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Kinetic models for the exospheres of Jupiter and Saturn

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ABSTRACT

The exospheric theory based on the Kappa velocity distribution function (VDF) is used to model the exosphere of the giant planets Jupiter and Saturn. Such Kappa velocity distribution functions with an enhanced population of suprathermal particles are indeed often observed in space plasmas and in the space environment of the planets. The suprathermal particles have significant effects on the escape flux, density and temperature profiles of the particles in the exosphere of the giant planets. The polar wind flux becomes several orders larger when suprathermal electrons are considered, so that the planetary ionosphere becomes then a significant source for their inner magnetosphere. Moreover, the number density of the particles decreases slower as a function of the altitude when a Kappa distribution is considered instead of a Maxwellian one. Two-dimensional maps of density are calculated for typical values of the temperatures. The exospheric formalism is also applied to study the escape flux from the exospheres of Io and Titan, respectively, moons of Jupiter and Saturn.

1. Introduction

Spacecraft recently explored the space environment of the giant planets and their moons. Cassini reported new measurements concerning Saturn and Titan (Porco et al., 2005), Galileo and Ulysses for Jupiter and some of its moons (for instance, Mihalov et al., 2000). Even if quite scarce, these observations are useful to give constraints to the models developed for the planetary exosphere of these planets. The present paper uses an analytical model to calculate estimations of the number density, flux and temperature profiles of the particles in the exosphere of Jupiter and Saturn, as well as for some of their moons, i.e., Io and Titan. It shows the large differences that appear in the evaluations of the flux, density profiles and temperatures depending on the basic assumptions made at the reference altitude.

The exosphere is defined as the region where the collisions between constituent molecules become sufficiently infrequent to be negligible in determining their dynamics. The critical level is called the exobase and corresponds to the altitude where the mean free path of the particles is equal to the density scale height (Fahr and Shizgal, 1983). This level is different for neutral particles and for charged particles. For instance, for the Earth, the neutral exobase is located around an altitude of 500 km while the plasma exobase is around 2000 km due to the long-range nature of the Coulomb collisions.

A kinetic model for the ion-exosphere has been developed by Pierrard and Lemaire (1996) on the basis of Kappa particle velocity distribution functions (VDFs). This useful formalism is adapted to model different regions of the terrestrial and solar exospheres. Such kinetic models were developed to characterize the auroral regions using the current–voltage relationship (Pierrard, 1996; Pierrard et al., 2007), the terrestrial plasmasphere (Pierrard and Lemaire, 2001; Pierrard and Stegen, 2008; Pierrard et al., 2009), the terrestrial polar wind (Lemaire and Pierrard, 2001), the solar wind (Maksimovic et al., 1997a; Pierrard et al., 2001; Lamy et al., 2003; Zouganelis et al., 2003) and the solar corona (Pierrard and Lamy, 2003). The Lorentzian exospheric formalism was also generalized to the case of non-monotonic potential differences (Pierrard et al., 2004).

In the present paper, a kinetic model based on a similar formalism is developed to describe the exosphere of the giant planets Jupiter and Saturn. The next section presents briefly the principles of the model. The third section gives the characteristics used to describe the exosphere of Jupiter and more specifically the regions of the polar wind and the plasmasphere. The fourth section describes the model applied to Saturn. The fifth section estimates the thermal escape flux from moons, Titan and Io, and provides comparisons with the characteristics of the giant planets. The last section presents discussions and conclusions.

2. Description of the exospheric model

The comprehensive treatment of the ion exosphere proceeds from the Vlasov equation in the regions where Coulomb collisions are neglected. Assuming the velocity distribution function of the different particle species at the exobase (with given number

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density and temperature of the particles at this level), the VDF can be deduced at any higher altitude from the theorem of Liouville. The Maxwellian VDF has been generally adopted for ion exospheres as well as for the neutral atmospheres (Lemaire and Scherer, 1971). Nevertheless, it is observed that particle VDF in space plasmas have generally non-Maxwellian high-energy tails, well fitted by Lorentzian (also called Kappa) VDF (Meyer-Vernet, 2001). A kinetic model of the ion exosphere based on Lorentzian velocity distribution functions was developed by Pierrard and Lemaire (1996). A parameter κ characterizes the suprathermal tails of the velocity distribution function: a small value of the κ index indicates the presence of large suprathermal tails, while the Kappa VDF becomes identically Maxwellian when κ tends to infinity. Typical values of κ in space plasmas are ranging between 2 and 7 (Maksimovic et al., 1997b).

In the present paper, the model is applied to rotating exospheres of the giant planets Jupiter and Saturn and to some of their moons. Depending on the velocity and pitch angle of the particles, four classes of trajectories can be identified (Lemaire and Scherer, 1971). Escaping trajectories correspond to particles that have enough energy and small enough pitch angles to escape. Along closed magnetic field lines, charged particles travel to the other hemisphere and form the plasmasphere. Along open magnetic field lines, they escape to the interplanetary space forming the polar wind. Incoming particles are those that have escaped from the conjugate hemisphere along closed magnetic field lines. Along open magnetic field lines, it is assumed that there are no particles coming in from the interplanetary space. Ballistic particles have not enough energy or have a too large pitch angle at their hemisphere of origin: they are reflected back into the exobase. Trapped particles have mirror points above the exobase.

We call a model in diffusive equilibrium (DE) when all the trajectories are assumed to be fully populated, including the trapped orbits. Such an ideal state of equilibrium is maintained if the number of Coulomb collisions is sufficient inside the plasmasphere. In the terrestrial plasmasphere, the DE number density profiles decrease too slowly with the radial distance compared to the observations (Pierrard and Lemaire, 2001). That is why exospheric models have also been developed, where the trapped orbits are assumed to be empty or only partially filled to fit the quiet observations (Pierrard and Stegen, 2008). Note that the trapped particles have no influence on the escape flux and are not present at the level of the exobase.

For each class of particles, the moments of the VDF are calculated analytically to determine the number density, the flux, the temperatures and the heat flux of the different particle species of the plasma. The analytical expressions of the moments of exospheric particles based on Lorentzian velocity distribution functions are given in Pierrard and Lemaire (1996) along open magnetic field lines corresponding to the polar wind case and Pierrard and Stegen (2008) along closed field lines corresponding to the plasmaspheric case. They will not be repeated here. In the present paper, the same formalism is applied to develop exospheric models of the giant planets Jupiter and Saturn and some of their moons. The interesting consequences resulting from the presence of suprathermal particles are presented.

Note that the kinetic treatment of the neutral exosphere is similar in many respects to the description of the ion exosphere. Similar exospheric models were developed for neutral atmospheres and can be used to estimate the neutral fluxes escaping from the planets and their moons. In the case of neutral atoms, Maxwellian VDF (or Lorentzian with very high value of the κ index) are generally considered (Pierrard, 2003). Nevertheless, when suprathermal atoms or molecules are present in the neutral atmosphere, as reported for instance for N and N_2 in the atmosphere of Titan (Shematovich et al., 2003), Lorentzian VDF can also be used.

The ion exosphere differs from the neutral exosphere by the influence of an electric potential that accelerates the particles outside, and the presence of a magnetic field. The magnetic field lines are open in the polar regions, leading to the ion escape flux of the polar wind.

The velocity distribution function of each species of particles α is assumed to be a Lorentzian (or Kappa) distribution:

$$f_\alpha(r_0) = \frac{n_0}{2\pi}\left(\frac{1}{\kappa w_\alpha^2}\right)^{3/2} A_\kappa \left(1 + \frac{v^2}{\kappa w_\alpha^2}\right)^{-(\kappa+1)} \tag{1}$$

where k is the 1.38×10^{-23} J/K is the Boltzmann constant, m_α is the mass of the particle species, $A_\kappa = \Gamma(\kappa{+}1)/\Gamma(\kappa{-}1/2)\Gamma(3/2)$ is a constant depending on the index $\kappa > 3/2$, Γ is the Gamma function and the equivalent thermal speed is $w_\alpha = \sqrt{(2\kappa-3)kT_\alpha/\kappa m_\alpha}$.

The profiles generated by the models depend on the following variables that are given for each planet:

1. The radial distance of the exobase (r_0). The variation of this distance within a reasonable range does not significantly affect the model result.
2. The temperature T and number density $n(r_0) = n_0$ of each particle species at the exobase.
3. The kappa index κ of the distributions if suprathermal particles are present. We assume in the paper that the species are only electrons and protons, and that they have similar temperatures and kappa index. As shown in the present paper, the profiles are very sensitive to the kappa parameter. When no suprathermal particles are assumed to be present, the index kappa is assumed to be very high and the results tend to those obtained with a Maxwellian VDF.
4. The rotation velocity of the planet that influences the equatorial number density at large radial distance.

When these parameters are given as an input, the model gives the velocity distribution function of the particles at any radial distance above the exobase. The density, the thermal escape flux, the bulk velocity, the (parallel and perpendicular) temperature profiles, the heat fluxes of each particle species present in the planetary exosphere are obtained analytically by calculating the moments of the VDF.

3. Jupiter

Kappa distributions are observed in many space plasmas like the solar wind and the magnetosphere of the Earth. They are also observed in the space environment of Jupiter. For instance, such suprathermal distributions have been observed by Voyager 2 in the plasmasheet of Jupiter (Collier and Hamilton, 1995). They were also used to model the latitudinal structure of the Io plasma torus to explain Ulysses observations like temperature inversions (Moncuquet et al., 2002). A kappa distribution with $\kappa = 2.4$ has been discovered in the Io plasma torus from Ulysses results (Meyer-Vernet et al., 1995), and confirmed by UV data on Cassini (Steffl et al., 2004) and with the Hubble Space Telescope (Retherford et al., 2003).

It seems likely that the VDF of the Jovian plasma at the exobase is also non-Maxwellian since it is immersed in suprathermal radiation. Hasegawa et al. (1985) showed indeed that a plasma which is immersed in superthermal radiation suffers velocity–space diffusion which is enhanced by the photon-induced