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Plasma dynamics in Saturn's middle-latitude ionosphere and implications for magnetosphere-ionosphere coupling

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ABSTRACT

A multifluid model is used to investigate how Saturn's magnetosphere affects ionosphere. The model includes a magnetospheric plasma temperature of 2 eV as a boundary condition. The main results are: (1) H^+ ions are accelerated along magnetic field lines by ambipolar electric fields and centrifugal force, and have an upward velocity of about 10 km/s at 8000 km; (2) the ionospheric plasma temperature is 10,000 K at 5000 km, and is significantly affected by magnetospheric heat flow at high altitudes; (3) modeled electron densities agree with densities from occultation observations if the maximum neutral temperature at a latitude of 54° is about 900 K or if electrons are heated near an altitude of 2500 km; (4) electron heating rates from photoelectrons (≈100 K/s) can also give agreement with observed electron densities when the maximum neutral temperature is lower than 700 K (note that Cassini observations give 520 K); and (5) the ion temperature is high at altitudes above 4000 km and is almost the same as the electron temperature. The ionospheric height-integrated Pedersen conductivity, which affects the magnetospheric plasma velocity, varies with local time with values between 0.4 and 10 S. We suggest that the sub-corotating ion velocity in the inner magnetosphere depends on the local time, because the conductivity generated by dust–plasma interactions in the inner magnetosphere is almost comparable to the ionospheric conductivity. This indicates that magnetosphere–ionosphere coupling is highly important in the Saturn system.

1. Introduction

Saturn's magnetosphere–ionosphere coupling is active in the auroral region at high latitudes between 75° and 80° (e.g., Cowley et al., 2004) and corresponding to about 15 and 35 R_S in the equatorial magnetosphere. R_S is the Saturn radius of 60,268 km. The coupling process between the inner magnetosphere at less than 10 R_S and the ionosphere at latitudes lower than ≈70° is not well understood. However, the interaction between the ionosphere and Saturn's ring particles was recently observed by studying patterns in the emissions of $H_3{}^+$ in the low latitude ionosphere (i.e., below 50° which is equivalent to ≈2.0 R_S in the equatorial magnetosphere). These emissions were likely due to the "ring rain" demonstrated by O'Donoghue et al. (2013). Ring rain consists of ion fluxes that are probably generated by photoionization of the ring surface and then precipitate into the ionosphere (Connerney, 2013). A similar phenomenon is expected to occur in the inner magnetosphere in the region of the E ring, since this region also contains mainly water group ions and water ice dust from Saturn's Moon Enceladus. The south polar region of Enceladus is known to be a source of water vapor and grains (Dougherty et al., 2006; Porco et al., 2006; Waite et al., 2006), which can then supply the inner magnetosphere (Horányi et al., 2004; Smith et al., 2010).

Stallard et al. (2008) have found a "secondary auroral oval" that might be caused by interaction with the inner magnetosphere inside 10 R_S, and they showed that the oval extends to a latitude of 60° corresponding to ≈3.5 R_S in the equatorial magnetosphere. Sakai et al. (2013) showed that the magnetospheric electric field generated by ion–dust collisions slows ions with respect to the corotation speed in Saturn's inner magnetosphere and suggested that the dust–plasma interactions occur via magnetosphere–ionosphere coupling. This magnetospheric electric field also strongly depends on the ionospheric Pedersen conductivity (Sakai et al., 2013). The Pedersen conductivity has been calculated in many models (Connerney et al., 1983; Cheng and Waite, 1988; Saur et al., 2004; Cowley et al., 2004; Moore et al., 2010). However, the conductivity

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values differ considerably between the models largely due to the dependence on the ionospheric plasma density (e.g., Moore et al., 2010) and to the effects of the subcorotation of the thermospheric neutral wind field (e.g., Smith and Aylward, 2008; Müller-Wodarg et al., 2012).

Saturn's ionospheric plasma, which is important for Pedersen conductivity, has been observed and modeled many times. The electron density was measured using the radio occultation technique by the Pioneer 11, Voyager 1 and 2, and Cassini spacecraft (Kliore et al., 1980; Tyler et al., 1981, 1982; Lindal et al., 1985; Nagy et al., 2006; Kliore et al., 2009, 2014). These observations showed that the peak electron density was about $10^{10}\,\mathrm{m}^{-3}$ (e.g., Nagy et al., 2006; Kliore et al., 2009). The altitudes of the peak density depend on the local time (LT) and latitude. Peak altitudes varied between 1000 km and 3000 km. Saturn's ionosphere has also been investigated by Moore et al. (2004, 2008) using the Saturn Thermosphere Ionosphere Model (STIM). Moore et al. (2008) showed the dominant ion is $H_3{}^+$ and the electron temperature above 1300 km reaches 500 K during the day. This model included water influxes which varied with latitude, which affects the loss of H^+ and the abundance of $H_3{}^+$. Moore et al. (2015) showed increases in $H_3{}^+$ intensity to areas of increased water influx, i.e. water actually increases $H_3{}^+$ density and therefore emissions. This is because the water influx leads to a reduction in electron density, which then slows down the dissociative recombination loss rate of $H_3{}^+$.

In this paper we investigate ionospheric plasma densities, velocities, and temperatures using a model that includes the effects of the magnetosphere, and we discuss dust–plasma interactions and magnetosphere–ionosphere coupling in the Saturn system.

2. Model

2.1. Continuity, momentum, and energy equations

The plasma densities, velocities, and temperatures in Saturn's ionosphere are evaluated using a multifluid model in order to investigate the effects of magnetospheric plasma on the ionosphere. Orthogonal dipolar coordinates, first introduced by Dragt (1961), are used in the mid-latitude ionosphere because we neglect the thermospheric wind driven by solar extreme ultraviolet (EUV) radiation for simplicity (Huang and Hill, 1989). The ion densities and velocities are calculated from the following continuity and momentum equations:

$$\frac{\partial \rho_i}{\partial t} + \frac{1}{A}\frac{\partial \left(A\rho_i u_{i,||}\right)}{\partial s} = S_i - L_i, \tag{1}$$

$$\rho_i \frac{\partial u_{i,||}}{\partial t} + \rho_i u_{i,||}\frac{\partial u_{i,||}}{\partial s} = -\frac{n_i}{n_e}\frac{\partial p_e}{\partial s} - \frac{\partial p_i}{\partial s} - \rho_i g - \sum_k \rho_i \nu_{ik}\left(u_{i,||} - u_{k,||}\right), \tag{2}$$

where ρ_i is $m_i n_i$; m_i is the ion mass; $n_{i(e)}$ is the ion (electron) number density; A is the cross-sectional area of a magnetic flux tube; $u_{i,||}$ is the ion field-aligned velocity; S_i is the ion production rate; L_i is the ion loss rate; $p_{i(e)}$ is the ion (electron) pressure; g is the difference between gravitational and centrifugal forces; ν_{ik} is the ion collision frequency between species i and k, including electrons, neutral gas (nonresonant and resonant collisions), dust, and other ion species (Schunk and Nagy, 2009; Sakai et al., 2013); and s is the coordinate along the magnetic field line. The ion species taken into account are: H^+, $H_2{}^+$, $H_3{}^+$, He^+, H_2O^+, and H_3O^+. We assume that the velocities of water group ions are zero because the relative momenta of the species are smaller than the other species. The ion temperature T_i is assumed to be equal to the electron temperature T_e:

$$T_i = T_e. \tag{3}$$

We will discuss the validity of this assumption in Section 4.3.

The electron temperature is given by (e.g., Schunk and Nagy, 2009)

$$\frac{\partial T_e}{\partial t} - \frac{2}{3}\frac{1}{A}\frac{\partial}{\partial s}\left(A\kappa_e\frac{\partial T_e}{\partial s}\right) = Q_{e,net}, \tag{4}$$

where κ_e is the thermal conductivity and $Q_{e,net}$ is the net electron heating rate. The thermal conductivity is

$$\kappa_e = \frac{u_{eth}}{\sum_k n_k \sigma_{ek}}, \tag{5}$$

where u_{eth} is the electron thermal velocity and the subscript k indicates ion, dust, and neutral species. σ_{ek} is the collision cross section for ion (general Coulomb collision), dust (e.g., Khrapak et al., 2004) and neutral (e.g., Itikawa, 1974). The electron temperature is assumed to be always larger than the neutral temperature ($T_{\mathrm{e}} \geq T_{\mathrm{n}}$). The electron number density is given by the quasi-neutrality condition:

$$n_e = \sum_i n_i - \frac{q_d}{e} n_d, \tag{6}$$

where q_d is the dust charge and n_d is the dust density. The dust charge is given by $q_d = 4\pi\varepsilon_0 U r_{\mathrm{d}}$ (Horányi et al., 2004; Yaroshenko et al., 2009), where ε_0 is the vacuum permittivity, U is the dust surface potential and r_{d} is the dust radius, which is taken to be 100 nm (Sakai et al., 2013). We assumed that the dust potential is negative because most dust grains have a negative charge in the inner magnetosphere (e.g., Horányi et al., 2004). We also assumed negatively charged dust in the inner magnetosphere (at the outer boundary). The field-aligned electric field is given by

$$E_{||} = -\frac{1}{en_e}\frac{\partial p_e}{\partial s}. \tag{7}$$

2.2. Model settings and magnetospheric effects

The magnetospheric plasma density and temperature are given as boundary conditions in order to investigate how the magnetospheric plasma affects the ionosphere. Fig. 1 shows plasma and dust density profiles in the inner magnetosphere as a function of the L shell parameter. The electron and dust densities are based on Persoon et al. (2009) and Sakai et al. (2013). The ion density is derived from charge neutrality. Fig. 2 is a cartoon of coordinate system used in this model. The Saturn-centered dipole magnetic field line corresponding to $L = 3$ at equatorial plane is used as an example in this work, which is a good approximation for $L < 10$ (Connerney et al., 1984; Saur et al., 2004). The magnetic field strength at the equator (B_0) is about 2.1×10^{-5} T (e.g., Belenkaya et al., 2006). Wahlund et al. (2009) and Gustafsson and Wahlund (2010) showed that the electron temperature was 1–2 eV in the inner magnetosphere, so we used 2 eV as the magnetospheric electron temperature at the upper boundary of equatorial region (Sakai et al., 2013). We assume a constant 2 eV as an average thermal energy (i.e., temperature) in the inner magnetosphere since we are investigating how the magnetospheric plasma affects the ionospheric plasma. Ion–dust collisions are also included in our model (Sakai et al., 2013).

An atmospheric pressure of 1 bar is used at 0 km altitude and the lowest altitude is 300 km in this model. We calculated the time evolution and found the quasi-stationary solution of plasma density, velocity, and temperature along a hemispheric field line