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Development of shoulders and plumes in the frame of the interchange instability mechanism for plasmapause formation

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[1] The mechanism of plasmapause formation based on interchange instability and a Kp-dependent magnetospheric electric field model, enables us to determine the position of the plasmapause as a function of Kp and local time. We illustrate here how this physical mechanism is able to account for the formation of shoulders like those observed by EUV on IMAGE. A wide variety of other structures observed by IMAGE like tails (also called plumes), and notches are also obtained with this mechanism for the formation of a "knee" in the high altitude cross-L distribution of the cold plasma density distribution. *INDEX TERMS:* 2730 Magnetospheric Physics: Magnetosphere—inner; 2760 Magnetospheric Physics: Plasma convection; 2753 Magnetospheric Physics: Numerical modeling; 2768 Magnetospheric Physics: Plasmasphere; 2788 Magnetospheric Physics: Storms and substorms. **Citation:** Pierrard, V., and J. F. Lemaire (2004), Development of shoulders and plumes in the frame of the interchange instability mechanism for plasmapause formation, *Geophys. Res. Lett.*, *31*, L05809, doi:10.1029/2003GL018919.

1. Introduction

[2] The EUV (Extreme UltraViolet) instrument on board the IMAGE spacecraft launched in March 2000, provides new global images of the Earth's plasmasphere. During active intervals, it reveals rather irregular plasmapause shapes characterized by different structures such as shoulders, plumes, notches, and crenulations [*Sandel et al.*, 2001; *Burch et al.*, 2001; *Spasojevic et al.*, 2003]. Except for plumes, these features could hardly have been observed by early in situ or whistler observations. Such local time-dependent locations of the plasmapause can be identified unambiguously only with full global images available since 2000.

[3] *Spasojevic et al.* [2003] studied the evolution of the plasmapause observed by EUV during two isolated geomagnetic substorms. They show the formation of plumes in the afternoon/dusk sector, of crenulations (azimuthal plasmapause irregularities) and of large-scale shoulders. Another well identifiable shoulder was also formed in the morning sector of the plasmapause during the magnetic storm of 24 May 2000.

[4] Different explanations have been proposed for the formation of plumes [*Grebowsky*, 1970; *Lemaire*, 1985], but for the formation of shoulders, only one first tentative explanation has been proposed by *Goldstein et al.* [2002]. It is based on variations of the convection parametric electric field predicted by the Magnetospheric Specification Model (MSM) [*Lambour et al.*, 1997] for appropriately adjusted boundary conditions. According to this physical magnetospheric model, overshielding of the convection electric field would be produced in the post-midnight sector inside the plasmasphere when the interplanetary magnetic field turns northward. However, the internal physical mechanism leading to the overshielding inside this numerical model is not elaborated by *Goldstein et al.* [2002]. According to their numerical simulations, for model adjusted boundary conditions in the solar wind (e.g., the variation of the north-south component of the interplanetary magnetic field) and in the magnetosphere (e.g., the variations of Dst, Kp, Ae, etc.), an eastward electric field component is generated in a limited range of Magnetic Local Time (MLT). This produces an outward radial plasma motion and therefore may explain the formation of shoulders observed in this MLT sector.

2. Mechanism for the Formation of the Plasmapause

[5] The simulations presented in this letter illustrate the formation of shoulders in the post-midnight and dawn sectors following a different mechanism than simulation of ideal MHD plasma convection of an initial plasmapause surface given at $t = 0$, which does not coincide with the "last closed equipotential" of the adopted E-field model at that time like in steady state MHD. We adopt an empirical Kp-dependent E5D model inferred from dynamical proton and electron spectras measured on board the geostationary satellites ATS5 and 6 [*McIlwain*, 1986]. Furthermore, instead of assuming an ab-initio position and shape of the equatorial plasmapause as a function of MLT angles at an initial time (t_0), as it is done for instance in the numerical simulation of Goldstein et al., we determine in the following kinetic simulations the plasmapause position as the location where plasma interchange peels off the plasmasphere, i.e., where and when the magnetospheric convection velocity is enhanced at the onset of substorms [*Lemaire*, 1974, 1985, 2001].

[6] According to this physical mechanism (i.e., interchange and quasi-interchange as reviewed by *Ferrière* [2001]), the plasmapause is formed in the post-midnight MLT sector where and when the field-aligned component of the centrifugal pseudo-force overcomes that of the gravitational force. The plasmapause is determined by the innermost convection contour tangent to the Zero Parallel Force surface (ZPF) where the field-aligned components of the gravitational force and of the centrifugal force balance each other. Outside this surface, centrifugal force dominates and plasma elements with an excess mass density drift away

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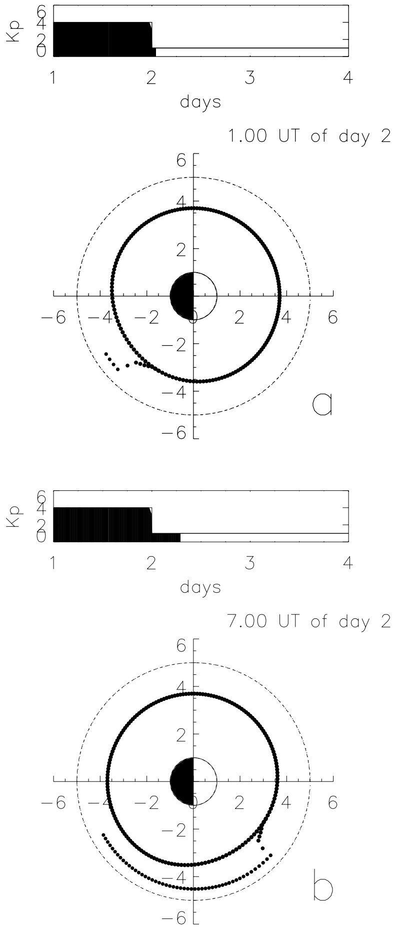

Figure 1. a. Shoulder created during a sudden decrease of the level of geomagnetic activity as determined by the value of Kp illustrated in the top panel. The dashed circle corresponds to R = 5 Re. b. The shoulder corotates with the plasmasphere. The vestigial plasmapause is still present, so that the cross-L density profile in the post-midnight sector has two separate knees.

from Earth, whereas the particles inside the surface are trapped and corotate with the Earth. The geomagnetic index Kp determines the ZPF surface. The deepest point of penetration of this surface happens to be in the post-midnight sector where the magnetospheric convection electric field is largest and most sensitive to the level of geomagnetic activity. When Kp is low, the plasmapause is forming at large radial distances from the Earth. When Kp increases, the electric field increases in the post-midnight sector, so that the convection velocity becomes significantly larger than the corotation velocity in this local time sector. The plasmasphere is peeled off deeper into the magnetosphere, and the plasmapause forms closer to Earth. The mechanism for the formation of the plasmapause by interchange motion is described in more detail in *Lemaire and Gringauz* [1998] and *Lemaire* [2001].

3. Formation of a Shoulder Associated With a Kp Decrease

[7] Figures 1a and 1b illustrate how a sharp decrease of the Kp index leads to the formation of a new plasmapause further away from Earth in the post-midnight sector, where the convection velocity in the dawnside is larger than in any other MLT sector. This feature is built in McIlwain's E5D model for the magnetospheric convection electric field. *McIlwain* [1986] inferred the E5D electric field model from satellite data for different values of Kp and showed that the convection electric field is highly variable in the dawnside sector, where the Pedersen conductivity is most reduced. This partly explains why the magnetospheric convection most easily and significantly departs from corotation in this sector.

[8] In Figure 1, the dots represent the successive positions of test plasma elements, which are driven toward the plasmapause by the mechanism of interchange motion. Their positions illustrated on the figures determine the plasmapause. When the geomagnetic index Kp (which is here the only free parameter controlling the convection E-field distribution in the E5D model) is independent of time, the plasmapause obtained according to the interchange instability process is quasi-circular with a LT average radius of 3.6 R_E for Kp = 4, as shown on Figure 1a. In the midnight sector, R_{eq} = 3.5.

[9] Figure 1a shows how the time-dependent change (decrease) in the E5D E-field intensity creates a shoulder (see Figure 1a) similar to those observed in EUV data. Note that this shoulder is not the result of an outward radial motion of plasma, as in the overshielding model. It is here the consequence of the outward shift of the ZPF surface. This is consistent with whistler motion showing evidence of inward plasma convection in the night sector during substorms, but no outward drift of whistler ducts in this MLT sector. The vestigial plasmapause is still present, so that the cross-L density profile in the post-midnight sector has two separate "knees", as sometimes observed by satellites [*Horwitz et al.*, 1990]. Once created, the shoulder subsequently corotates (see Figure 1b) with the unperturbed inner core of the plasmasphere wherein the substorm electric field has not penetrated. With the interchange instability process and the E5D electric field model, shoulders appear in the post-midnight or pre-morning LT sector and then corotate with the plasmasphere. Shoulders can possibly form at other local times or under other circumstances (e.g., for magnetospheric electric field distributions departing from the E5D quasi-stationary electrostatic model) or presumably due to other mechanisms than interchange instability.

4. Formation of a Plume Associated With a Kp Increase

[10] The plasmapause is far from Earth when Kp is low: for Kp = 1, it is located at L = 4.5 when averaged over all LT. When the Kp index increases (e.g., at the onset of a magnetic substorm or when the IMF turns southward), the plasmapause forms closer to Earth in the post-midnight LT sector. The plasmasphere is peeled off, and the vestigial plasmapause is convected away with the outer shell of the plasmasphere. We do not show drifting plasma elements between 1 h and 2 h LT because this corresponds approximately to the LT sector where the plasma becomes unstable by interchange. When Kp assumes suddenly a high value, a dawnside bulge is carved in the plasmasphere surface as illustrated in

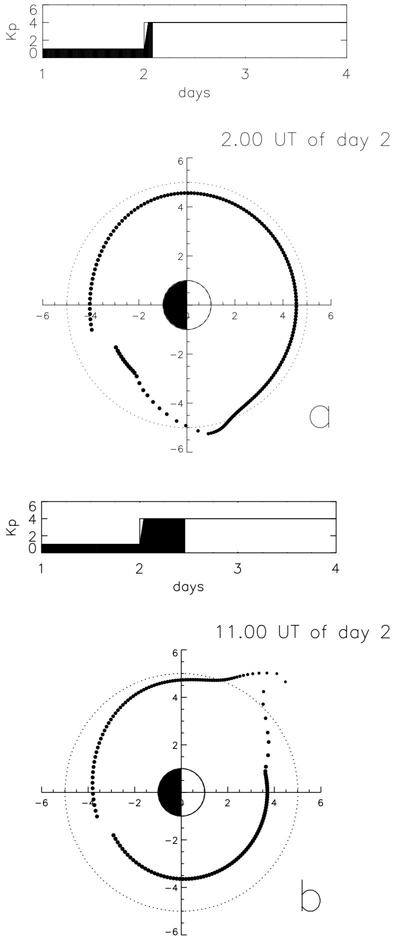

Figure 2. a. Bump created after a sharp increase of the geomagnetic activity as determined by the sudden increase of Kp illustrated in the upper panel. b. The bump evolves into a plume.

Figure 2a. Note that the bump shown in Figure 2a does not simply corotate with the inner part of the plasmasphere. It bulges in the sunward direction due to the enhanced dawn-to-dusk component of the electric field in the morning and dayside sectors. In this MLT sector, the azimuthal component of the convection velocity decreases with L in the dayside sector. This shear in the azimuthal velocity component leads to the formation of a tail. Indeed, due to the enhancement of the day-night asymmetry of the electric field, the bulge formed in the dayside plasmasphere evolves into a plume-like structure in the afternoon sector, since the angular convection velocity is smaller at the tip of the bulge than at L closer to Earth. This feature of E5D is also found in any E-field model that is the superposition of cross-tail plus corotation components. An example of the formation of such a plume is illustrated in Figure 2b. The formation of a plume following this mechanism had been proposed first by *Lemaire* [2000] and corresponds rather well to some features observed by *Spasojevic et al.* [2003].

[11] Of course, this scenario for the formation of attached plasma tails does not exclude that similar or other types of tails can be formed in a more direct way by the sunward surges of plasma inside a "teardrop shaped plasmapause" drifting sunwards in the dusk sector, as suggested and modelled by *Grebowsky* [1970].

5. Formation of a Notch Associated With a Fast Increase and Decrease of Kp

[12] When geomagnetic activity increases and then decreases over a short period of 2–3 hours UT, as illustrated by the black region in the top panel of Figure 3, the ZPF surface forms closer to Earth in the post-midnight sector and recovers soon after its initial position. This kind of Kp evolution creates a so-called notch in the plasmapause region. This feature corotates with the Earth angular speed. This effect is illustrated in Figures 3a and 3b. Narrower notches (less extended in MLT) can be carved when the enhancement of the E-field intensity lasts a shorter time (i.e., less than 2 hours).

[13] Of course, more gradual Kp variations can lead to an infinite variety of more or less pronounced and complicated features and irregularities of any size at the surface of the plasmasphere. Short periodic variations of Kp with very large amplitude should produce irregular plasmapauses with crenulations. Smooth plasmapause shapes are expected during extended periods over which the level of geomagnetic activity remains almost constant. Note, however, that

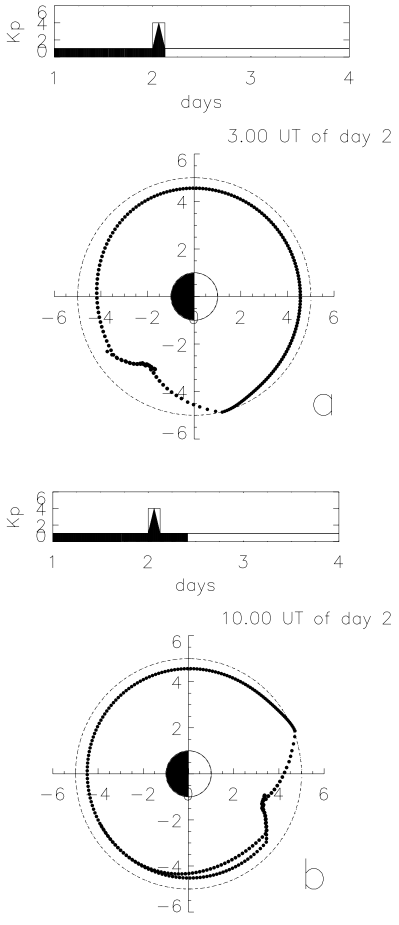

Figure 3. a. Notch created by a short time burst enhancement in the level of geomagnetic activity determined by the value of Kp illustrated in the upper panel. b. The notch corotates with the plasmasphere.

during extended periods of very low activity, the density of the plasmaspheric particles decreases smoothly beyond $L = 7 - 8$ so that the plasmapause is not identifiable.

6. Conclusions

[14] We have presented simulations based on a simple kinetic model that utilizes McIlwain's E5D Kp-dependent electric field model as a given input and the physical mechanism of interchange instability to form the plasmapause. Shoulders are formed in the post-midnight and dawn sectors when the level of geomagnetic activity is suddenly and significantly reduced after a period of rather high level of magnetic agitation. Notches, plumes and other features of the plasmapause can also be obtained according to this physical process using the E5D E-field for various other specific time sequences of the Kp variations.

[15] The example simulations (animations available on the Web at http://www.magnet.oma.be) presented in this paper show that Lemaire's physical mechanism for the formation of the plasmapause based on interchange instability can satisfactorily reproduce the formation of structures observed at the plasmapause with EUV experiment. We do not claim that all observed features discovered in these 2D maps of the plasmasphere can be simulated in detail with the numerical code used here. Indeed, the program employs electrostatic and magnetostatic field models that are global scale averages: the actual dynamical E-field and B-field distributions at any time are currently out of grasp. Therefore, nobody should expect that these field models, depending only of one 3-hourly Kp activity index, represent the actual E- and B-field intensities anywhere in the magnetosphere, and at any time. Furthermore, it should be pointed out that these quasi-static E- and B-field models are assumed to vary consistently, systematically and synchronically with Kp, at any point in the magnetosphere: i.e., with no phase shift or time delay between the dayside and nightside sector, between dawn and dusk, between $L = 2$ and $L = 4$ or 6. This emphasizes the limitations of the E5D model, which is certainly not the ultimate electric field model we need for space weather predictions. Nevertheless, this global empirical model is far more representative in the high altitude plasmapause region than other ad hoc models or empirical models derived from ionospheric radar observations (i.e., far from the high altitude equatorial region where the plasmasphere is peeled off). More detailed comparisons of the predicted plasmapause positions with EUV observations would ideally require comprehensive dynamical E- and B-field models with higher time resolution, and appropriate physical models for the fields and plasma distributions along and accross magnetospheric field lines.

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