THE EARTH SYSTEM: LIVING IN SPACE – A CLUSTER PERSPECTIVE

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1. THE EARTH AS A SYSTEM

Looking up at the sky, we experience every day that the Earth is not an isolated system in the universe. While in ancient times the cosmos was thought of as eternally unchanging and the subject of remote observation only, the advent of spaceflight has enabled us to sample the Earth's backyard in space, the magnetosphere, directly – and it turns out to be a very dynamic place. The behaviour of the Earth system is driven by external factors: gravitational attraction from the Sun and the Moon, the impact of meteorites, electromagnetic radiation from the Sun, and corpuscular radiation such as the solar wind and cosmic rays. For a proper understanding, we must also study the internal organization of the magnetosphere.

This contribution focuses on the magnetosphere and its interaction with the solar wind. The magnetosphere is a cavity that surrounds the Earth. It is carved out by the geomagnetic field in the interplanetary medium as the solar wind plasma, which is tied to the interplanetary magnetic field lines, cannot easily penetrate into the magnetosphere, which is threaded by the geomagnetic field lines. The magnetosphere thus forms an obstacle for the supersonic solar wind stream, which leads to the formation of a bow shock, where the flow becomes subsonic in the magnetosheath; the magnetosheath plasma is forced to flow around the magnetosphere. The interface between the magnetosheath and the magnetospheric plasma is the magnetospheric boundary; it forms the transition between the interplanetary magnetic field and the geomagnetic field, and thus carries an electric current, the magnetopause current (see Figure 1). Two special places are the polar cusps, the funnel-like channels formed by the earthward extension of the geomagnetic field lines just inward of the magnetopause. While the magnetosphere is compressed on the dayside, it is elongated at the nightside and forms a long magnetotail. Magnetospheric plasma on closed magnetic field lines in the inner magnetosphere and populated by particles of ionospheric origin more or less corotates with Earth, forming the plasmasphere, while plasma in the outer magnetosphere often is of mixed magnetospheric and solar wind origin, convecting in a way that is dictated by the details of the magnetosphere – solar wind interaction. The magnetosphere is electromagnetically coupled to the upper atmosphere by field aligned electric currents into and out of the ionosphere. The aurora is a beautiful example of such a magnetosphere-ionosphere interaction, in which magnetospheric electrons are accelerated downward, producing a large degree of ionization in the ionosphere; radiative recombination gives rise to the auroral emission.

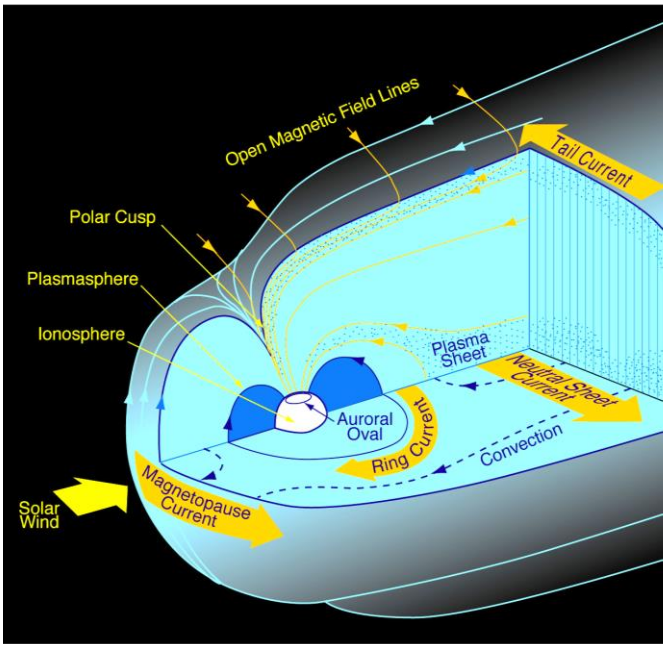

Figure 1 : The terrestrial magnetosphere and its main regions.

Europe has gained solid experience in space science, as highlighted by the present-day ESA/Cluster mission, in which Belgium actively participates. Because remote sensing techniques for studying the tenuous plasmas in the outer magnetosphere are fairly limited, the properties of such media have to be measured in situ. Such measurements, however, are very local. Only a multi-spacecraft configuration, like the four Cluster satellites providing simultaneous measurements at four non-coplanar points, allows to unambiguously distinguish between temporal and spatial variations, that is, to determine spatial differences in each coordinate direction at every point in time.

2. THE SOLAR WIND AS AN EXTERNAL DRIVER

The magnetospheric boundary was already detected by space probes during the first years of space exploration [*Cahill and Amazeen*, 1963]. Later missions showed that this boundary usually consists of both the magnetopause (MP) and a plasma boundary layer (BL, inward of the magnetopause). Indeed, while the magnetopause is basically an impermeable interface between the solar wind and the magnetosphere, it appears that under certain circumstances some plasma can leak through it, so that a plasma boundary layer may be formed. A more profound understanding of the MP/BL developed with the ISEE-1 and -2 missions, as well as with the AMPTE spacecraft [see, for instance, *Russell and Elphic*, 1978; *Sckopke et al*., 1981; *Berchem and Russell*, 1982; *Paschmann et al*., 1986; *Phan and Paschmann*, 1996]. The debate over the precise physical mechanisms responsible for plasma transport from the solar wind into the magnetosphere is not settled yet, despite the importance of the problem: determining how the solar wind can actually drive the Earth system. Observations such as those provided by Cluster may help to clarify the issue.

The MP/BL forms where the total solar wind pressure balances the pressure of the geomagnetic field: Higher (lower) ram pressure pushes the boundary inward (outward) until it equals the higher (lower) magnetic pressure of the dipolar geomagnetic field there. Because the solar wind ram pressure is extremely variable, the MP/BL position is constantly changing in a continuous attempt to re-establish the dynamical equilibrium. Total pressure changes of only a few percent cause the MP/BL to move in- or outward with an amplitude on the order of a few 1000 km; extreme compressions/decompressions of the magnetosphere correspond to inward/outward displacements of several Earth radii. The MP/BL speed may be several tens to hundreds of km/s, larger than the typical speed of the observing spacecraft. As a consequence, a spacecraft usually has multiple encounters with the MP/BL during an in- or outbound pass, as the MP/BL moves back and forth rapidly across the spacecraft. The irregular oscillatory motion of the boundary thus produces strongly time-varying observations. With data from a single spacecraft, it has been very hard to find out whether the observed time variability is due to boundary motion or to some intrinsic time variability of the boundary, which could signal the action of one of the candidate plasma transport mechanisms.

Multi-spacecraft observations have been extremely valuable in this respect. A number of techniques have been developed to analyze a joint crossing of the MP/BL by the four Cluster spacecraft. The general result is that the magnetopause is essentially always moving with speeds of typically tens of km/s, and that its motion is very often strongly accelerating or decelerating. This acceleration had been ignored in most of the single-spacecraft studies, implying a large uncertainty on the MP speeds and thicknesses.

Further advances in the field rely on new analysis methods that are able to put the multi-point information together to create a coherent meso-scale picture of the MP/BL, the so-called 'empirical reconstruction methods', a Belgian contribution to the Cluster project. Sophisticated reconstruction methods are a powerful means to establish MP/BL motion over long time intervals (hours, the typical duration of a boundary pass), as well as to produce pictures of the structure of the boundary. These methods attempt to interpret the observations in terms of a time-stationary structure that is convected across the spacecraft as the boundary moves back and forth. Suppose that the boundary is locally planar, with x the normal direction. The basic idea is that the x-component of the plasma velocity, measured in the vicinity of the boundary, gives an indication of the speed of the boundary itself. Integrating that speed over time should then give the time-varying position of the boundary. All the observations made by any of the spacecraft can then be plotted in terms of the distance of the observing spacecraft from the boundary, resulting in spatial profiles.

The principle of this method was first put forward by *Paschmann et al.* [1990]. Although the principle is simple, a number of difficulties prohibit a straightforward implementation, such as the need to intercalibrate observations made by different spacecraft, the limited precision and time resolution of plasma velocity measurements, data gaps, and so on. In recent years this class of methods has matured [*De Keyser et al*., 2002, 2004, 2005a]. At present, it has become possible to track the motion of the MP/BL for as long as several hours, throughout an entire in- or outward pass of the four Cluster spacecraft, including multiple complete and/or partial traversals of the boundary. Figure 2 shows an example for the Cluster inbound MP/BL pass on April 23, 2001. Figure 2a shows 15 s resolution data for the electron density n_e and the electron perpendicular temperature $T_{e\perp}$ (from the PEACE electron spectrometer on the four spacecraft, after intercalibration), and for the magnetic field B_z component (from the FGM magnetometer on the four spacecraft). Note that, at this resolution, all spacecraft observe essentially the same time profiles, except very close to the transients (color coding: C1 in black, C2 in red, C3 in green, C4 in blue). The data are shown in a boundary aligned reference frame, where x is the outward normal direction. An empirical reconstruction was computed for the three-hour time interval with a 30 s time resolution. As a proxy for MP/BL speed, the x-component of the perpendicular velocity, $v_{\perp x}$ (measured by the CIS/HIA plasma spectrometer, operational on Cluster 1 and 3 only), was used. The reconstruction was based on the assumption that one-dimensional spatial profiles exist for the variables n_e, $T_{e\perp}$, and B_z. Specific details about this particular reconstruction are given by *De Keyser* [2005b].

The result of the reconstruction is two-fold. First, one obtains the boundary position during the time interval under consideration as depicted in Figure 2b. The black oscillating curve represents MP/BL position (up to an arbitrary additive constant). The four parallel lines in standard Cluster colors represent the spacecraft trajectories. The main magnetopause crossing occurs around 14:30 UT; according to the reconstruction, this corresponds to a sudden outward movement of the MP/BL. The transient around 16:30 UT corresponds to a brief inward-outward motion of the boundary. Note that the spacecraft are rather close to each other, so that only minor observational differences result, e.g., near the end of the transient. A second result are the spatial profiles. In fact, once the MP/BL position is known, one can plot any measured variable as a function of the distance of the spacecraft from the MP/BL, thus leading to correlation plots like those shown in Figure 2d. If the underlying structure is one-dimensional, the scatter of the data points is minimal: The data define an unique average spatial profile. Given such a spatial profile and the position of the moving boundary, one can 'predict' the time profile that each spacecraft should observe (Figure 2c). The comparison of these curves to the original observational time series helps one to assess whether the apparent temporal variations indeed can be explained in terms of a moving MP/BL with a fixed structure. We believe that that is true to a large extent in the present example.

Any displacement of the MP/BL, be it driven by the external solar wind pressure or by internal phenomena, in general gives rise to the formation of surface waves on the MP/BL, as the displacement will be coupled to the tailward flow of the shocked solar wind plasma in the magnetosheath. The ratio of the amplitude of the motion relative to its wavelength determines whether a one-dimensional or a surface geometry is appropriate. We have found that reconstruction methods often show that the observed time is largely due to motion of a boundary with a fixed (often 1D) structure. This forms a baseline against which to check for the presence of time-dependent physical processes that significantly alter MP/BL structure. The 30 s averaged boundary speeds have a normal distribution with a variance of typically 20 km/s, though speeds in excess of 100 km/s are possible. Boundary acceleration is often significant, as also found from multi-spacecraft single-crossing analysis. Reconstruction techniques can also give information about boundary structure, such as density substructure [*De Keyser et al.*, 2004], which constrains the possible boundary layer formation mechanisms.

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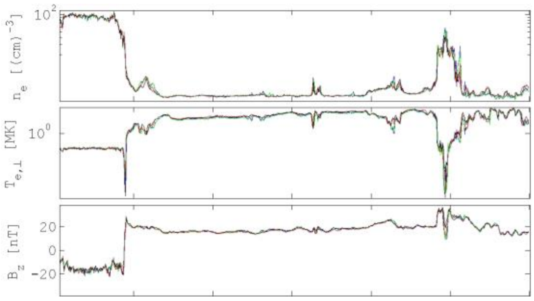

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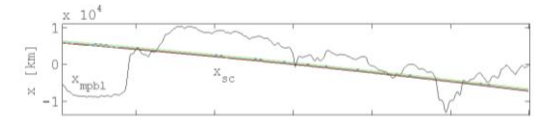

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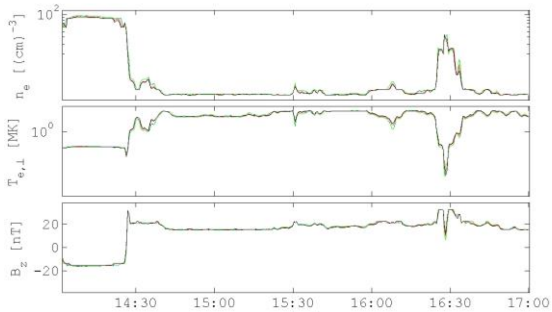

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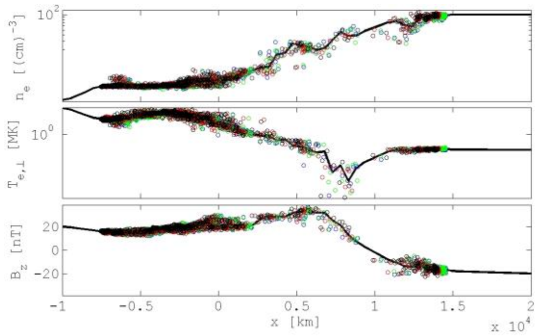


Figure 2: Reconstruction for a Cluster MP/BL pass on April 23, 2001. (a) Time profiles of electron density n_e, electron perpendicular temperature $T_{e\perp}$, and magnetic field B_z; (b) Position of the MP/BL and the spacecraft trajectories (C1–C4); (c) Time profiles predicted from average spatial profiles and knowing the MP/BL position; and (d) Spatial profiles of n_e, $T_{e\perp}$, and B_z. (C1 black, C2 red, C3 green, C4 blue; x is the outward normal).

Once we are confident that we know the actual position of the magnetospheric boundary – a fundamental characteristic of the terrestrial system, namely its size – as a function of time, one can wonder how it is affected by the external influences on the system. To that end, we compare it to the total solar wind pressure, 99% of which is the ram pressure. We have looked up the available solar wind measurements for this event. In particular, the ACE spacecraft provides near-continuous monitoring of the solar wind from its vantage position around the Sun–Earth L1 point. Allowing for a 5200 second solar wind propagation time delay from L1 to the Cluster observation site, Figure 3 compares the MP/BL position obtained from the reconstruction to the time-shifted solar wind ram pressure; the anti-correlation between both is obvious. That implies that, for this particular time interval, the position of the MP/BL is controlled completely by the solar wind ram pressure, with Figure 3b giving the transfer function. In other words, the size of the terrestrial system is completely determined by this one characteristic parameter of the external driver.

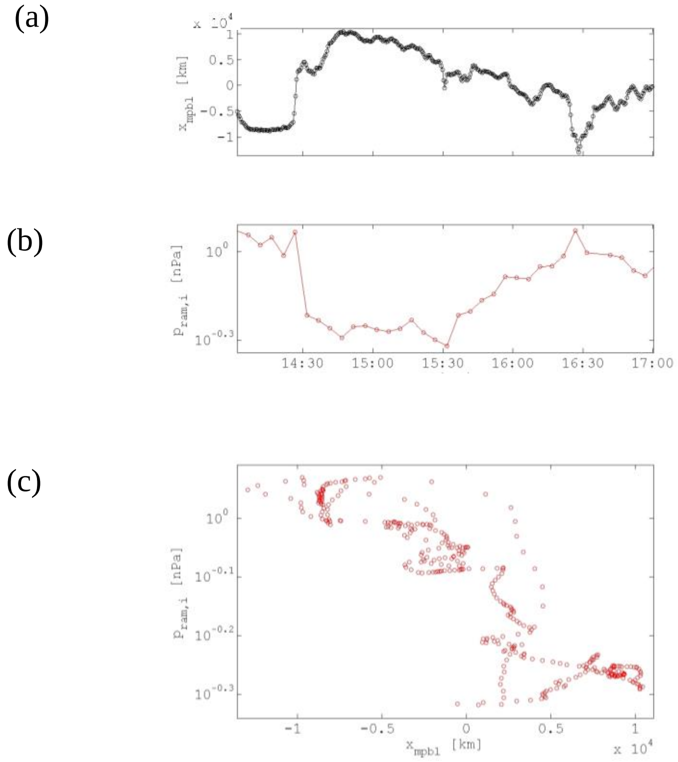
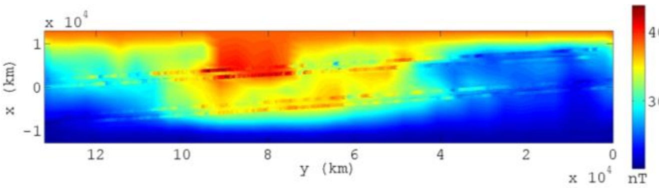


Figure 3: Correlation between solar wind pressure and MP/BL position. (a) MP/BL position on April 23, 2001, as reconstructed from in situ Cluster data. (b) Solar wind ram pressure p_{ram} from ACE measurements, time shifted to account for the solar wind propagation delay from ACE to Cluster. (c) Anti-correlation between p_{ram} and MP/BL position.

(a)



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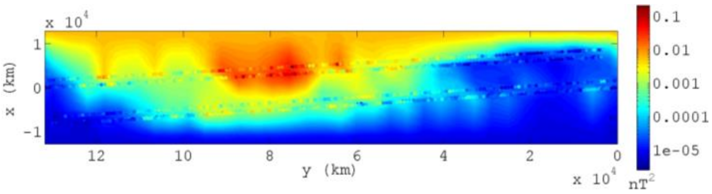

Figure 4: Two-dimensional reconstruction of a surface wave on the MP/BL in a reference frame that moves with the wave. The magnetosheath is at the top, the magnetosphere at the bottom, the sun to the right, the tail to the left. The straight lines with colored patches represent the measured data along the spacecraft tracks as the spacecraft observe two wave periods on November 25, 2001; the tracks of C1 and C3, and of C2 and C4, respectively, nearly coincide and essentially overlap on the plots. (a) Magnetic field strength (from the FGM magnetometer). (b) Perpendicular magnetic wave intensity in the frequency range 0.3-10 Hz (from the STAFF instrument). Note that a reconstruction plot can be made for any kind of measurement [De Keyser et al., 2004].

3. SELF-GENERATED MAGNETOSPHERIC DYNAMICS

From the example discussed in the preceding section, it may seem that the shape of the magnetospheric boundary and the waves traveling downtail along it are fully controlled by the external conditions in the solar wind. While this may be true to a large degree, it is not necessarily so. Indeed, there are phenomena that generate displacements of the MP/BL as the result of intrinsic dynamic properties. Boundary motion can also be induced by a plasma instability, such as the Kelvin-Helmholtz instability [see *Sckopke et al.*, 1981; *Fitzenreiter and Ogilvie*, 1995; *Owen et al.*, 2004, and references therein] in which the free energy implied in the shear flow along the MP/BL drives a surface wave. Especially when the Earth is embedded in a fast solar wind stream the flow shear may be significant. The Kelvin-Helmholtz instability may be suppressed for certain orientations of the interplanetary magnetic field, because of the additional work involved in counteracting the magnetic field line curvature pressure. Nevertheless, at times, Cluster has observed the MP/BL to move in a regular, quasi-periodic, oscillatory fashion, sometimes for several hours long. Typical surface wave frequencies are 0.001–0.05 Hz. Such events are strongly indicative of the presence of the Kelvin-Helmholtz instability, although some solar wind pressure variations might play a minor role in modulating the oscillations.

Using the idea of empirical reconstruction as discussed in the previous section, and also assuming the tailward motion of surface waves to correspond to a fixed wave speed, a two-dimensional reconstruction of the wave structure can be obtained, especially in the case of periodic waves [*De Keyser and Roth*, 2003]. Figure 4 shows such a reconstruction obtained from Cluster measurements on November 25, 2001 [for more details, see *De Keyser et al.*, 2004]. By producing a global picture of the shape of the surface waves, and by putting data from all instruments in the same topological context, the reconstruction systematizes a huge amount of Cluster data, which furthers our understanding of the physical processes involved. In the November 25, 2001 case, the strong tailward magnetosheath flow strongly suggests that the Kelvin-Helmholtz instability was the cause of an extended period of MP/BL waves, indeed. Note that, while the solar wind conditions are still important in creating the environment for the onset of the instability, the behavior of the system itself can no longer be correlated with a particular external driver.

4. THE INNER MAGNETOSPHERE AND COUPLING TO THE IONOSPHERE

As can be seen on Figure 1, there is a lot of structure inside the magnetosphere. While the overall shape of the magnetosphere and the outer regions of the magnetosphere are dominated by the interaction with the solar wind, the structures in the inner magnetosphere arise as the result of the coupling of the outer magnetosphere with the ionosphere.

One of the aspects of this coupling gives rise to the plasmasphere. This is a doughnut-shaped region quite close to Earth, located completely on closed geomagnetic field lines, which is progressively filled with charged particles that escape from the upper ionosphere, and which in principle are moving along a field line, bouncing between their mirror points in the northern and southern hemisphere, and corotating with the geomagnetic field. At the same time, the solar wind-magnetosphere interaction creates an overall electric potential difference across the magnetosphere, which dictates the electric field environment in the rest of the magnetosphere. Obviously, in the outer regions of the plasmasphere the electric field associated with corotation and the solar wind induced electric field must interact. While the former is essentially constant, the latter is highly variable, so that the outer plasmasphere is a dynamic region as well.

This is illustrated in Figure 6. This figure shows Cluster observations of the dynamic electrostatic wave spectrograms in the frequency range 2-80 kHz obtained by the WHISPER instrument on April 11, 2002 [*Darrouzet et al.*, 2004, 2005]. From the emissions at the electron plasma frequency f_{pe}, which are fairly obvious in these spectrograms, one can deduce the ambient electron density n_e, from the relation $f_{pe}\{\text{kHz}\} \sim 9\ [\ n_e\{\text{cm}^{-3}\}]^{1/2}$). Since the energies of plasmaspheric particles are often too low (a few eV) to be easily detectable by plasma spectrometers, largely because of the effects of spacecraft charging, this is one of the only alternatives we have to determine the plasma density there. The figure shows a time interval centered around perigee. At perigee, the spacecraft reside well within the plasmasphere, where the density is high, such that the electron plasma frequency is beyond the measured frequency range. In the outer skirts of the plasmasphere, however, the density and the corresponding plasma frequency drop to measurable levels, around 40 kHz. But at the edges of the plasmasphere, we observe short-duration peaks in density, with plasma frequency peaking at slightly below 80 kHz, which correspond to so-called ‘plasmaspheric plumes’. The peaks observed on the inbound pass (IP) and on the outbound pass (OP) correspond to the same plume, sampled at different local time, magnetic latitude, and later in its evolution.

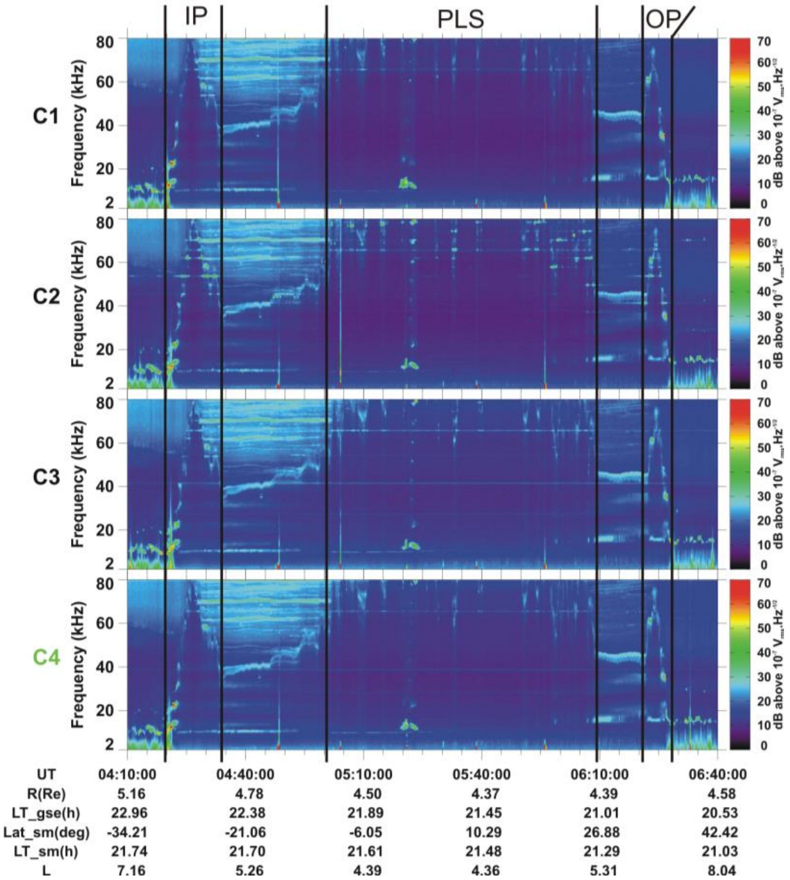

Figure 5: Spectrograms obtained in the inner magnetosphere on April 11, 2002, by the WHISPER instruments on the four Cluster spacecraft. The panels show the power spectral density of electrostatic waves in the range 2-80 kHz. The dominant feature is the wave emission at the electron plasma frequency, which is related to the plasma density. The center of the time interval corresponds roughly to perigee, at a geocentric distance of 4.36 Earth radii. At that time, the spacecraft are well inside the plasmasphere (PLS), characterized by a high density, so that the electron plasma frequency is above 80 kHz and cannot be observed. In the outer regions of the plasmasphere the density drops and the emission is visible at around 40 kHz, but both before and after the plasmasphere pass one observes a brief high-density interval, with a density peaking at slightly less than 80 kHz. These correspond to 'plasmaspheric plumes' (IP: inbound plume crossing; OP: outbound plume crossing). Outside the plumes, in the plasmatrough, the density is extremely low. [Figure adapted from Darrouzet et al., 2005]

While the measurements represent a local sampling of the structure, the four Cluster electron density profiles allow one to extract interesting information. In particular, the orientation and motion of the surfaces bounding the plumes can be obtained by using a four-point technique from the individual spacecraft positions and the time delays between the crossing of the inner and outer edges of the plumes by the four spacecraft, respectively, at least if one assumes those edges to be planar surfaces travelling at a constant velocity along its normal. It is also possible to compute the spatial gradient of the electron density from simultaneous measurements, but only if all four spacecraft are embedded in the same structure at the same time; in practice, this means that the spacecraft separation (which is tunable during the mission) should be smaller than the physical scale of the structures in which one is interested.

These new Cluster analysis tools help to develop a more global picture of the plumes and their evolution, which is related to geomagnetic activity. Belgian researchers have also endeavoured to compare this information with remote sensing techniques, which have matured to the point that they can produce images of at least the inner plasmasphere, such as produced by the EUV imager on the IMAGE spacecraft [*Darrouzet et al.*, 2005]. These remote sensing techniques create a global picture with line-of-sight integrated information. Comparing that information with in situ Cluster measurements results in mutual benefits.

5. CONCLUSIONS

Even though we are, at present, far away from modelling the terrestrial magnetosphere as a whole, the 'systems' point of view proves to be an interesting one. We have illustrated how the system is subject to external drivers, how dynamic behaviour may be generated internally in the system, and how different regions are coupled. At the same time, we have indicated how Belgian researchers are contributing to the quest for understanding the physical principles that underlie the complex behaviour of the overall system through an active participation in the Cluster mission, presently the flagship European magnetospheric research endeavour.

Apart from the intellectual goal of understanding magnetospheric physics, we cannot ignore the practical importance of such knowledge for predicting 'space weather'. As our society creates and utilizes technological and human assets in Earth orbit or beyond, the need for a rational management of these assets becomes mandatory. A proper knowledge of the environment these assets have to work in seems therefore unavoidable.

ACKNOWLEDGEMENTS

Data from the Cluster mission were kindly provided by M. W. Dunlop (FGM; Rutherford Appleton Laboratory, UK), H. Rème (CIS; CESR, Toulouse, France), C. J. Owen (PEACE; Mullard Space Science Laboratory, UK), G. Paschmann (EDI; International Space Science Institute, Berne, Switzerland), P. Décréau (WHISPER; LPCE/CNRS-Université d'Orléans, France), and N. Cornilleau-Wehrlin (STAFF; CETP/CNRS-Vélizy, France). ACE data were provided by the SWEPAM instrument team (D. McComas). The authors acknowledge support by the Belgian Federal Science Policy Office, mainly through the PRODEX programme.

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