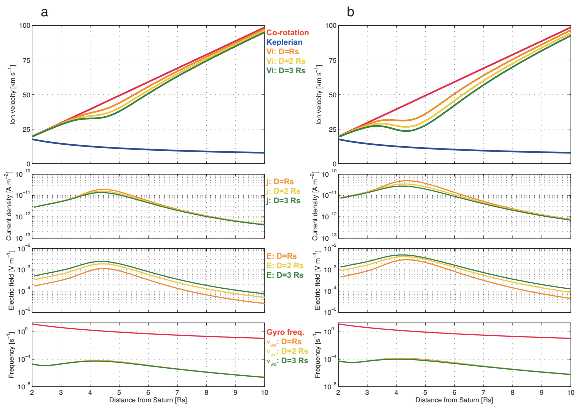

Figure 1: Modeling results. (a) is a less dust density than (b). Orange, yellow and green lines indicate ion velocities calculated when D is 1, 2 and 3 R_S. (top) Ion velocity profile. Red line indicates the ideal co-rotation speed, and blue line indicates the Keplerian speed. (second) Total current density profile. (third) Electric field generated by the difference of motion among ions, electrons and dusts. (bottom) Ion–dust collision frequency profile. Red line indicates ion cyclotron frequency for water group.

3. Discussions

Our modeling results are consistent with the LP observations when the dust density is large (Figure 2b). Our results are also consistent with observations even if the dust density is small if the thickness of dust distribution, D, is large (green line in Figure 2a). The ion speeds strongly depend on the magnetospheric electric field. The magnetospheric electric field is governed by the inner magnetospheric total current, and the current is generated by the collisions and the mass loading. The current flows along the magnetic field line and weaken the dynamo electric field in Saturn's ionosphere. Accordingly, the magnetospheric electric field is smaller than the co-rotational electric field and the ion speeds are less than the co-rotation speed. The magnitude of the current is dependent on each density and D. A higher current flows in the inner magnetosphere when each density or D is large. Since more density is needed when D is small, we suggest that the maximum of dust density is larger than ~10^5 m^{-3} in Saturn's inner magnetosphere (Figure 2).

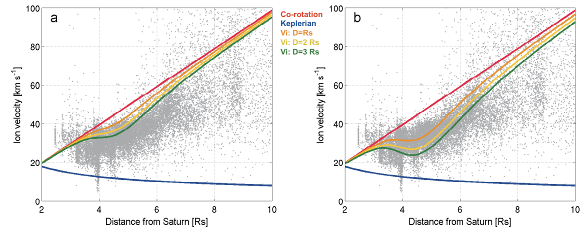

Figure 2: Comparisons between modeling results and RPWS/LP observations. The separation of (a) and (b) is same as Figure 1. Ion velocities are superposed on the LP observations from *Holmberg et al.* (2012). Grey dots are observation points, red line indicates the ideal co-rotation speed, and blue line indicates the Keplerian speed. Orange, yellow and green lines indicate ion velocities calculated when the thickness of dust distribution, D, is 1, 2 and 3 R_S, respectively.

4. Summary

A dust–plasma interaction occurs through the magnetosphere–ionosphere coupling. The inner magnetospheric total current along a magnetic field line weakens the dynamo electric field in Saturn's ionosphere. The ion speeds are Keplerian due to the large total current when the ion and dust densities are large. The dust–plasma interaction is significant when the thickness of the dust distribution is large and/or the density of ions and dusts is high.

References

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