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Space weather models for the solar wind and the plasmasphere

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Abstract

At BIRA-IASB, we develop kinetic models for the solar wind and its interactions with the magnetosphere of the Earth and other planets. Recent progresses were made especially for the solar wind for which our kinetic model takes into account the suprathermal particles observed in situ in this space plasma. In the magnetosphere, predictive kinetic models are also developed for different regions and especially for the plasmasphere. The model is coupled to the ionosphere and is dynamically influenced by the solar wind variations and geomagnetic activity. Radio waves are used to make observations needed for forecast, for boundary conditions and comparisons with model results.

1 Introduction

Space weather refers to conditions on the Sun, in the solar wind, and within Earth's magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. Radio waves can play an important role in this topic by allowing precise measurements in space plasmas like the solar wind and the magnetospheric environment of the Earth. In this paper, we present recent progress we have made in the analysis of the data and the development of models for the particles of the solar wind and of the plasmaspheric region.

2 Solar wind models

Different models to describe the characteristics of the solar wind have been developed at BIRA-IASB using the kinetic approach [1 for a review]. They are based on the resolution of the evolution equation to determine the velocity distribution function (VDF) of the particles and their moments at different radial distances from the solar corona to the limits of the heliosphere. The solutions depend on the approximations and assumptions made in the development of the models. The simplest models are exospheric. Such solar wind models are obtained by solving the Vlasov equation and enable us to understand the physical mechanisms implicated in the acceleration of the particles. They are computationally economic because the VDF of the particles and their moments can be calculated analytically. Assuming appropriate boundary conditions based on photospheric observations, they provide satisfactory predictions for the values of the average moments. These arguments make these exospheric models very suitable for solar wind forecasting, even if coronal mass ejections and other exceptional events need additional modelisation. In such exospheric models, the presence of suprathermal electrons observed in the solar wind can be taken into account by assuming a Kappa distribution at low altitude at the exobase reference level [2]. Indeed, the velocity distribution functions of the solar wind electrons are generally observed to be non-Maxwellian and anisotropic, not only in the solar wind, but also more generally in all low density space plasmas where the collisions are rare [3]. The Kappa distributions decrease as a power law of the square velocity instead of exponentially and thus to have more suprathermal particles in their tails [4, 5]. Low values of the parameter kappa are associated to an enhanced population of suprathermal electrons, leading to higher velocities at large radial distances. The introduction of a regularized Kappa distribution prevents any diverging moment, even for low kappa values [6].

We have also developed more sophisticated solar wind models that include particle interactions by adding a Fokker-Planck term in the evolution equation. We showed that Coulomb collisions maintain an almost isotropic Maxwellian core. The energetic particles can be influenced by whistler wave turbulence, so that it is a potential candidate for the formation of suprathermal electrons and for the scattering of the strahl electrons aligned to the magnetic field to form a more isotropic halo population at large distances [7]. We have also shown that kinetic Alfven waves can cause proton tails and even generate the beams observed in the solar wind proton distributions [8].

For solar wind especially, a detailed analysis of boundary conditions in the corona has been done for improvement of the predictions at the vicinity of the Earth. Photospheric magnetograms serve as observational input in semi-empirical coronal models used for estimating the plasma characteristics up to coronal heliocentric distances taken as boundary conditions in solar wind models. To obtain predictions in three dimensions at larger distance in the heliosphere, especially at the orbit of the Earth, we use as observational input photospheric magnetograms, i.e. the magnetic field at the photosphere. The initial magnetic field is then reconstructed using a potential field source surface (PFSS) scheme to provide the magnetic field from the photosphere up to 2.5 Rs, corresponding to the source surface [9]. The magnetic field reconstruction is illustrated in Fig. 1 and allows to associate specific structures observed in the photosphere (like coronal holes and sunspots) to specific solar wind sources.

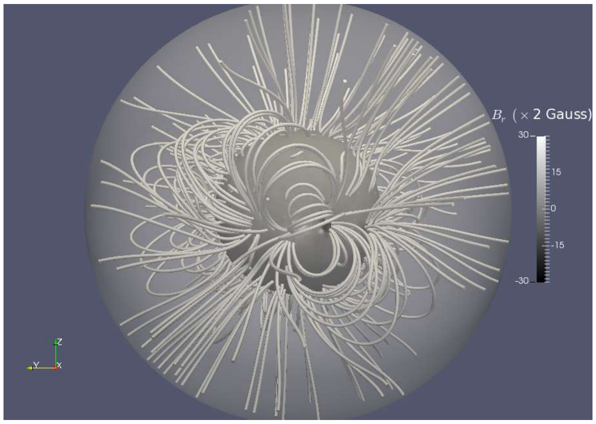

Figure 1. Global view of the solar magnetic field topology from the photosphere to the source surface at $2.5R_s$ observed for the synoptic map of CR2059 in July-August 2007.

Conditions of densities, Kappa indexes (associated to the velocity) and temperatures of the different particle species at the exobase level are then associated to the magnetic field characteristics on the basis of previous observations. All of these are used as boundary conditions at the exobase (chosen in our model to be at 2.5 Rs) to obtain an extended radial profile of the velocity distribution functions of the particles from the corona to the whole heliosphere. To obtain the best empirical relations providing the moments at the exobase, observations of OMNI at 1 AU were used as boundary conditions in steady state models. An example of the velocity obtained by the exospheric model in the ecliptic plane for September 2008 is illustrated in Fig. 2. However, we are not limited to the ecliptic plane: the latitudinal dependence can also be obtained.

3 Solar radio bursts

In addition to the continuous flux of particles emitted by the Sun in the interplanetary space, specific events like eruptions can happen. Such events are especially important to forecast since they constitute a risk for space missions and a source of perturbation for the Earth space environment when emitted in this direction. Radio observations can be useful for such predictions since flares and Coronal Mass Ejections (CME) are correlated with solar radio bursts. High-resolution radio spectra are for instance obtained by large radio telescopes UTR-2 and URAN-2 (Ukraine). In addition to the well-known type III and type II bursts, we focus on ALF bursts, narrow-band bursts with relatively low frequencies 15-30 MHz and drift rates around 100 kHz/s [10]. A theory has been developed to explain their formation.

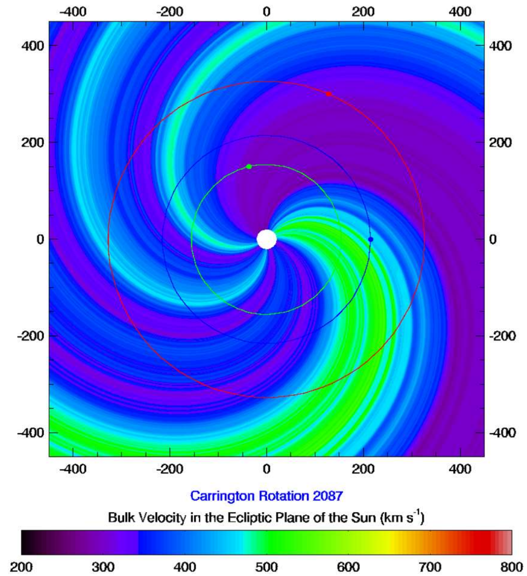

Figure 2. Solar wind velocity found for Carrington Rotation 2087 with the kinetic solar wind model. The positions of Venus, Earth and Mars are also illustrated.

4 Plasmasphere

The solar wind variations influence the dynamics of the space environment of the Earth and generate perturbations called geomagnetic storms. In the inner magnetosphere of the Earth especially, recent progresses have been made to model the dynamics of the plasmasphere associated to solar perturbations. This plasmasphere region is in fact the extension of the ionosphere along closed magnetic field lines. A kinetic model has also been developed for this region at BIRA-IASB [11]. The SWIFF plasmasphere model is coupled with the International Reference Ionosphere that is used to determine the boundary conditions at 700 km. An example of the electron density provided by the plasmasphere kinetic model is illustrated in Fig. 3 in the equatorial and meridian plane. The model, available for nowcasting and free run at any date on Space Situational Awareness website of ESA (http://swe.ssa.esa.int), provides also the temperature of electrons, protons and helium ions. It is very dynamic since the position of the plasmapause (the limit of the plasmasphere where sharp density gradients are observed) is highly variable with time and geomagnetic conditions associated to the solar wind variations [12]. The results provide good comparisons with satellite measurements, like Cluster, THEMIS, CRRES, KAGUYA, MAGION and Van Allen Probes for instance [13, 14, 15].

5 Radio observation of the plasmasphere

Radio observations are used to study the ionosphere, and also its extension at low and middle latitudes, the plasmasphere. This last region, filled by the charged particles circulating along the magnetic field lines, was discovered in the late 50's by measuring VLF waves on the ground.

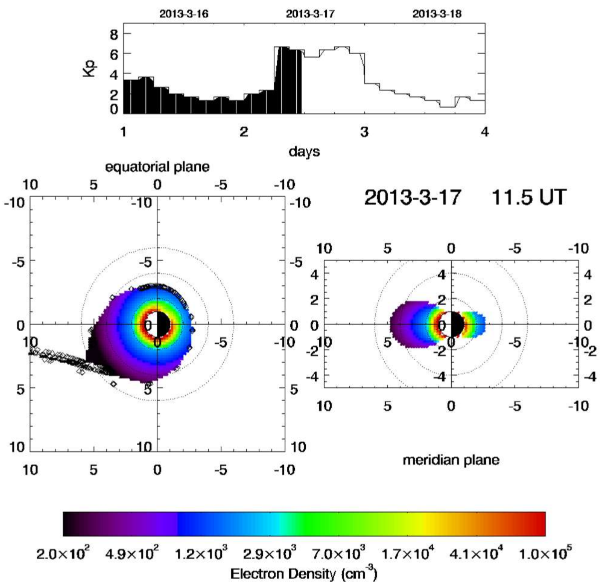

Figure 3. Electron density in the Earth's plasmasphere obtained with the kinetic model for the date of 17 March 2013 on 11:30 UT in the equatorial plane (left panel) and meridian plane (right panel). A plume appears during this geomagnetic storm in the afternoon MLT (Magnetic Local Time) sector due to the increase of geomagnetic activity illustrated by the planetary index Kp on the upper panel.

Indeed, natural whistler radio waves created by storm lightnings propagate along magnetic field lines crossing the equatorial region of the plasmasphere. Detection of these whistlers at frequencies between 5 and 20 kHz as a function of the magnetic latitude of the observations by ground-based magnetic antennas yields the determination of the electron density in the plasmasphere and the position of the plasmapause, the limit of the plasmasphere. Radio wave instruments on board satellites also allow the determination of the plasma frequency, and thus the number density of the electron along the orbit of the spacecraft. For instance, the instrument WHISPER on board Cluster measures in situ the plasma frequency in the range [2–80 kHz]. The number density Ne of the electrons along the orbit of the spacecraft can easily be deduced from these observations for Ne in the range from 0.05 to 79 cm^{-3}, as well as the position of the plasmapause where sharp density gradients can be observed. On the two Van Allen Probes spacecraft, the instrument EMFISIS is a passive sounder that detects the plasma frequency between 2-500 kHz, allowing to deduce Ne between 0,05 and 3000 cm^{-3}. These measurements are compared with the 3D dynamic model of the plasmasphere developed at BIRA-IASB, which illustrates the plasmaspheric variations during geomagnetic storms. VLF antennas have also been installed by BIRA-IASB at the Belgian Princess Elisabeth station in Antarctica and in Belgium in Humain. These two antennas are part of the international global network AWDA (Automatic Whistler Detector and Analyzer). The ultimate goal of this network is to provide data to feed a data-assimilative model of the plasmasphere.

Different waves circulate inside and outside the plasmasphere and also along the plasmapause, so that such a model of the plasmasphere is very useful to determine its influence on the radiation belts dynamics [16]. Such models are essential for space weather, especially to improve the understanding of the effects of the solar wind on the inner magnetosphere and auroral regions [17].

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