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THE PLASMASPHERE AS SEEN BY "IMAGE"

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Abstract. The IMAGE spacecraft launched in March 2000 provides the first global comprehensive images of the Earth's plasmasphere. The EUV (Extreme UltraViolet) instrument on board this spacecraft gives intensity maps of the 30,4 nm emissions of Helium ions integrated along the line of sight. It reveals the global behavior of the plasmasphere and its dynamics as influenced by the solar wind and interplanetary magnetic field variations. These observations are compared with the simulations developed at IASB-BIRA for the deformations of the plasmasphere during geomagnetic substorms and other variations in the level of geomagnetic activity.

1. Introduction

The plasmasphere is the high altitude extension of the ionosphere. To ensure accuracy and reliability of communications, navigation and military satellites stationed in this region, there is a considerable interest to understand the plasmaspheric environment and its dependence on external parameters. The plasmasphere is filled by cold plasma distributed along geomagnetic field lines and co-rotating with the Earth. The number density of particles decreases sometimes sharply at the limit of the plasmasphere, called the plasmapause. This discontinuity crosses the geomagnetic equatorial plane at radial distances ranging from 2 Re to 7 Re depending on the geomagnetic activity level. This region of the inner magnetosphere of the Earth and some of its characteristics as discovered by in situ satellites like the recent CLUSTER spacecraft have already been discussed in Physicalia Magazine [Lemaire, 2002; Darrouzet et al., 2002].

New progress in the plasmaspheric field of research is provided by the recent observations of EUV on board IMAGE [Sandel et al., 2003]. After four decades of study by in situ measurements of the number density profiles and remote sensing (whistler) techniques, IMAGE provides the first global views of the plasmasphere by imaging the distribution of He^+ in its 30.4 nm resonance line. The details of the plasmaspheric dynamics are then revealed: new structures such as shoulders, channels, notches and the formation of plumes, appear frequently in the observations [Pierrard, 2004]. These are keys to understanding the ways that electric fields affect the plasma distribution and the mechanisms influencing the formation of the plasmapause.

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The formation of the plasmapause by the mechanism of instability has been studied since 1974 at the Belgian Institute for Space Aeronomy [Lemaire, 1974, 1985]. Recently, dynamical simulations based on this mechanism have been developed [Pierrard and Lemaire, 2004] and compared with recent observations of the plasmasphere by AURORAL PROBE, CLUSTER, CRRES and IMAGE [Bezrukikh et al., 2003; Dandouras et al. 2005; Pierrard et al., 2005; Pierrard and Cabrera, 2005]. In the present paper, some typical results of the dynamical simulations are presented and compared with the observations of EUV/IMAGE during quiet periods, when the plasmasphere is quite extended, and during geomagnetic substorms, when plumes are generated. The advances in plasmaspheric research as revealed by EUV are summarized.

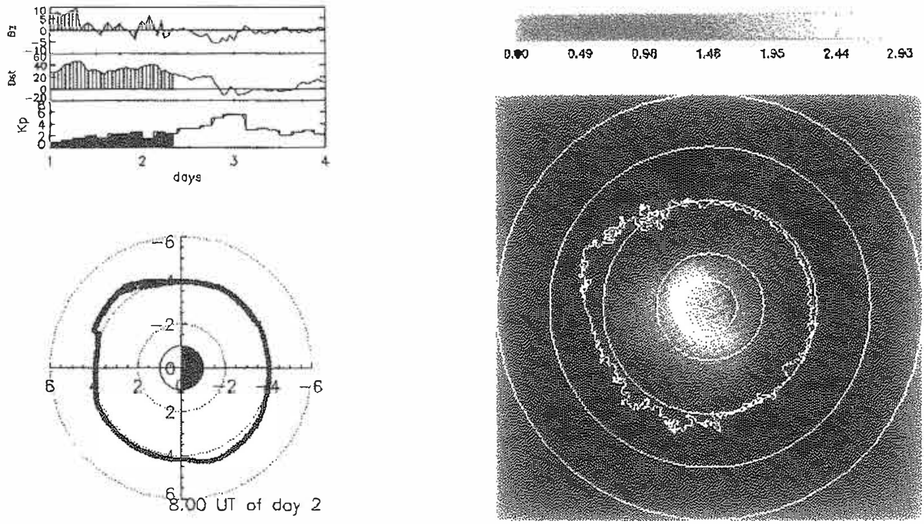
2. Plasmapause formation

The dynamical simulations presented in the present paper use a given Kp-dependent magnetospheric electric field model. This electric field is the E5D model determined from dynamical proton and electron spectra measured on board the geostationary satellites ATS-5 and ATS-6 [McIlwain, 1986]. The Kp index observed during the period of time and 24 h before is the only input of the time-dependent model. The convection electric field intensity is the largest in the post-midnight sector. Due to the increased convection velocity during periods of increased geomagnetic activity, the plasmasphere is peeled off in this region, according to the physical mechanism of plasma instability used in the numerical simulations. The plasmapause is then closer to the Earth in the postmidnight sector during geomagnetic substorms. Moreover, due to the differential rotation, a plume is formed later in the afternoon or dusk region. The mechanism is described in details in Pierrard and Lemaire [2004].

The model predictions are compared with EUV observations from IMAGE. The instrument consists of three wide-field cameras that are tuned to the 30.4 nm resonance line of sunlight. The observations are intensity maps of these emissions of Helium ions integrated along the line of sight. They are projected in the geomagnetic plane to have the same view over the pole as in the simulations. In the Figures, sunlight is incident from the left. The plasmapause is assumed to be the sharp edge where the brightness of 30.4 nm He^+ emissions drops drastically. To better visualize the plasmapause, a white line is drawn corresponding to a threshold of 40 % of the maximum intensity of the image, where the intensity is the logarithm of the luminosity.

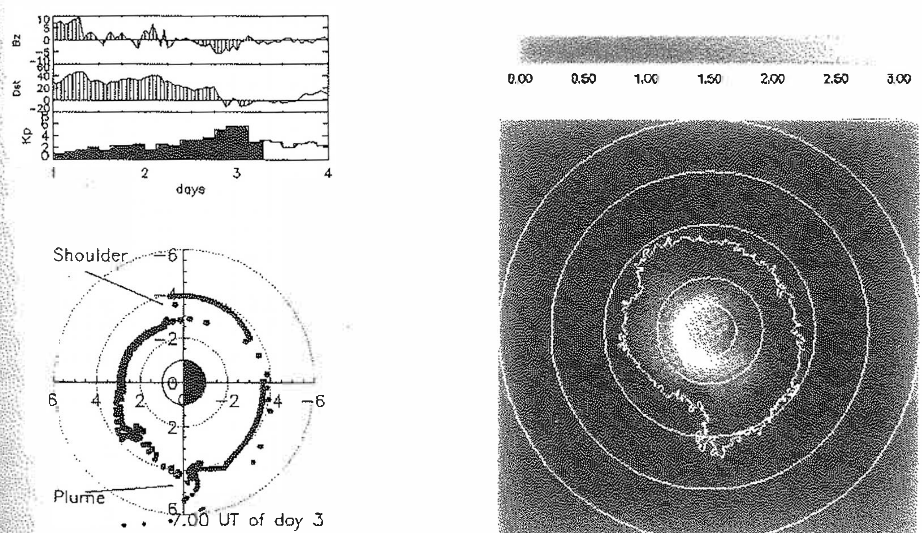
3. June 9-10, 2001

Let us show the example of June 9-10, 2001. During this period of time, Kp gradually increases up to 5^+ and then decreases. The upper panel of Fig. 1a shows the geomagnetic activity index Kp observed from June 8 to June 10, 2001. Bz, the z component of the interplanetary magnetic field and the Dst index are also illustrated. Periods of geomagnetic substorm events are particularly interesting to study because of the development of a so-called plume in the plasmasphere. This kind of plume is often observed by IMAGE and follows even moderate increases of Kp (above 3^+-4).



(a) (b)

Fig.1. Left panel: result of the simulation based on the instability mechanism and the value of Kp for 9 June 2001, 8h00. The plasmapause in the geomagnetic equatorial plane corresponds to the blue line. The indexes Bz, Dst and Kp observed during the previous and following days are also displayed. The dotted circles correspond to L=1, 2, 4 and 6.
Right panel: EUV observations at 8h05, projected in the geomagnetic equatorial plane. The white line corresponds to 40% of the maximum intensity of the image.and allow us to visualize the plasmapause. The white circles correspond to L=1, 2, 4, 6 and 8.



(a) (b)

Fig. 2. Same as Fig. 1 for 10 June 2001, 7h00 (left panel, simulation) and 7h03 UT (right panel, EUV observation).

The lower panel shows the result of the simulation on June 9, 2001 at 8h00 UT. Kp is then observed to be equal to 2^+. Due to the rather low value of Kp, the model predicts a plasmapause quite far from the Earth, around 4 Re. Because Kp was low and almost constant during the previous 24 hours, the plasmapause is quasi-circular.

The result of the simulation is compared with the plasmasphere observed by EUV on June 9, 2001 at 8h05 illustrated in Fig. 1b. The plasmasphere is viewed from a point of view above the North pole and projected in the geomagnetic equatorial plane. The circles on the figure correspond to a radial distance of 1, 2, 4, 6 and 8 earth radii. One can see that the plasmapause is indeed quite circular as often observed during quiet periods and located near R = 4 Re.

At 23h00 UT (14 hours later), Kp becomes maximum (5^+). The plasmasphere is then peeled off in the postmidnight region due the increase of convection velocity. The peeling off process combined with the differential rotation leads later on to the development of a plume in the dusk LT sector on Fig. 2a corresponding to June 10, 2001 at 7h00. Plumes develop because the plasma rotates more slowly around the Earth at large radial distance than closer to the Earth. Moreover, the sudden decrease of Kp at 3h00 UT leads to a shoulder in the dawn sector.

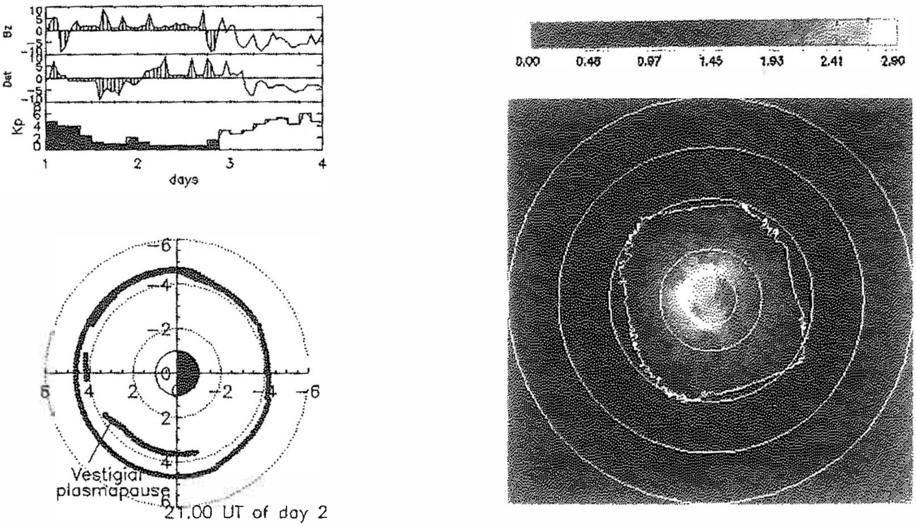
The IMAGE observation illustrated in Fig. 2b shows that a plume is indeed observed in the same LT sector as predicted by our simulations. The shoulder is clear in the observations, but there is a slight delay in MLT compared to the model prediction. Note that Kp is a three-hour index, and leads to a +/- 3 h UT or +/- 3 MLT indetermination.

Later on, Kp remains almost constant and small ($< 2^+$), so that the plume and the shoulder simply rotate with the plasmasphere. The rotation velocity is close to co-rotation in this case, but is very often lower and variable following the MLT sector. The edges of the plume rotate with different velocities so that the plume becomes thinner with time.

4. June 25-26, 2000

Another example of plume formation was observed between June 25 and 26, 2000. Fig. 3a shows the result of our simulation obtained at 21h00 UT on June 25. The plasmapause is rather extended, due to the low values of Kp in the previous hours. The quiet period was however preceded by a substorm the day before, that is why the vestigial plasmapause is also shown closer to the Earth at R=3.8 Re in the afternoon sector. The plasmasphere is also quite circular due to the quasi-stationarity of Kp during the previous 24 hours.

The EUV observations in Fig. 3b show the quasi-circular plasmasphere at 21h03 on June 25. Note that a density depletion that is mostly extended in the radial direction is also visible in the dawn sector. These kinds of features discovered in the EUV observations are called "channels". So far, there is no clear physical explanation of this new phenomenon. Note also the auroral oval clearly visible in this EUV image.



(a) (b)

Fig. 3. Same as Fig. 1 for June 25, 2000, 21h00 (left panel, simulation) and 21h03 UT (right panel, EUV observation).

In Fig. 4a, the results are shown 19 h later, at 16h00 on June 26, 2000. A nice plume has developed due to the Kp increase. This plume is clearly identifiable in the EUV image in the same LT sector. The plasmapause density gradients are very sharp after such events and the plasmapause position is well defined in the integrated intensity plots of EUV. Simulations reproduce rather satisfactorily the formation of plume [Pierrard and Cabrera, 2005]. They are always formed in the afternoon LT sector during geomagnetic substorms and storms, like in the EUV observations. Subsequently, they tend to co-rotate with the Earth when the geomagnetic activity decreases.

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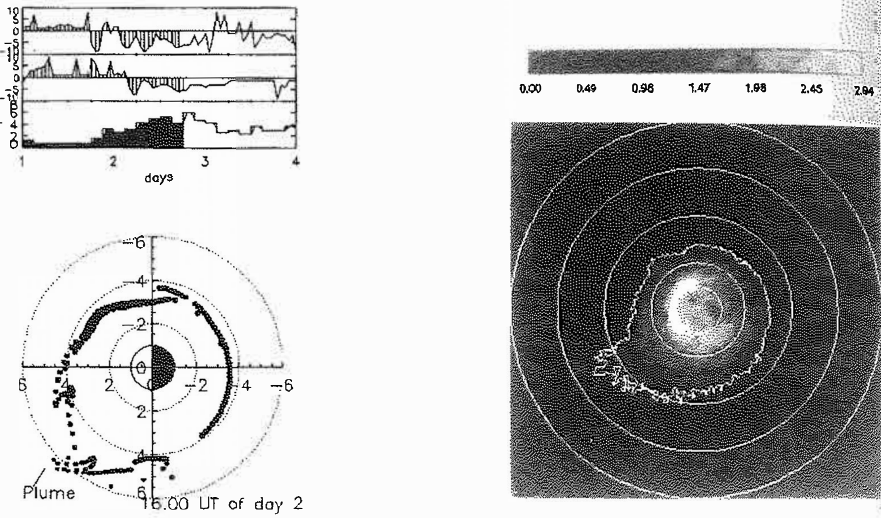

(a) (b)

Fig. 4. Same as Fig. 1 for June 26, 2000, 16h00 (left panel, simulation) and 15h56 UT (right panel, EUV observation).

5. What was revealed by EUV?

During the first two years of the IMAGE mission, most EUV observations have been from high latitudes with a favorable viewpoint for studying the distribution of plasma in the equatorial plane. For the first time, it was possible to observe the plasmapause in different MLT. Global imaging of the plasma distribution inside the plasmasphere led to new types of observations and of investigations summarized in this section.

1. Comparisons between EUV images and in situ measurements permit the determination of the particles number density inside the plasmasphere and show that the sharp outer boundary in EUV images corresponds indeed to the plasmapause.

2. Formation of plumes is a common consequence of increased convection. As they form, the connection is in the afternoon or dusk sector and the plumes extend sunward. The plumes slowly rotate.

3. An unexpected feature of the plasmasphere seen for the first time in EUV images is the "shoulder", an asymmetric bulge in the plasmapause.

4. "Notches" were also discovered by EUV: they are localized density cavities in the plasmapause.

5. In times of increasing magnetospheric convection, the plasmasphere shrinks rapidly. The observations show that the plasmasphere is eroded, not compressed. Erosion occurs over the antisunward hemisphere, but not uniformly. The plasmapause moves at different times and at different rates at different local times. The plasmapause can move fast inward, for instance by almost 2 Re in less than 3 hours on 10 July 2000.

6. When convection returns to normal, flux tubes depleted by convection refill from the ionosphere. This slow process can be studied with EUV observations. Faster refilling processes like interchange can also contribute and explain some observations like shoulder formations.

7. "Channels" are regions of lower density extending roughly in the azimuthal direction. They usually appear first in the pre-midnight sector and allow the measurement of the rotation velocity. Some channels are formed by plume wrapping: the inner part of a plume nearly co-rotates while the outer part remains nearly fixed in local time.

8. Low-density regions (notches, channels) can serve as natural markers to track the angular velocity of the plasma over a range of L values. Some notches can persist for periods as long as 60 hours. Cold plasma in the range $2 < L < 4$ most frequently rotates at a rate 85-90 % of the co-rotation. But it may move at the co-rotation velocity for a time and then begin to lag.

6. Conclusions

From the direct comparison between the EUV observations from IMAGE and numerical simulations of the plasmapause position determined from the value of Kp using the instability mechanism with the E5D electric field model, it appears that the formation of the plumes is well reproduced by the simulations. They are formed after a moderate increase of Kp and rotate then with the plasmasphere during the quieting period following the enhanced magnetic activity. The observed shoulders are produced at the end of magnetic substorms or storms and generally develop one or two hours before a sharp decrease of Kp. The plasmapause position obtained with the simulations corresponds in average to the position observed by EUV: it is not simply determined by the instantaneous Kp value, but it depends also on its past history.

The new observations of EUV/IMAGE will help to improve the theory for the formation of the plasmapause and the understanding of the new structures recently discovered in the plasmasphere.

Acknowledgments

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