32nd URSI GASS, Montreal, 19-26 August 2017

Dynamical Simulations of the Plasmapause and the Plasmasphere

Viviane Pierrard* (1,2)
(1) Royal Belgian Institute for Space Aeronomy (BIRA-IASB), Space Physics and STCE, 3 av. Circulaire, B-1180 Brussels, Belgium, http://www.aeronomie.be
(2) Université Catholique de Louvain, Center for Space Radiations, Georges Lemaître Centre for Earth and Climate Research (TECLIM), Earth and Life Institute (ELI), 3 place Louis Pasteur bte L4.03.08, B-1348 Louvain-La-Neuve, Belgium

Abstract

Plasmapause and plasmasphere simulations have been developed at BIRA-IASB to better understand the physical mechanisms implicated in this region of the inner magnetosphere. The simulations include convection and co-rotation and can also take into account the interchange mechanism for the formation of the plasmapause. The simulations show an inward motion of the plasmapause when the geomagnetic activity increases, in good agreement with satellite observations. A plume is formed in the afternoon and dusk Magnetic Local Time (MLT) sectors during geomagnetic storms. Comparisons with observations of different satellites including IMAGE, CRRES, CLUSTER, THEMIS and KAGUYA show an excellent agreement with the simulations including co-rotation, convection with E5D electric field and interchange. These simulations can be run for any date on the space weather portal www.spaceweather.eu.

1. Introduction

The outer surface of the plasmasphere is often characterized by a sharp decrease of the plasma density: the plasmapause. Whistlers and in situ satellite observations show that the plasmapause forms closer to Earth when the geomagnetic activity level is enhanced. Depending on the strength of the level of geomagnetic activity, usually determined by the value of the planetary Bartels Kp index, the equatorial position of the observed plasmapause knee changes from 7 Re to 2.5 Re.

2. Plasmapause Simulations

Different mechanisms have been proposed to form the plasmapause. Our simulations explore two main processes to determine the plasmapause position [1 for a review]: 1. the plasmapause is assimilated to the Last Closed Streamlines (LCS), 2. the plasmapause is obtained from interchange instability. Simulations have been developed for both mechanisms and examples are illustrated on Fig. 1 for a simulation based on LCS. In this case, we launch plasma elements at different radial distances and follow their motion influenced by co-rotation and convection due to the solar wind and geomagnetic activity. The plasmapause corresponds to the last closed streamline, since the plasma elements along open field lines are lost at the magnetopause. The results of such LCS simulations depend on the conditions assumed at the initial time t_0. Here, we launch plasma elements at all radial distances and determine the plasmaspheric distribution by running the simulation starting 24 hours before the time of the result and taking into account the Kp variations of the previous day. Fig. 1 illustrates such a simulation for the date of 26 June 2001 at 19h00 taking into account the convection electric field empirical model E5D [2].

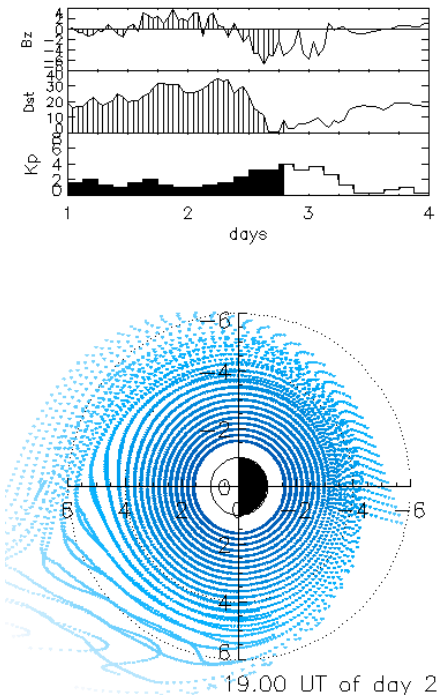

Figure 1. The plasmasphere as obtained with streamline simulation during the magnetic substorm of 26 June 2001 at 19:00 UT in the geomagnetic equatorial plane with E5D convection electric field. Bz, Dst and Kp observed from 25 to 27 June 2001 are also illustrated at the upper panels.

The plasmasphere corresponds to the region where the plasma elements almost co-rotate in the geomagnetic plane. It is not always obvious to determine the plasmapause position at all MLT with such LCS simulations. The upper panel of Fig. 1 illustrates the southward component of the interplanetary magnetic field Bz, the Disturbed Storm Time index Dst and the Bartels

planetary geomagnetic activity index Kp observed from 25-6-2001 at 0:00 UT up to 27-6-2001 at 24:00 UT.

3. Electric Fields

The electric field also plays an important role [2 for a more detailed comparison between the different electric fields]. An example of result obtained for the same date and time, but with another empirical convection electric field, Volland-Stern, is illustrated in Figure 2. A plume (tail) obtained in the afternoon MLT sector (bottom left) is then much more visible, because this electric field is stronger than E5D. The dayside (noon in MLT) is on the left of the Figure.

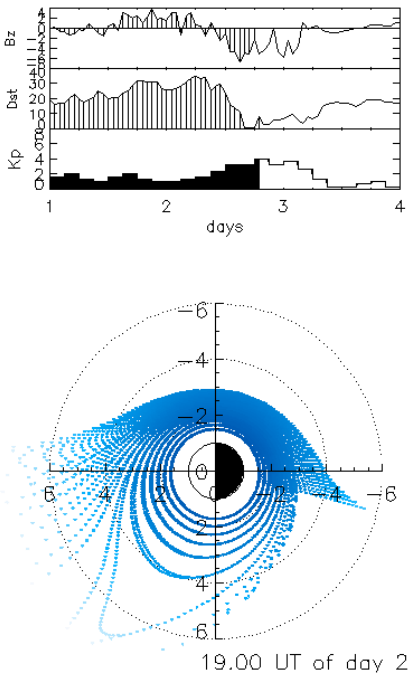

Figure 2. The plasmasphere as obtained with streamline simulation during the magnetic substorm of 26 June 2001 at 19:00 UT in the geomagnetic equatorial plane with Volland Stern convection electric field. A plume is formed in the afternoon MLT sector.

Such plumes appear when Kp increases. With the E5D electric field, the tail was further from Earth and the plasmasphere was less asymmetric. On 26 June 2001, Kp remains lower than 4-. Comparison with Fig. 1 shows that the chosen convection electric field is really important in the results of the simulations.

Kp dependent convection electric field models were obtained by averaging previous satellite observations during different periods of geomagnetic activity levels. Of course, the electric field can also be inferred from simultaneous observations when available, as it was done for instance with IMAGE/EUV observations providing global views of the plasmasphere in the equatorial plane when the spacecraft was above the North pole [3]. The agreement between observations and simulations are then high, but such global observations were only available at some specific dates between 2000 and 2006 during the operation time of the satellite IMAGE.

4. Global Plasmasphere Simulations

The mechanism of interchange instability for the plasmapause formation is also important to obtain more precise plasmapause positions. Figure 3 shows the result of the simulation when the mechanism of interchange is taken into account in the simulations.

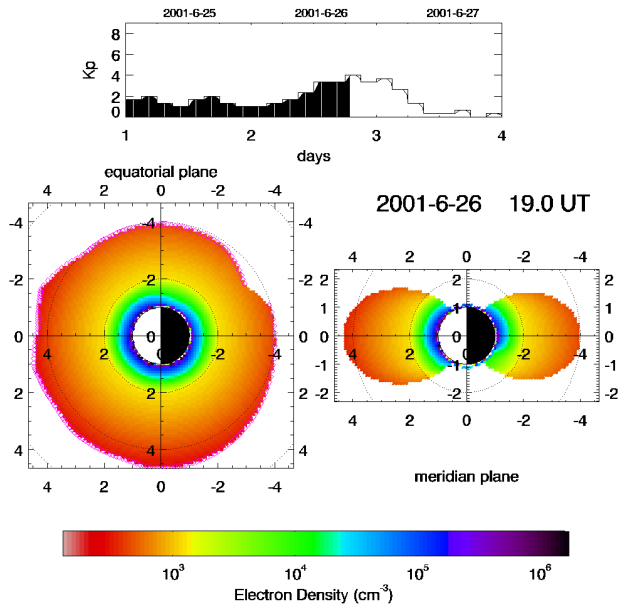

Figure 3. The plasmasphere as obtained with the global plasmasphere simulation that can be run on www.spaceweather.eu. Here the case of the geomagnetic substorm of 26 June 2001 at 19:00 UT and including interchange, 0.8 of co-rotation and the E5D convection electric field. The color scale indicates the electron density in the ionosphere and plasmasphere as estimated by the model [4]. The tridimensional global plasmasphere is here presented in the geomagnetic equatorial plane (left panel) and in the meridian plane (right panel).

Plasma holes are then launched, i.e., plasma elements with a density lower than the background density. Due to the interchange mechanism, the plasma holes drift to the plasmapause and show directly its position in all MLT sectors. These plasma holes are illustrated by the pink diamonds in Figure 3 left panel. The new plasmapause is mainly formed in the post-midnight sector due to Zero Parallel Force Surface and then propagates mainly eastward to the other Magnetic Local Times (MLT) due to co-rotation [1]. Such simulations show more clearly the position of the plasmapause and its evolution with time. The co-rotation velocity can also be adapted in the simulations. Indeed, it is often observed that the actual rotation velocity is slightly lower than co-rotation, so that the simulations can take into account chosen velocities between 0.8 and 1 of co-rotation. In the present

simulation, we show the results for 0.8 of co-rotation, but the differences with pure co-rotation are very small. The right panel shows also the plasmasphere in the meridian plane, as well as the density of the electrons inside the plasmasphere.

The model has been generalized to provide also the density of the other particle species inside and outside the plasmasphere in 3 dimensions, as well as an estimation of the temperature of the particles [4]. The model has also been coupled with the ionosphere [5].

5. Satellite observations

The results of the simulations have been compared with various satellite observations to determine the main physical mechanisms of plasmapause formation and the most appropriate electric field configurations depending on geomagnetic activity [1,2]. Statistical studies based on plasmapause observations from different satellites like CLUSTER [6], CRRES [7] and THEMIS [8] complete case studies obtained from IMAGE [9], Cluster [10] and the recent KAGUYA spacecraft [11] to compare with the simulations and help us to determine the most relevant physical processes. The global plasmasphere model including interchange gives excellent agreement with observations. Especially, EUV/IMAGE provided from 2000 to 2006 the first global images of the plasmasphere in the equatorial plane when the spacecraft was above the North Pole, allowing a MLT analysis of the plasmapause evolution with time [1, 2, 9]. More recently, the first global meridian images of the plasmasphere were obtained with KAGUYA/TEX instrument. The plasmapause positions at the postmidnight observed from the meridian perspective clearly agreed with those predicted by the dynamic simulations based on the interchange mechanism [11], with a plasmapause formation first near the equatorial region. Empirical relations between the plasmapause equatorial distance and a variety of geomagnetic indices like Kp, Dst or AE have been deduced as well as their dependence and propagation in MLT. More studies are nevertheless needed to better understand some specific features observed in the plasmasphere, like westward motion of the plasmapause, notches or channels.

6. Acknowledgements

This research work was subsidized by the Scientific Federal Policy in the framework of the program Interuniversity Attraction Pole for the project P7/08 CHARM. The author also thanks the Solar-Terrestrial Center of Excellence.

7. References

1. J. Lemaire, and V. Pierrard, “Comparison between two theoretical mechanisms for the formation of the plasmapause and relevant observations”, *Geomagnetism and Aeronomy*, **48**, 5, pp. 553-570, 2008 doi.org/10.1134/S0016793208050010.

2. V. Pierrard, G. Khazanov, J. Cabrera, and J. Lemaire, “Influence of the convection electric field models on predicted plasmapause positions during the magnetic storms”, *J. Geophys. Res.,* **113**, A08212, pp. 1-21, 2008, doi: 10.1029/2007JA012612.

3. J. Goldstein, R. A. Wolf, B. R. Sandel, P. H. Reiff, Electric fields deduced from plasmapause motion in IMAGE EUV images”, *Geophys. Res. Lett*., **31**, 480 L01801, 2004, doi:10.1029/2003GL018797.

4. V. Pierrard, and K. Stegen, “A three dimensional dynamic kinetic model of the plasmasphere”, *J. Geophys. Res*., **113**, A10209, 2008, doi: 10.1029/2008ja013060.

5. V. Pierrard, and M. Voiculescu, “The 3D model of the plasmasphere coupled to the ionosphere”, *Geophys. Res. Lett.*, **38**, L12104, 2011, doi:10.1029/2011GL047767.

6. G. Verbanac, V. Pierrard, M. Bandic, F. Darrouzet, J.-L. Rauch, and P. Décréau, “Relationship between plasmapause, solar wind and geomagnetic activity between 2007 and 2011 using Cluster data”, *Ann. Geophys.*, **33**, pp. 1271-1283, doi:10.5194/angeo-33-1271-2015, 2015.

7. M. Bandic, G. Verbanac, M. Moldwin, V. Pierrard, and G. Piredda, “MLT dependence in the relationship between plasmapause, solar wind and geomagnetic activity based on CRRES: 1990-1991”, *J. Geophys. Res*., **121**, pp. 4397-4408, 2016, doi: 10.1002/2015JA022278.

8. M. Bandic, G. Verbanac, V. Pierrard, and J. Cho, “Evidence of MLT propagation of the plasmapause inferred from THEMIS data”, submitted to *J. Atmos. Sol. Terr. Phys*., 2017.

9. V. Pierrard, and J. Cabrera, “Dynamical simulations of plasmapause deformations”, *Space Science Reviews*, **122**, Issue 1-4, pp. 119-126, 2006, doi: 10.1007/s11214-005-5670-8.

10. F. Darrouzet, J. De Keyser, P. M. E. Décréau, D. L. Gallagher, V. Pierrard, J. F. Lemaire, B. R. Sandel, I. Dandouras, H. Matsui, M. Dunlop, J. Cabrera, A. Masson, P. Canu, J. G. Trottignon, J. L. Rauch, and M. André, “Analysis of plasmaspheric plumes: CLUSTER and IMAGE observations”, *Annales Geophys*., **24**, pp. 1737-1758, 2006.

11. G. Murakami, K. Yoshioka, A. Yamazaki, Y. Nishimura, I. Yoshikawa, and M. Fujimoto, “The plasmapause formation seen from the meridian perspective by KAGUYA”, *J. Geophys. Res*., **121**, 12, pp. 11973-11984, December 2016, doi: 10.1002/2016JA023377.