

# ANALYSIS OF PLASMASPHERIC PLUMES: CLUSTER AND IMAGE OBSERVATIONS AND NUMERICAL SIMULATIONS\*

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## ABSTRACT

Plasmaspheric plumes have been routinely observed by the CLUSTER and IMAGE missions. CLUSTER provides high time resolution four-point measurements of the plasmasphere. The EUV imager onboard IMAGE provides global images of the plasmasphere. We present coordinated observations of one plume event and numerical simulations for its formation based on the interchange instability mechanism. We compare several aspects of the plume motion as determined by different methods: (i) boundary velocity calculated from time delays of plume boundaries observed by the WHISPER sounder on all four CLUSTER spacecraft, (ii) ion velocity derived from the ion spectrometer CIS onboard CLUSTER, (iii) drift velocity measured by the electron drift instrument EDI onboard CLUSTER and (iv) global velocity determined from successive EUV images. These different methods consistently indicate that plasmaspheric plumes rotate around the Earth, with their foot fully co-rotating, but with their tip rotating slower and moving farther out.

## 1. INTRODUCTION

The plasmasphere is a toroidal region located in the Earth's magnetosphere and populated by cold and dense ionospheric plasma [1]. Large-scale density structures have been observed in the Plasmasphere Boundary Layer, PLS [2]. These structures are usually connected to the main body of the plasmasphere, and extend outward. They have been called "plasmaspheric tails" in the past [3] but are now known as "plasmaspheric plumes" [4]. Such structures have been commonly observed by in-situ and ground-based measurements [5-7]. Recently, plumes

have been routinely observed in global plasmaspheric images by the IMAGE spacecraft [4,8,11] and also identified in in-situ measurements from the CLUSTER mission [12-16].

The formation of these plumes has been predicted on the basis of different models. One of the potential mechanisms is based on the interchange instability and a  $K_p$ -dependent electric field model [17]. This model is able to explain the formation of plasmaspheric plumes as a result of a short-time enhancement of geomagnetic activity ( $K_p$  increase) followed by a decrease [18].

The purpose of this paper is to compare plume observations by CLUSTER with global images by IMAGE and with numerical simulations. After presenting the instrumentation and the methods of analysis in Sect. 2, one event is discussed in Sect. 3. Sect. 4 contains a summary.

## 2. INSTRUMENTATION AND METHODS OF ANALYSIS

### 2.1 CLUSTER mission

The four CLUSTER spacecraft (C1, C2, C3, C4) cross the plasmasphere from the Southern to the Northern Hemisphere every 57 hours at perigee around  $4 R_E$  [19]. Each satellite contains 11 identical instruments. Data obtained from 5 of them are used in this paper.

WHISPER can unambiguously identify the electron plasma frequency  $F_{pe}$  (related to the electron density  $N_e$  by:  $F_{pe}\{\text{kHz}\} \sim 9 [N_e\{\text{cm}^{-3}\}]^{1/2}$ ) through its two modes [20]. In active mode, the sounder analyses the pattern of resonances triggered in the medium by a radio pulse. This allows the identification of  $F_{pe}$  [21]. In passive mode, the receiver monitors the natural plasma emissions in the frequency band 2-80 kHz. The local wave's cut-off properties lead to an estimation of  $F_{pe}$  [22]. Above this frequency range, EFW [23] is used to estimate  $N_e$  from the spacecraft potential  $V_{sc}$ , which is the potential difference between the antenna probes and the spacecraft body [24-26]. In order to facilitate inter-comparison of the data, we choose to plot the density as a function of the equatorial distance  $R_{\text{equat}}$  (in units of Earth radii): the geocentric distance of the magnetic field line on which the spacecraft is located, measured at the geomagnetic equator, which is identified as the location along the field line where the magnetic field strength reaches a minimum. A magnetic field model is used that combines the internal model IGRF95 and the external model Tsyganenko-96 [27]. These models are computed with the UNILIB library (<http://www.oma.be/NEEDLE/unilib.php/>).

CIS measures the complete three-dimensional distribution functions of the major ion species ( $H^+$ ,  $He^+$ ,  $He^{++}$  and  $O^+$ ) with a time resolution of 4 seconds [28]. Its energy range extends as low as the spacecraft potential in RPA (Retarding Potential Analyser) mode (0.7-25 eV/q), which is available on C1, C3, and C4. EDI measures the electron drift velocity using artificially injected electron beams [29]. This instrument works on C1, C2, and C3. The data used in this study have been cleaned and smoothed [30]. The FGM magnetometer provides high time resolution (22.4 Hz in normal mode) magnetic field measurements from all four spacecraft with an accuracy of at least 0.1 nT [31]. The data have been time-averaged to provide a time resolution of 4 seconds.

### 2.2 IMAGE mission

The IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) spacecraft was launched into a polar orbit with an apogee of  $8.2 R_E$  [32]. The Extreme Ultraviolet (EUV) imager onboard IMAGE provides global images of the plasmasphere every 10 minutes with a spatial resolution of  $0.1 R_E$  [4]. It is an imaging system, which detects the 30.4 nm sunlight

resonantly scattered by the  $\text{He}^+$  ions in the plasmasphere.

For better comparison with simulations, EUV images have been projected onto the dipole magnetic equatorial plane, by assigning to each pixel the minimum dipole L-shell along the line-of-sight (as EUV images are taken close to the Earth, a dipole magnetic field model can be used for low to moderate geomagnetic activity) [33-35]. The mapped signal is then converted to column abundance using estimates for the solar flux at 30.4 nm, based on the Solar2000 empirical solar irradiance model [36]. Finally, the column abundance is converted to pseudo-density by dividing by an estimate of the distance along the line of sight that contributes most to the image intensity at each location in the field of view [35]. Therefore the EUV images shown here give an equatorial distribution of  $\text{He}^+$  pseudo-density versus L and Magnetic Local Time (MLT). The lower sensitivity threshold of the EUV instrument has been estimated to be  $40 \pm 10$  electrons  $\text{cm}^{-3}$ , or 4-8  $\text{He}^+$  ions  $\text{cm}^{-3}$  [34].

### 2.3 Numerical simulation

In the frame of the interchange instability mechanism, the plasmopause is formed in the post-midnight MLT sector where and when the parallel components of the gravitational and centrifugal forces balance each other (the Zero Parallel Force (ZPF) surface [37]) [17,38,39]. The plasmopause is determined by the innermost equipotential surface tangent to the ZPF. Simulations show how this mechanism can lead to a plasmopause variable position, but also to the formation of plumes, shoulders or notches [18,40]. The  $K_p$ -dependent E5D electric field model is used in these simulations [41].

### 2.4 Velocities

To study the motion of plasmaspheric plumes, we use velocities determined from different techniques. The electron drift velocity  $\mathbf{V}_D$  is measured by EDI. The  $\text{H}^+$  velocity  $\mathbf{V}_H$  is determined from the ion distribution functions measured by CIS. The accuracy of the velocity measurements in the plumes is limited by the low particle counting statistics. A four-point technique is applied to the features identified in the electron density profiles at the inner and outer boundary (supposed to be locally planar) of the plumes. We determine the normal boundary velocity  $\mathbf{V}_N$  (assumed to be constant) with a time delay method, i.e. from individual spacecraft positions and times of the boundary crossings. We also compute the co-rotation velocity at the centre of mass of the four CLUSTER spacecraft:  $V_C = 2\pi R / (24 \times 60 \times 60)$ , where R is the distance from the spacecraft to the Earth's rotation axis.

To be able to compare the CLUSTER velocities between each other and with the IMAGE velocity, we project all the CLUSTER velocities on the  $R_{\text{equat}}$  axis by using the same magnetic field models as in the WHISPER density analysis. If we have a vector  $\mathbf{u}$  determined at the centre of mass C of the four spacecraft, we consider a small displacement (of the order of 100 km) of this point C to M with the velocity  $\mathbf{u}$ . We determine the projection C' of C along the magnetic field line, until the magnetic field strength reaches a minimum. By doing the same analysis with the point M, we determine the velocity  $\mathbf{u}_{\text{eq}}$  in the magnetic equatorial plane. We obtain thus the following velocities:  $\mathbf{V}_{D\text{-eq}}$ ,  $\mathbf{V}_{H\text{-eq}}$ ,  $\mathbf{V}_{N\text{-eq}}$ ,  $\mathbf{V}_{C\text{-eq}}$ . An average radial velocity,  $V_{\text{IO-eg}}$ , can be computed from the displacement in  $R_{\text{equat}}$  of a structure as seen during in- and outbound passes, when the spacecraft remains approximately in the same MLT sector. From IMAGE data, we determine the motion  $V_E$  of geometrically identified parts of the plume in successive EUV images equatorially projected.

### 3. OBSERVATIONS: 2 JUNE 2002

#### 3.1 CLUSTER observations

This event is observed for small separation distance between the four CLUSTER spacecraft (around 150 km), in the dusk sector (18:00 MLT) and when the geomagnetic activity had a peak value of  $K_p = 4$  in the previous 24 hours. Fig. 1 displays frequency-time spectrograms from WHISPER. The magnetic equator is crossed around 13:20 UT. A very wide plume is seen in the inbound (IP) and outbound passes (OP) on all four spacecraft. Each plume crossing is very similar for all four satellites, with for example a small structure inside the inbound crossing observed at 12:20 UT by the four spacecraft, and another one in the outbound crossing at 14:10 UT. This plume has a high maximum  $F_{pe}$ , around 80 kHz; it takes more than 30 minutes to be crossed during the inbound pass.

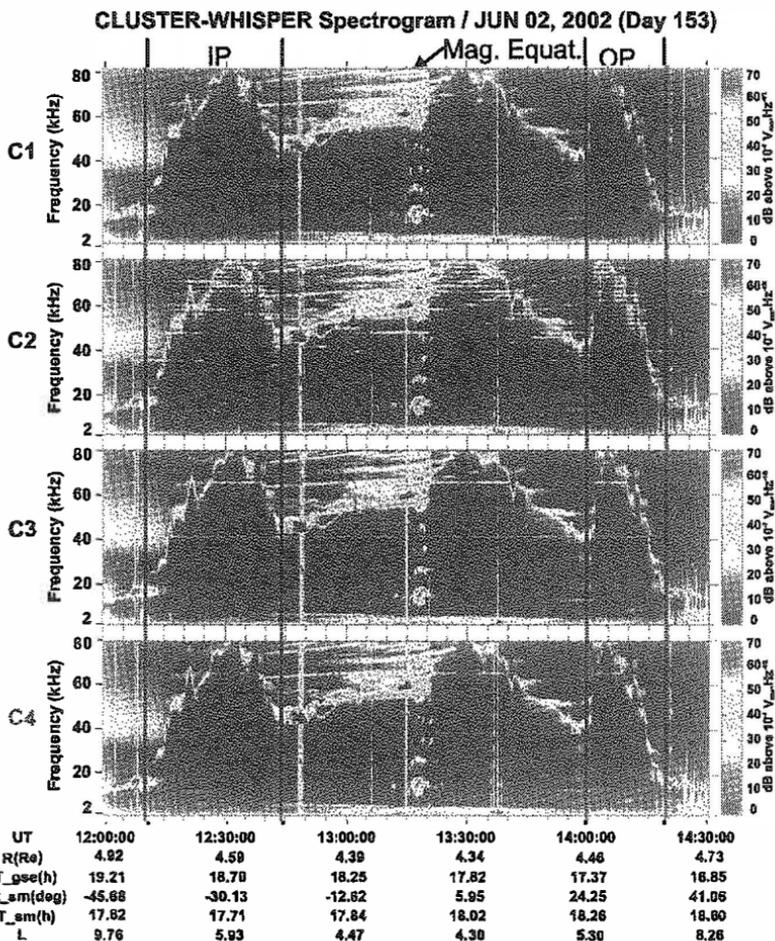


Figure 1. Frequency-time spectrograms measured by WHISPER onboard the four CLUSTER spacecraft on 2 June 2002, showing the entire plasmasphere crossing, with plume crossings in the inbound (IP) and outbound passes (OP). The orbital parameters correspond to C4.

The plume electron density profiles as determined from WHISPER and EFW (for the part above  $80 \text{ cm}^{-3}$ ) are shown in Fig. 2. Both structures have the same overall shape, with more variability during the inbound crossing. This similar global structure leads to consider that the same plume is crossed by the spacecraft at South and North latitudes of the plasmasphere. The similarity of the four profiles suggests that the plume has not moved significantly over the 2 hours time period between the inbound and outbound crossings. This is confirmed by the equatorial normal boundary velocities  $V_{N\text{-}eq}$  derived from the time profiles shown on Fig. 2.

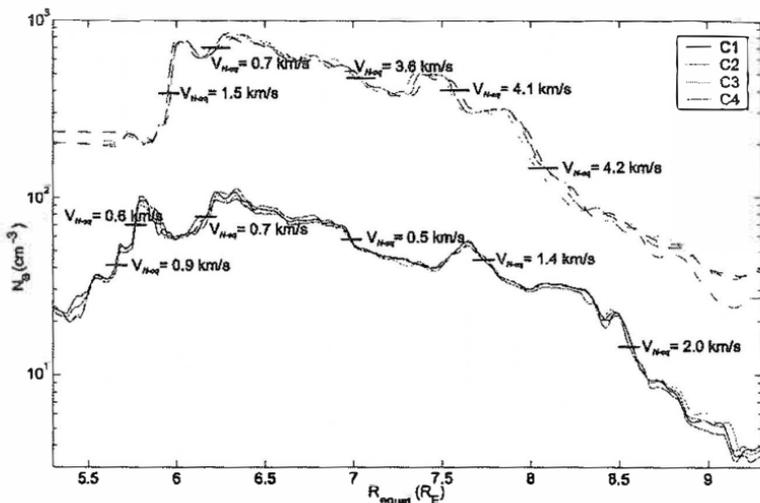


Figure 2. CLUSTER electron density profiles as a function of  $R_{\text{equal}}$  for the two plume crossings. The lower four curves correspond to the inbound pass, the upper curves (shifted by a factor 10) to the outbound one. The magnitude of the equatorially projected normal boundary velocities  $V_{N\text{-}eq}$  derived from the time delays of different features are indicated.

These equatorial normal boundary velocities are quite small for the inbound plume crossing (larger at the outer edge than at the inner one). Note the higher values at the outer boundary than at the inner one. This is less than 50% of the co-rotation velocity  $V_{C\text{-}eq}$  (2.4-4.1 km/s). The inner edge of the plume shifts  $0.5 R_E$  in 75 minutes, corresponding to  $V_{IO\text{-}eq} = 0.7 \pm 0.1 \text{ km/s}$ . For the outer edge, we find  $V_{IO\text{-}eq} = 0.5 \pm 0.1 \text{ km/s}$ . This suggests that the plume is thinner in the outbound pass in the Northern hemisphere than in the inbound one in the Southern one; its inner edge moves to a larger equatorial distance.

CIS data in RPA mode are shown on Fig. 3 for C1 and C3. The satellites enter the main plasmasphere at 12:45 UT and exit it at 13:55 UT (PLS region), as indicated by the increase of ion populations. The plume is clearly seen in the  $H^+$  populations in the inbound pass (IP: 12:20 - 12:45 UT), and also in the outbound one (OP: 14:00 - 14:20 UT). The CIS density values are much lower than those determined from WHISPER, because of the limited energy range of the instrument in the RPA mode (0.7-25 eV/q). Inside the plasmasphere, the equatorially projected velocity  $V_{H\text{-}eq}$  corresponds to the expected co-rotation orientation. But, during the inbound plume crossing, the Y component is higher, which means that the plume is

probably moving away from the Earth. For the outbound plume no clear conclusions can be drawn as the trend is very different between C1 and C3.

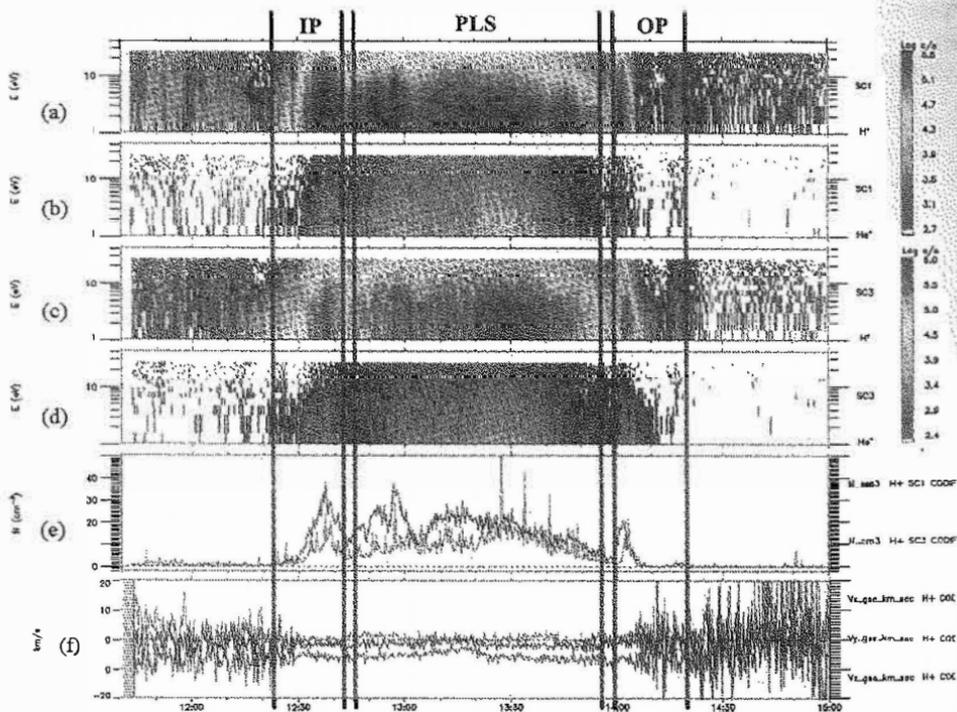


Figure 3. CIS data in RPA mode: (a)-(b) distribution of  $H^+$  and  $He^+$  for C1; (c)-(d) same data for C3; (e)  $H^+$  density for C1 and C3; (f)  $H^+$  velocity  $V_H$  for C1 in GSE coordinates.

The drift velocity components determined by EDI are shown on panels (a) to (c) of Fig. 4 for C1, C2 and C3, for the inbound plume crossing. During this inbound crossing, the equatorially projected electron drift velocity is  $V_{D-eq} = 1.7 \pm 0.2$  km/s ( $V_{D-eq}^X \sim -1.0$  km/s,  $V_{D-eq}^Y \sim 1.3$  km/s,  $V_{D-eq}^Z \sim -0.5$  km/s). This is around 50% of the co-rotation velocity (3.3 km/s). The average direction of  $V_{D-eq}$  is in the co-rotation direction; there is also a radial expansion of the plume ( $V_{D-eq}^Y > 0$ ). During the outbound plume pass,  $V_{D-eq} = 4.5 \pm 0.2$  km/s, opposite to the co-rotation direction, with a large X component ( $V_{D-eq}^X \sim 3.5$  km/s,  $V_{D-eq}^Y \sim 1.3$  km/s,  $V_{D-eq}^Z \sim -2.5$  km/s). This is consistent with the higher values of the velocity determined from WHISPER in the outbound plume. Inside the plasmasphere (12:50-13:50 UT, i.e.  $R_{equat}$  between 4.4 and 5.3  $R_E$ ),  $V_{D-eq} = 2.0 \pm 0.2$  km/s. Its magnitude and direction are close to the co-rotation velocity  $V_{C-eq}$  ( $2.1 \pm 0.1$  km/s).

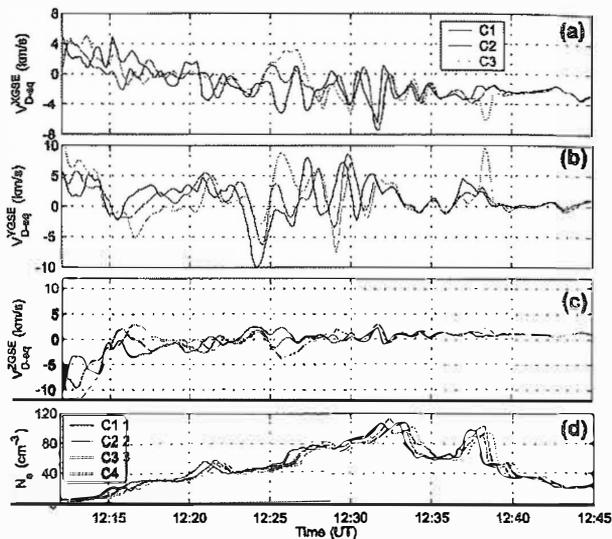


Figure 4. Inbound time profiles of (a)-(c) electron drift velocity  $V_{D-eq}$  from EDI projected onto the equatorial plane; (d) electron density from WHISPER.

### 3.2 IMAGE observations

Fig. 5 presents an equatorially mapped EUV image at 12:33 UT, around the time of the inbound plume pass by CLUSTER. A very large plume (delimited by the white line) is observed in the post-dusk sector, with its foot attached to the plasmasphere between 17:30 and 22:00 MLT. At 17:30 MLT, it is located between 6.0 and 7.5  $R_E$ , which is consistent with the observations by WHISPER, with a plume observed between 5.5 and 8.5  $R_E$  (but with an electron density above the estimated EUV threshold only between 5.7 and 7.8  $R_E$ ). The normal directions computed from the time delay method applied to WHISPER data coincide approximately with that indicated by the global view from EUV.

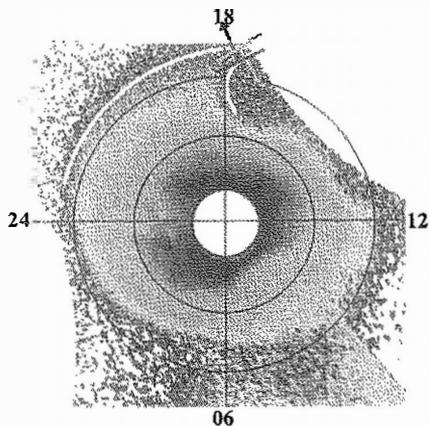


Figure 5. Equatorial projection of an EUV image at 12:33 UT. The white disk in the centre corresponds to the Earth. The big circles correspond to  $R_{equat} = 3$  and  $5 R_E$ . The plume is delimited by the white line. The normal directions deduced from the time delay method for the CLUSTER inner and outer plume crossings are shown by the dark and light arrows.

The plume is observed on EUV images from 10:10 UT until 14:30 UT. These successive images enable us to determine the motion of the plume. The foot of the plume (at  $3.7 R_E$ ) moves at  $V_E = 1.6 \pm 0.1$  km/s, close to the co-rotation velocity  $V_{C=eq} = 1.7$  km/s. It is hard to make the same calculation with the tip of the plume, which is difficult to identify unambiguously on the EUV images. From successive images, it can be seen that the tip is moving slower than the foot. EUV images show also that the tip is extending away from the Earth, consistent with CLUSTER showing the inner edge of the plume moving out from  $R_{equat} = 5.5$  to  $6 R_E$ .

### 3.3 Numerical simulations

Fig. 6 displays the plasmopause positions in the equatorial plane based on the  $K_p$ -dependent E5D electric field model and on the interchange instability scenario. At the beginning of the simulation (panel a), the plasmopause is almost circular and located around  $4.5 R_E$ , but with a slight bulge (B) formed in the post-midnight sector (panel b) after an increase of  $K_p$  up to 4 at 00:00 UT and the decrease of the  $Dst$  index (see left panel). This also corresponds to a southward turning of the IMF  $B_z$ . This bulge then evolves into a plume-like structure (B P), rotating around the Earth through all MLT sectors, at a velocity close to the co-rotation speed (panels c-d). At 12:30 UT the plume (P) is located in the dusk sector, between 17:00 and 18:00 MLT (panel d), and between 18:00 and 19:00 MLT at 14:15 UT. It is in the same local time sector where the CLUSTER spacecraft crossed the plume in the inbound (17:40-17:50 MLT) and outbound (18:15-18:30 MLT) passes.

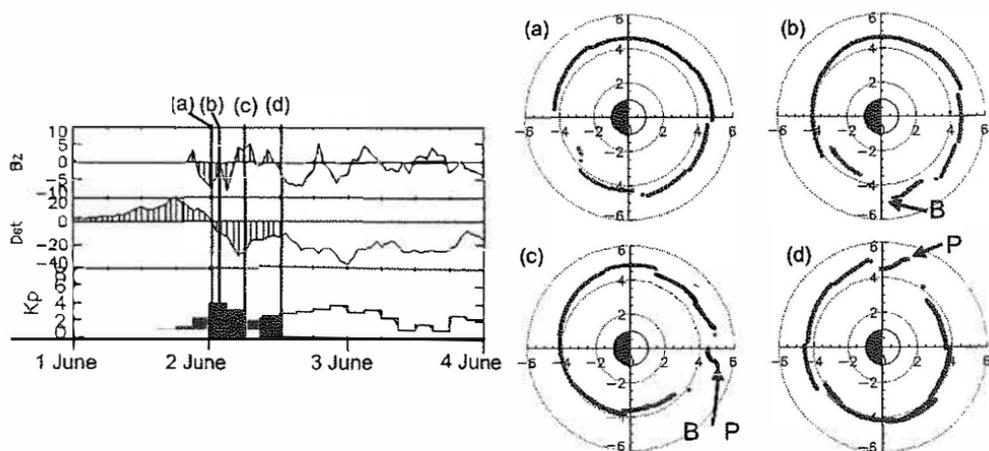


Figure 6. Predicted position of the plasmopause: left panel gives the solar wind and geomagnetic indices during the period of simulation ( $B_z$ ,  $Dst$  and  $K_p$ ); right panels indicate the plasmopause position and the evolution of a bulge (B) into a plume (P): (a) at 00:30 UT, (b) at 02:00 UT, (c) at 06:00 UT and (d) at 12:30 UT.

According to the EUV image at 12:33 UT (Fig. 5), the plume is located between 18:00 and 22:00 MLT, but between 17:00 and 18:00 MLT in the simulation. This 1-3 hours shift can be explained by the poor time resolution (only 3 hours) of the geomagnetic index  $K_p$  used in the simulation. There is a good correlation between the simulated and observed plasmopause positions. In the morning sector, between 08:00 and 10:00 MLT, the simulation shows a plasmopause around  $4 R_E$  and the EUV image exhibits a plasmopause between 4 and  $4.5 R_E$ .

In the post-midnight sector, it is located at  $4.5 R_E$  from the simulation, and between 4.5 and  $5 R_E$  according to EUV observations. It is interesting to notice that the plume is disappearing in the simulation around 23:00 UT, because  $K_p$  is still increasing. Therefore the plasmapause is now forming closer to the Earth in the post-midnight sector, and the plume, as well as the outermost shell of the plasmasphere, are peeled off and convected away from the central core of the plasmasphere. On EUV images, the plume is also disappearing at the end of the day.

#### 4. SUMMARY AND CONCLUSIONS

We have compared observations of plasmaspheric plumes by CLUSTER and IMAGE with numerical simulations. This study shows that the CLUSTER and IMAGE missions are complementary, because their different measurement techniques (global imaging and in-situ measurements) provide a more complete picture of plasmaspheric plumes.

The comparison between the global view from IMAGE and the in-situ measurements from CLUSTER gives consistent results concerning the position and size of the plumes. The plasmapause positions determined from WHISPER and EUV are consistent with the results predicted by the simulation code used in this article. The normal directions of the boundaries of the plumes as computed using the time delay method are consistent with EUV observations (see the projection of those normals on EUV image in Fig. 5).

The velocity analysis of the plumes gives consistent results between different techniques and different datasets. The main conclusion is that the plume is rotating around the Earth, with its foot attached to the main plasmasphere fully co-rotating, but with its tip rotating more slowly and moving outward, away from the Earth. This result is consistent with the topology of a plume, extending farther out at earlier MLT, as shown in earlier studies [11,12]. Note that in the case studied here the plume is not moving inward, as might be expected from standard sunward MHD convection scenarios based on the enhancement of a uniform dawn-dusk convection electric field considered in earlier teardrop models of plasmasphere. As expected, the angular velocity of the inner edge of the plume is closer to co-rotation than the outer one.

The numerical simulation of the plasmapause positions is based on McIlwain's  $K_p$ -dependent empirical magnetospheric electric field model E5D and on the interchange instability mechanism for the formation of the plasmapause. It reproduces rather well the formation and motion of the plasmaspheric plumes when the level of geomagnetic activity increases suddenly by sufficiently large step ( $\Delta K_p \approx 2$ ). Indeed, with a  $K_p$  in the preceding 24 hours increasing suddenly from a small value to  $K_p > 3$ , a bulge is formed in the post-midnight MLT sector, and develops subsequently into a plume while it co-rotates around the Earth into the dusk MLT sector. The comparison with the observations works well in terms of radial and MLT position of the plume. Some shifts in the simulated MLT positions are observed because of the 3 hours time resolution of the  $K_p$  index used to modulate the E5D model. Note that this model is an average quasi-static electric field model whose limitations may also explain some differences between the observations and the simulation [1,18].

To conclude, this study gives a global idea of the formation, evolution and motion of plasmaspheric plumes from three different datasets.

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