FORMATION OF THE CUSP AND DAYSIDE BOUNDARY LAYERS AS A FUNCTION OF IMF ORIENTATION: CLUSTER RESULTS

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ABSTRACT

This summary, which follows from a presentation at the Cluster – Double Star symposium for the fifth year anniversary of Cluster in space, aims at addressing the solar wind – dayside magnetosphere large-scale interaction. We summarize a number of Cluster results pertaining to the structure of the high-altitude cusp regions of the terrestrial magnetosphere and to the formation of the dayside boundary layers as a function of IMF orientation. These have been the topic of numerous studies using the multi-spacecraft data from the ESA-Cluster mission. We explore the role played by the cusps for solar wind plasma penetration and transport into the magnetosphere by examining the effects of the orientation of the interplanetary magnetic field (IMF) and of the occurrence of the magnetic reconnection process.

1. INTRODUCTION

The overall nature of the interaction of the solar wind with the Earth's magnetic field is now quite familiar. The terrestrial magnetic field is an obstacle to the solar wind. The solar wind is diverted and decelerated at the bow shock, located approximately 15 Earth radii (R_E) Sunward of the Earth. The transition through the shock gives rise to a hot plasma region, the magnetosheath, which has an interface with the Earth's magnetic field at the magnetopause (Fig. 1a, b). The magnetosphere is a magnetic cavity that lies inside the magnetopause and arises due to the confinement of Earth's magnetic field by the solar wind. Because the magnetospheric field is approximately dipolar, it possesses two singularities at the northern and southern poles where the topology of the magnetic field is not well known. These are the magnetospheric cusps (Fig. 1).

The location and magnetic topology of the cusps make them a prime site for solar wind plasma penetration into the magnetosphere (e.g. [1] and [2]). At low and middle altitudes (below 5 R_E), the cusps are well explored. They are known to extend 1-2° in latitude, 1-2 hours in local time and are characterized by the presence of low energy solar wind ions and electrons [3].

Low and mid-altitude satellites have provided major advances in the understanding of the role and characteristics of the cusp, but such spacecraft only remotely sense the solar wind interaction with the outer cusp which actually occurs at higher altitudes. The early evidence for the existence of a slow flow region of magnetosheath plasma outside of a probable magnetopause indentation (although now thought to be located inside the magnetopause) were outlined by [4], [5] and [6], using the HEOS-2 data. While [5] referred to that region as the 'exterior cusp', [4] and [6] proposed the existence of a 'stagnation region', and of an adjacent 'entry layer', which could permit plasma and momentum entry into the magnetosphere through eddy diffusion at their boundary (see also [7]). Their picture of the cusps was therefore close to an aerodynamic view, and the characteristics of the 'stagnation region' compared with those inferred from the model of [8] for this high-altitude region. Although the term 'stagnant' is often used in the literature since these early studies, plasma stagnation is qualitatively not obvious to occur in such a dynamic region, as noticed by [9].

More recently, the Interball spacecraft [e.g. 10] and the Polar spacecraft [e.g. 11] observed the high-altitude regions of the dayside magnetosphere with high data sampling rates. The Interball spacecraft predominantly passed at high latitudes and altitudes in the cusp and plasma mantle regions but did not sample the most central part of the high-altitude cusp. On the other hand, the Polar spacecraft has an apogee of 9 R_E and only rarely had access to the magnetosheath. Thus, it did not permit extensive studies of the high-altitude cusp and its interface with the magnetosheath [12].

Despite these earlier explorations, the cusps at high altitude in the vicinity of the magnetopause, and especially their dependence on the properties of the

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interplanetary magnetic field (IMF), are only now being investigated fully using results from Cluster.

2. ORBIT AND INSTRUMENTATION

The European Space Agency Cluster mission was launched in the summer of 2000, and is unique. It is composed of four identical satellites, each with a suite of 11 instruments that study plasmas and electromagnetic fields. It has a polar orbit with a perigee of 4 R_E and an apogee of 19.6 R_E, and its line of apside is along the Sun-Earth direction. The spacecraft thus sample the high-altitude cusp and solar wind during spring and the mid-altitude cusp in summer and autumn, as seen by the orbits shown in Fig. 1a and 1b. The average separation between the spacecraft has varied throughout the mission from ~100 km to ~1 R_E. The spacecraft form a tetrahedron configuration which is optimized in the high-altitude cusps.

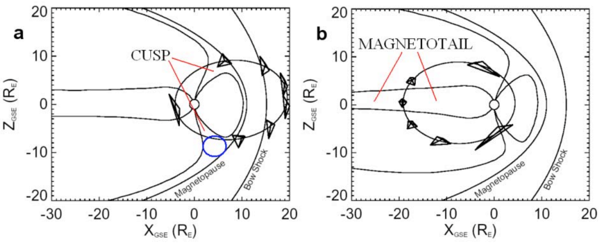

Fig. 1: The Cluster orbit showing its passage through the different regions of the magnetosphere during the spring (a: left) and fall (b: right) seasons. The Sun is located to the right of each panel and in this representation Cluster moves clockwise (counter-clockwise) in spring (autumn). The topology of the tetrahedral spacecraft configuration is shown at a number of times. The high-altitude cusp (circled in blue for the southern hemisphere in the left panel) is only sampled during spring (see text for further description).

The high capabilities of the onboard instruments and the tetrahedral spacecraft configuration of the Cluster fleet both permit very accurate and precise determination of the physical particle and wave phenomena and small-scale dynamical analysis. The data which were primarily used to obtain the results summarized in this paper are the Cluster Ion Spectrometry (CIS) experiment [13], the Flux-Gate Magnetometer (FGM [14], and the Plasma Electron And Current Experiment (PEACE) [15]. The CIS package is capable of obtaining full three-dimensional ion distribution functions with a good time resolution (down to 1 spin resolution ~ 4s). CIS is composed of two complementary sensors, the CODIF sensor (COmposition and DIstribution Function analyser) which handles a Time of Flight system in order to resolve ion masses, and the Hot Ion Analyser (HIA) that does not separate ion species but has a better angular resolution. The FGM magnetic field instrument can produce high-time resolution (67 and 22.4 Hz) data at high absolute accuracy (< 0.1 nT). The PEACE electron data came from both the LEEA (Low Energy Electron Analyzer) and HEEA (High Energy Electron Analyzer) sensors, which essentially cover the energy range from 0.6 eV to 26 keV. ACE data were also used to monitor the solar wind conditions.

After five years of Cluster operations, the exploration of the high-altitude cusps has reached a level of maturity. The following discussion presents an overview of where the subject is at this time, i.e. of the Cluster – Double Star symposium. It is not exhaustive; it focuses on the large-scale structure/formation of the high-altitude cusp and dayside boundary layers.

3. PLASMA ENTRY MECHANISMS

Prior to Cluster, there was much uncertainty as to what determined the overall cusp structure. Some workers proposed an "inward sag" or indentation of the magnetopause at the cusp, leading to a range of complex flows and shock waves (see [4], [6], [16] and introduction). As is summarised in this paper, the results from Cluster have established convincingly that many properties of the high-altitude cusp can be attributed to magnetic reconnection processes occurring at the magnetopause. The way reconnection influences the cusp depends on the orientation of the IMF.

Below we summarize few expectations from the occurrence of reconnection before giving the observational evidence in the next sections. Fig. 2a and 2b show in qualitative terms how the IMF influences the cusp properties. Readers may find it useful to refer to this when examining later figures.

For southward IMF, magnetic reconnection occurs in the sub-solar region of the magnetopause (labelled "X-line" on Fig. 2a). This leads to a large-scale convection electric field in the cusp region which results in a "velocity filter" effect on the entering solar wind plasma [e.g. 17]. The plasma mantle, at the poleward edge of the cusp, is formed by the tail of the dispersed cusp plasma and so contains mainly tailward and up-flowing plasma.

For northward IMF, Sunward convection is present in the cusp, probably due to magnetic reconnection occurring at the high-latitude magnetopause tailward of the cusp. Under such conditions, the magnetosheath and magnetospheric fields are anti-parallel in the lobe region (labeled "X-line" in Fig. 2b). This northward IMF scenario should lead to the absence of a plasma mantle and a different large-scale plasma flow behavior in the whole region.

The formation of the dayside magnetopause boundary layers, at low latitudes, is explained by the occurrence of magnetic reconnection in the sub-solar region under southward IMF. It leads to the presence of open field lines, inside the magnetopause, which are connected to the solar wind and therefore contain solar wind plasma. However, the presence of low-latitude boundary layers at the dayside magnetopause under northward IMF is not well understood. It has long been thought that reconnection cannot account for their formation. Diffusion through wave – particle interactions has been proposed, but a number of studies (see review by [18]) have precluded this mechanism since it may not explain the existence of boundary layers thicker than 0.5 R_E (and would further only become effective after time has elapsed along the flanks). Similarly, the Kelvin-Helmholtz instability has been proposed to account for the flank low-latitude boundary layer formation [e.g. 19]. But, due to the lack of velocity shear, it may not explain their formation at the dayside magnetopause either. An alternate scenario comes from the model of [20], where magnetosheath field lines under northward IMF may reconnect in both the southern and northern lobes to create newly closed field lines. These field lines would lead to the formation of a boundary layer at the dayside magnetopause which contains trapped magnetosheath plasma of solar wind origin.

We now explore (section 4) the consequences of reconnection on the structure of the high altitude cusp. The formation of the dayside boundary layers is discussed more specifically in section 5 thereafter.

4. LARGE-SCALE STRUCTURE OF THE HIGH-ALTITUDE CUSPS

In this section we describe the results obtained from both large-scale statistical studies and single event analysis of Cluster high-altitude cusp crossings.

4.1 Statistical results

A survey of three years of Cluster data in the high-altitude cusp has been undertaken using magnetic field and ion data from the FGM and CIS instruments respectively. The aim was to establish the global magnetic field and plasma properties of the high-altitude cusp and the nature of the boundaries with the surrounding regions as a function of the IMF orientation [21, 22]. Because the cusps respond quickly and readily to solar wind conditions, the technique accounts for cusp displacement, as well as for radial magnetopause motion [21].

Fig. 3 shows the spatial distribution of the ratio of the measured magnetic pressure ($B^2/2\mu_0$) to that estimated from the semi-empirical vacuum magnetic field model of [23] (T96). The distribution shows the presence of a transition region between the magnetosheath and magnetosphere which is referred to as either the high-altitude cusp or "exterior cusp". It is characterized by the presence of cold and dense plasma of solar wind origin [21], resulting in a diamagnetic effect and leading to a region of depressed magnetic pressure when compared to the T96 model.

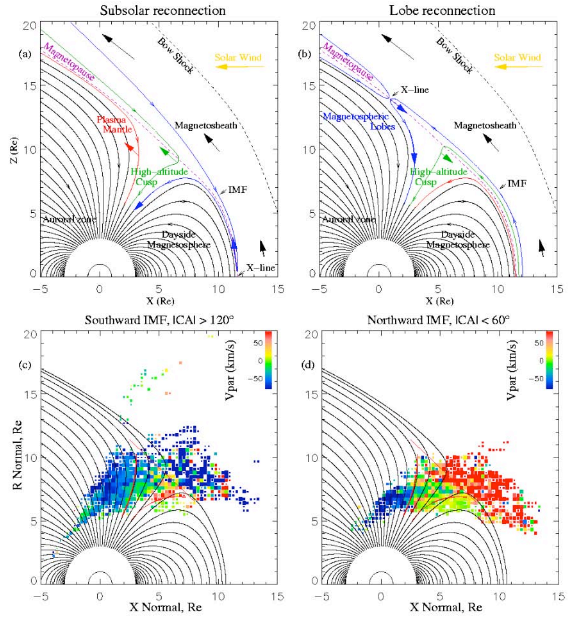

Fig. 2: Panels (a) and (b) show schematically the large-scale structure of the magnetic field topology and of the plasma flows in the high-altitude cusp and surrounding regions for (a) southward and (b) northward IMF directions. The location of the X-line is indicative of an approximate location of the reconnection process for both IMF geometries. The dashed purple (black) line is the approximate location of the magnetopause (bow shock) and the colored arrows are indicative of the plasma flow directions expected for each case (yellow – solar wind, black – magnetosheath, blue – reconnection-associated, green and red – large-scale convection). The lower panels show spatial distributions of the field-aligned plasma flows in the high-altitude cusp region when IMF conditions are restricted to (c) southward and (d) northward IMF orientations. The flow magnitude (in km/s) is shown by the color palettes. The plasma data are averaged over bins of 0.3 RE and the sizes of the squares are proportional to the number of samples but are saturated at the maximum (0.3 RE) for more than 20 samples. The background field lines are calculated from the T96 model: note that in the northern hemisphere, a parallel flow is directed Earthward.

Using a combination of the magnetic field and plasma distributions, Cluster has unambiguously demonstrated the presence of three distinct boundaries surrounding the high-altitude cusp [21]. Guidelines for their positions are shown by the red lines in Fig. 3. Both statistical and event studies have indeed highlighted the presence of boundaries which separate the high-altitude cusp from (a) the lobe at the poleward edge, (b) the dayside magnetosphere at the equatorward edge, and (c) from the magnetosheath outward.

Fig. 2c and 2d show the distributions of the plasma flow aligned with the magnetic field for southward and northward IMF orientations respectively [22]. Southward (Northward) IMF orientation corresponds to observations occurring during lagged IMF absolute clock angle measurements greater (lower) than 120º (60º). For southward IMF, solar wind plasma penetrating the cusp is observed to be flowing earthward (parallel flows are red) and primarily at the equatorward side of the cusp (Fig. 2c). This is to be expected if magnetic reconnection occurs at the low latitude magnetopause (Fig. 2a). Although not shown here, the field-aligned flows are correlated with a large tailward convection (perpendicular flow), which is compatible with the scenario shown in Fig. 2a.

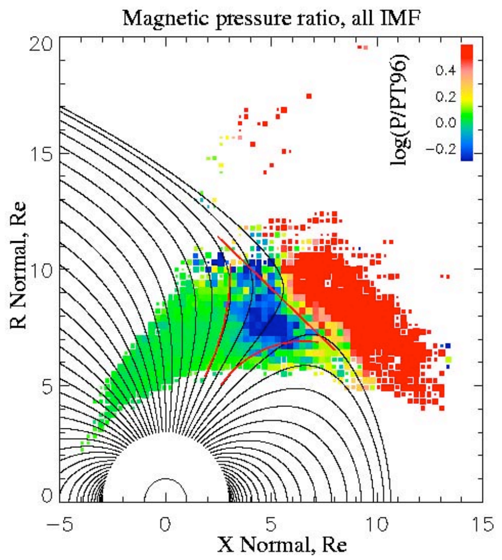

Fig. 3: Spatial distribution of the ratio of the measured magnetic pressure (B2/2μ0) to that calculated from the T96 model. The color palette illustrates the amplitude of the magnetic pressure ratio with blue indicating a small measured magnetic pressure. In this figure all IMF conditions are taken into account. The three red lines surrounding the magnetic field cavity correspond to approximate boundaries of the high-altitude cusp. Other details are given in the caption for Figure 2.

For Northward IMF, no downward flows are observed at the equatorward edge of the cusp (Fig. 2d), but field-aligned downward flows are rather seen near the boundary with the lobes at higher latitudes. Although not shown, a slight sunward convection is also present near the poleward boundary of the cusp, and is correlated with the aforementioned flows. Thus, the statistical properties of the region are this time compatible with magnetic reconnection occurring at high latitudes, at the magnetopause in the lobes, as shown in Fig. 2b. The location of the Earthward plasma flows and orientation of subsequent convection in the high-altitude cusp are compatible with expectations from magnetic reconnection as introduced in section 3.

4.2 Single event illustrations

To illustrate these statistical results, we now present the magnetic field and plasma properties for two individual Cluster encounters with the high-altitude cusp. Fig. 4 displays Cluster data for two traversals of the northern cusp on April 1st, 2003 and February 4th, 2001 when Southward and Northward IMF conditions existed respectively. The former event has been studied by [24] and [25], and the latter by [26].

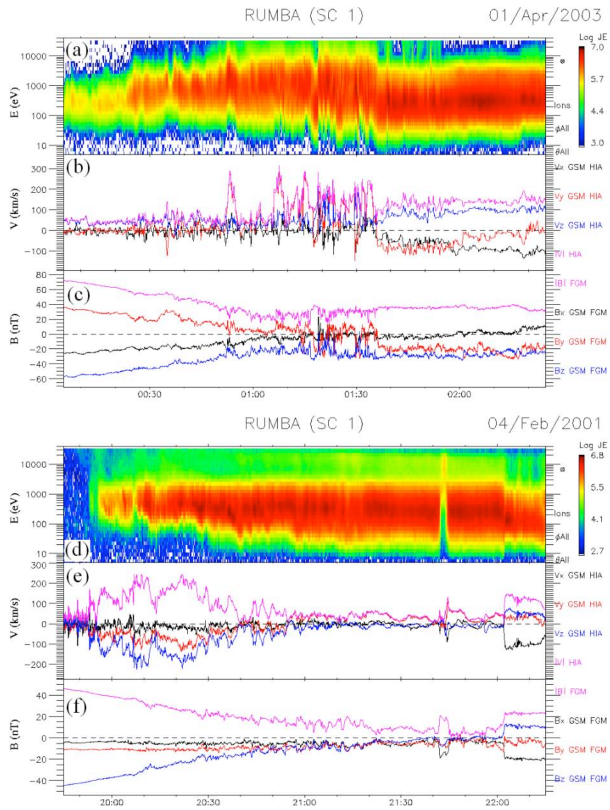

Fig. 4: Cluster time-series of two selected outbound traversals of the high-altitude cusp region on April 1st, 2003 for southward IMF (upper part) and on February 4th, 2001 for northward IMF (lower part). The three panels show: the ion energy-time spectrogram, the ion velocity components, where all ions are assumed to be protons, and the magnetic field components. Magnetopause crossings are located at 01:40 and 22:02 UT respectively for the two events.

At 00:05 UT on April 1st, 2003 Cluster was in the plasma mantle characterized by predominantly up-flowing ions ($V_Z > 0$ in panel b). The mean energy of the ions (panel a) and their velocity gradually increased until 01:30 UT as the spacecraft moved towards higher altitudes and lower latitudes. This is consistent with the velocity filter effect described earlier [17]. The highest velocities were observed at the lowest latitudes and the whole high-altitude cusp region showed very large ion speeds, mainly duskward and upward (V_Y and $V_Z > 0$). The magnetopause was encountered at about 01:40 UT.

Such plasma properties are consistent with the occurrence of magnetic reconnection below the spacecraft location, at the low-latitude magnetopause.

On February 4th, 2001 Cluster first sampled a region basically void of plasma (panel d) until high-speed downward flows at 19:55 UT were detected ($V_Z < 0$ in panel e). This void region is the northern magnetospheric lobe, so Cluster observed no plasma mantle. Furthermore, large downward flows were detected at high magnetic latitudes, which, together with the absence of a plasma mantle, is consistent with the occurrence of magnetic reconnection at the lobes. Reversed velocity dispersion is subsequently observed, with velocities gradually decreasing until about 21:30 UT, and then staying small in the high-altitude cusp until 22:02 UT. This is consistent with the reversed plasma flow pattern depicted in Fig. 2b for northward IMF conditions and lobe reconnection. The spacecraft encounter the magnetopause at 22:02 UT. This crossing also shows an encounter with the equatorward boundary of the high-altitude cusp at ~21:43 UT (see [26]).

5. BOUNDARY ANALYSIS AND FORMATION OF THE BOUNDARY LAYERS

In this section we explain the major difference, arising from the above described structure of the high-altitude cusps, in terms of boundary structure and subsequent solar wind plasma transport and circulation in the magnetosphere.

5.1 Southward IMF case

Under southward IMF, magnetic reconnection occurs in the sub-solar region of the magnetopause. It leads to the formation of a rotational discontinuity which propagates northward and tailward (for the northern hemisphere). Solar wind plasma can enter through the boundary and form a low-latitude boundary layer at the dayside magnetopause. Solar wind plasma ultimately feeds the whole cusp region (see [24, 25] for more details), and as a result of large-scale tailward convection the plasma mantle (i.e. a boundary layer) is formed at the poleward edge of the cusp, as seen in the beginning of the interval in panels a and b of Fig. 4.

The resulting outer boundary between the high-altitude cusp and the magnetosheath may also be a rotational discontinuity. After five years of Cluster studies, this boundary is now called the magnetopause. The analysis of the magnetopause crossing of April 1st, 2003 by [24] and [25] indeed suggest that the cusp – magnetosheath boundary is rotational in nature, as shown by the results of the deHoffmann-Teller analysis and Walén test of Fig. 5a. The deHoffmann-Teller velocity is large and directed predominantly northward. This large convection velocity is compatible with northward acceleration of the entering plasma so that the plasma in the high-altitude cusp region, inside the magnetopause, has larger velocities than the adjacent magnetosheath region itself. This characteristic is well observed in panel b of Fig. 4. The high-altitude cusp is thus characterised by very large velocities, in accordance with expectations from [9]. However, this fact strongly contrasts with the northward IMF case discussed next.

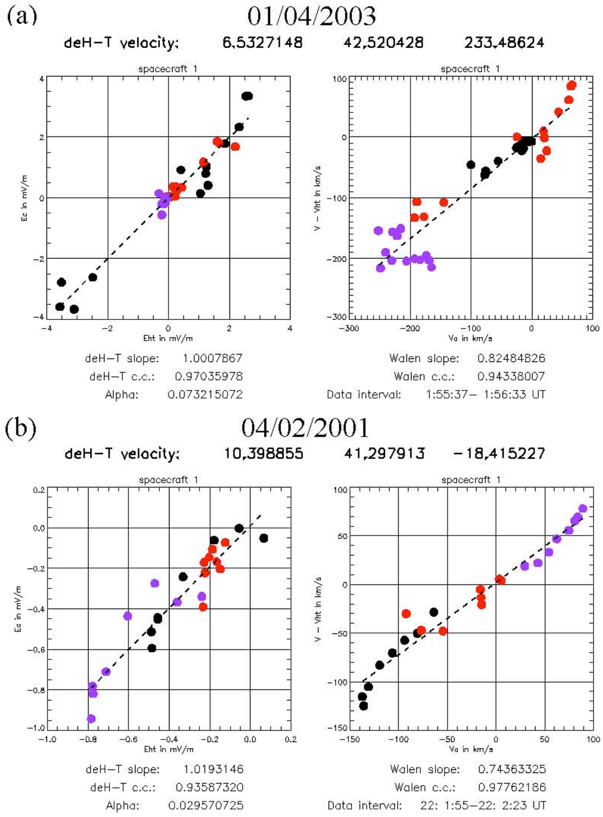

Fig. 5: Results from the deHoffmann-Teller analysis and Walén test for the two high-altitude cusp – magnetosheath boundaries encountered on (a) April 1st, 2003 and (b) February 4th, 2001, respectively. For each case, the deHoffmann-Teller velocity is given, as well as the values of the slopes and correlation coefficients of the analysis. Also, the time intervals and the values of alpha (temperature anisotropy term, cf. [24]) are given.

5.2 Northward IMF case

Under northward IMF, magnetic reconnection rather occurs in the lobes, tailward of the cusp. Large downward flows are observed at the poleward edge of the cusp and no plasma mantle is observed at all (see previous sections and Fig. 4). This is the result of the presence of a low sunward convection in the high-altitude cusp region.

The occurrence of lobe reconnection results in the sunward propagation of the magnetopause rotational discontinuity, as suggested by [27]. Reference [26] first showed that the deHoffmann-Teller analysis at the high-altitude cusp – magnetosheath (or magnetopause) boundary gives a very slow, sunward and southward velocity for the event of February 4th, 2001 (Fig. 4). This result is shown in Fig. 5b together with that of the Walén test, which is roughly satisfied. This deHoffmann-Teller velocity is compatible with the slow sunward convection in the cusp region. It is further consistent with the presence of sub-alfvenic flows in the adjacent magnetosheath, as a result of the presence of a plasma depletion layer (PDL) [28, 27]. Indeed, without the presence of such sub-alfvenic flows in the PDL, the reconnection site in the lobes would be swept tailward and a slow, sunward deHoffmann-Teller velocity would not be observed for this boundary.

Finally, the occurrence of a slow sunward convection together with low parallel flows in the high altitude cusp (after reflection of the penetrating plasma at low altitude and their return to the satellite) results in both low parallel and perpendicular plasma velocity in the high-altitude cusp. That region, under northward IMF, was therefore termed the “stagnant exterior cusp” by [26]. While the high-altitude cusp can be strongly convective under southward IMF [9], it is thus rather stagnant under northward IMF [27].

5.3 Solar wind plasma circulation and formation of the plasma sheet

As stated in section 3, the presence of dayside low-latitude boundary layers under northward IMF is not well understood. Wave-particle interactions, Kelvin-Helmholtz instability and double high-latitude reconnection have been proposed as potential mechanisms for their formation. The two former processes are thought to be insignificant at the front-side of the magnetosphere. However, they may become dominant along the flanks of the magnetosphere in terms of plasma transfer efficiency. Numerous current studies aim at disentangling the potential role of each process.

Fig. 6a and 6b present the expected large-scale solar wind plasma circulation and magnetic field topology arising from the occurrence of magnetic reconnection, respectively in the context of southward and northward IMF orientations. Circulation of solar wind plasma from the sub-solar region, through the cusp and plasma mantle under southward IMF (Fig. 6a) supposedly leads to plasma rarefaction (dispersion effect). Solar wind plasma may ultimately get access to the mid-tail regions of the magnetosphere after its passage via the distant tail region (Fig. 6a). Distant tail reconnection leads to sunward convection and the associated adiabatic heating renders the plasma sheet hot and (already) tenuous, as is usually observed under southward IMF conditions in the mid-tail regions. Under northward IMF, the scenario of double high-latitude reconnection leads to the formation of dayside, newly closed boundary layers containing cold and dense plasma of solar wind origin. The subsequent convection of the plasma along the flanks may ultimately permit to fill the mid-tail plasma sheet with cold and dense plasma, without significant adiabatic heating, as compared to the southward IMF scenario.

The investigation of the relative efficiency of these plasma transfer processes has regained interest in the context of the formation of the plasma sheet, which has been shown by numerous studies to be hot and tenuous under southward IMF, but denser and colder under northward IMF [29]. The Cluster mission will be further used in the forthcoming years to address these issues. Its multi-spacecraft capabilities will be of particular importance in trying to assess the actual plasma transport that may result, e.g., from the Kelvin-Helmholtz instability [30].

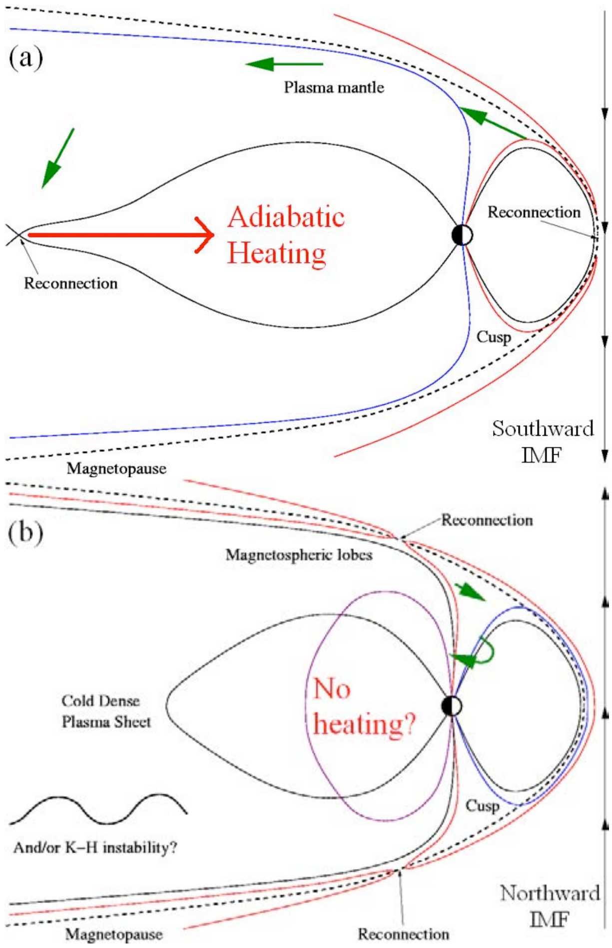

Fig. 6: Schematic of solar wind plasma circulation and magnetic topology of the magnetosphere in the context of magnetic reconnection for (a) southward and (b) northward IMF directions.

6. CONCLUSIONS

After five years of Cluster operations, major advances have been obtained concerning the structure of the high-altitude magnetospheric cusps and surrounding boundaries and boundary layers. The dominant role of magnetic reconnection in determining the large-scale structure of the cusp as a function of IMF orientation has been revealed. The measured plasma and magnetic field properties are consistent with this interpretation, indicating that the cusp is a structure that cannot be considered in isolation from the rest of the high-altitude magnetosphere. The overall topology of the cusp and its boundaries are now much clearer, as is their absolute motion, scale, and whether plasma can penetrate them. It appears that the overall circulation of solar wind plasma in the magnetosphere may at least partially be the results of processes occurring at the dayside magnetopause. The formation, location and convective properties of the dayside boundary layers (cusp, low-latitude boundary layer, and plasma mantle) indeed seem to be directly controlled by the occurrence and location of magnetic reconnection. Nonetheless, the Cluster data archive has only begun to be explored. In particular, the cusp encounters that have undergone a full study are still small. While it is a reasonable expectation that the overall picture presented here will be sustained on further analysis, we may expect surprises.

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