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Plasma sheet and magnetosheath plasma mixing in LLBL: Case study

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Abstract

Low latitude boundary layer (LLBL) of the magnetosphere of the Earth is formed due to the mixing of magnetosheath and plasma sheet plasma. The mixing process is studied on the base of Interball/Tail probe observations. The variations of the fluxes of ions (measured by CORALL instrument), electrons (measured by ELECTRON instrument) and particles with energies more than 25 keV (measured by DOK-2 instrument) are analyzed for the case of 21 September 1995 when the satellite intersects LLBL/plasma sheet boundary on the GSM (-4.1, -13.6, 2.2) R_e distance. The variations of the magnetic field measured by MIF instrument are compared with the variations of particle fluxes. The thickness of the boundary region containing plasma from LLBL is estimated. The stress balance across the analyzed boundary is discussed. We find that the plasma pressure inside the LLBL is essential in understanding the pressure balance across the magnetopause.

Keywords: Low latitude boundary layer; Magnetosheath; Plasma mixing; Magnetospheric pressure balance; Interball project

1. Introduction

The low latitude boundary layer (LLBL) has been the subject of many case and statistical studies (see reviews by Lundin, 1988; Eastman, 2003; Němeček et al., 2003, and references therein). The physical nature of LLBL, the region just earthward of the magnetopause where the magnetosheath-like and magnetosphere-like plasmas coexist is of great interest since it could control the rate of mass, momentum, and energy transfer between the magnetosheath and the magnetosphere. The density, temperature and velocity in LLBL are intermediate between the magnetospheric and magnetosheath values. Along the boundary layer local noon to nightside, the flow moves faster and the layer becomes thicker. LLBL represents the ion mixing region, which contains simultaneously dense ions of the solar wind origin and hot magnetospheric ions. Under southward IMF conditions, magnetic reconnection is believed to be one of the dominant processes to form the LLBL (see Haerendel et al., 1978; Fedorov et al., 2003, and references therein). There is to date no consensus about the formation mechanism of the LLBL under northward IMF conditions. Several mechanisms, such as diffusive entry processes (Treumann and Sckopke, 1999, and references therein) and reconnection process at high-latitudes in both hemispheres (Song and Russell, 1992), have been proposed, but their relative importance remains still unclear. The ion mixing region under extended northward IMF (see Hasegawa et al., 2003) is almost always accompanied by field-aligned, bidirectional electrons of a few hundreds eV, which energy is higher than that of typical magnetosheath electrons. The flux of >2 keV electrons, that is, electrons of the

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magnetospheric origin is significantly reduced in the mixing region as compared to that in the region earthward of the mixing region.

Developed theories of LLBL formation suggests that the regime of LLBL formation does not change under conditions of comparatively stable parameters of IMF. At the same time, it is well known that the magnetosheath is a highly turbulent region. The value of turbulent fluctuations in the magnetosheath is much larger than the value of turbulent fluctuations in the solar wind (Lacombe et al., 1995; Schwartz et al., 1996; Sibeck et al., 2000; Němeček et al., 2002; Shevyrev et al., 2003). The possibility of the development of Kelvin–Helmholts instability on the magnetopause also cannot be excluded.

The verification of different theoretical approaches requires the analysis of the data of experimental observations in the conditions of the comparatively stable IMF orientation. The problem of stress balance on the magnetospheric flanks is also not solved to date. In this paper, we select for the analysis the event 21 September 1995 when Interball/Tail probe cross magnetopause, LLBL and the boundary of the plasma sheet of the Earth's magnetosphere when interplanetary magnetic field (IMF) was comparatively stable and IMF B_z component has the northward direction. We analyze the

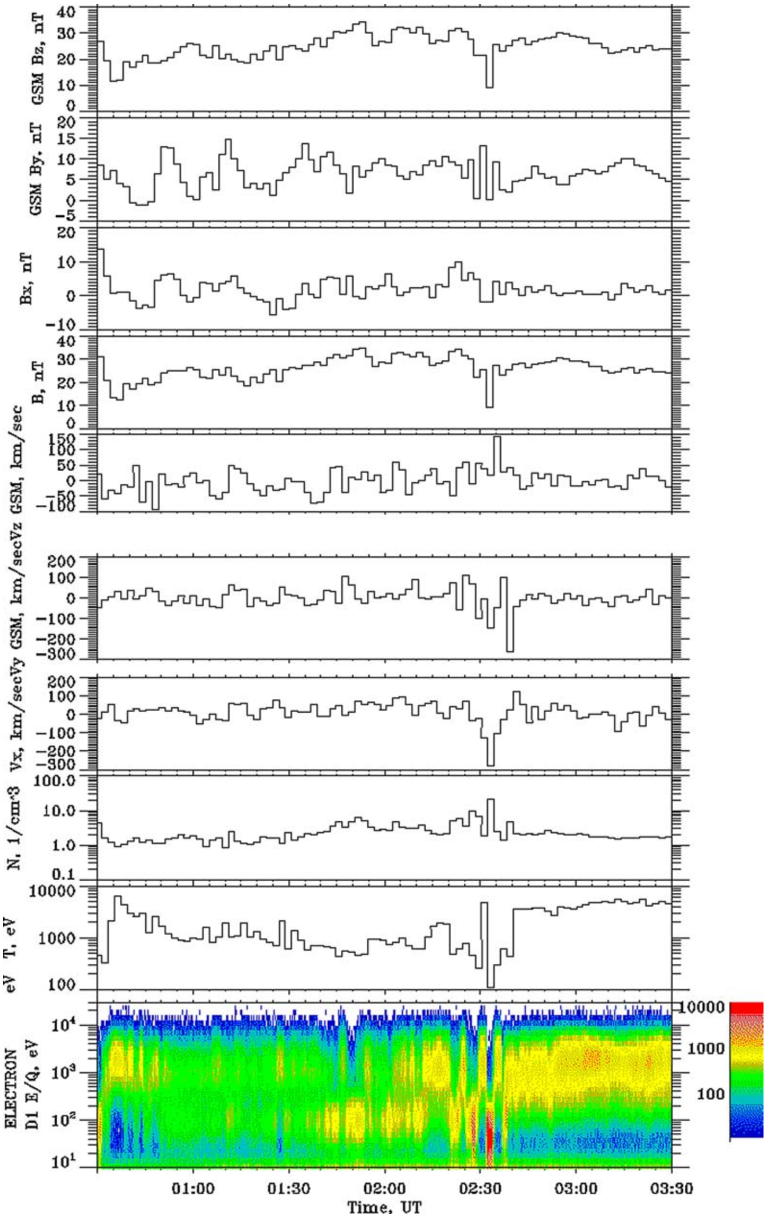

Fig. 1. The variation of the hydrodynamic parameters along the satellite trajectory. Panels a–c show the components of magnetic field and its magnitude. Panels d–f present the velocity components. Density and temperature and of ions are illustrated at the g and h panels. The results of Electron measurements – at the bottom panel i.

change of the regime of plasma flow and investigate the change of such regime (from highly structured thick LLBL to absence of LLBL). We also analyze the distribution of the component of the tensor of plasma pressure across the flow direction in LLBL and show that particle pressure can be considered as the important factor in stress balance at low latitudes.

2. Instrumentation and data analysis

We use data obtained by the Corall low-energy ion experiment (Yermolaev et al., 1997), the Electron low-energy electron experiment (Sauvaud et al., 1997), DOK-2 energetic particle experiment (Lutsenko et al., 1998) and the MIF magnetic field instrument (Klimov et al., 1997) on board the Interball/Tail spacecraft. The plasma moments such as the ion density, bulk velocity vector, ion temperature, etc. are computed on the basis of the Corall measurements.

The period covered is 0030–0330 UT on 21 September 1995 during which Interball/Tail encountered a region that contains cold, dense magnetosheath-like and hot magnetospheric ions simultaneously. The satellite was moving from the morningside magnetosheath to the dawn flank magnetosphere. Fig. 1 shows the variation of the magnetic field measured on the satellite by MIF instrument (panels a–c), hydrodynamic parameters (panels d–f show velocity components; panel g shows density and panel h shows temperature) and the spectrogram of Electron instrument (panel i). The intensity of the color on the spectrogram are gray-coded according to the logarithm of the measured count rate per sample as shown by the gray bar on the right of the figure. Fig. 2 shows spectrograms of DOK-2 for channel measured ions with energies greater than 25 keV at the angle 62° to the Sun–Earth direction (panel a) and Corall for channel measured ions at the angle 65° to the Sun–Earth direction (panel b). Three first panels of Fig. 3 show solar wind parameters measured by the Wind spacecraft and shifted to Interball/Tail by propagation time. Panel a shows IMF clock angle, panel b IMF value and panel c the solar wind dynamic pressure. IMF was directed northward till 0310 UT for about 3 h prior to and during the Interball/Tail probe measurement of the boundary region. IMF B_x component was close to zero, IMF B_y varies in range of -3 to -6 nT from 0030 to 0310 UT. After 0240 the results of Corall measurements show the characteristics of plasma typical for the plasma sheet. At ~0315 UT IMF B_y component becomes about briefly zero and then restores to be negative values. IMF B_z component changed their polarity at 0310. Fig. 1 shows that, during the analyzed intervals excluding 0226–0238 the magnetic field fluctuated but was oriented predominantly northward and had positive B_z component, hydrodynamic velocity fluctuated near zero indicating that Interball/Tail probe was in the magnetosphere. B_x component was close to zero, indicating the position of the satellite in vicinity of the equatorial plane. This feature is especially important for the analysis of the stress balance across the magnetopause. The interval 0000–0223 UT is the typical interval of LLBL crossings when IMF B_z has northward direction. The colder ion and electron components (see Figs. 1 and 2) are well separated from the hotter components in energy space, and their energies are similar to that of the magnetosheath ions and electrons. The ion and electron count rates were generally well correlated with each other. The field-aligned electrons were counterstreaming and well balanced in both directions, being consistent with the view that the field lines are closed in the mixed ion region. Ions in the investigated region are almost stagnant and consisted of cold-dense anizotropic component and hot more isotropic ion populations.

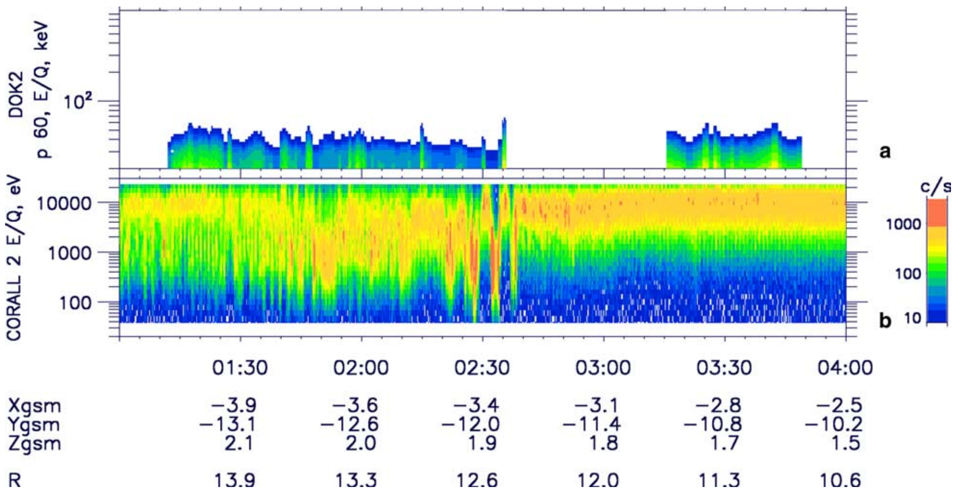

Fig. 2. Spectrograms of DOK-2 (panel a) and Corall (panel b) instruments.

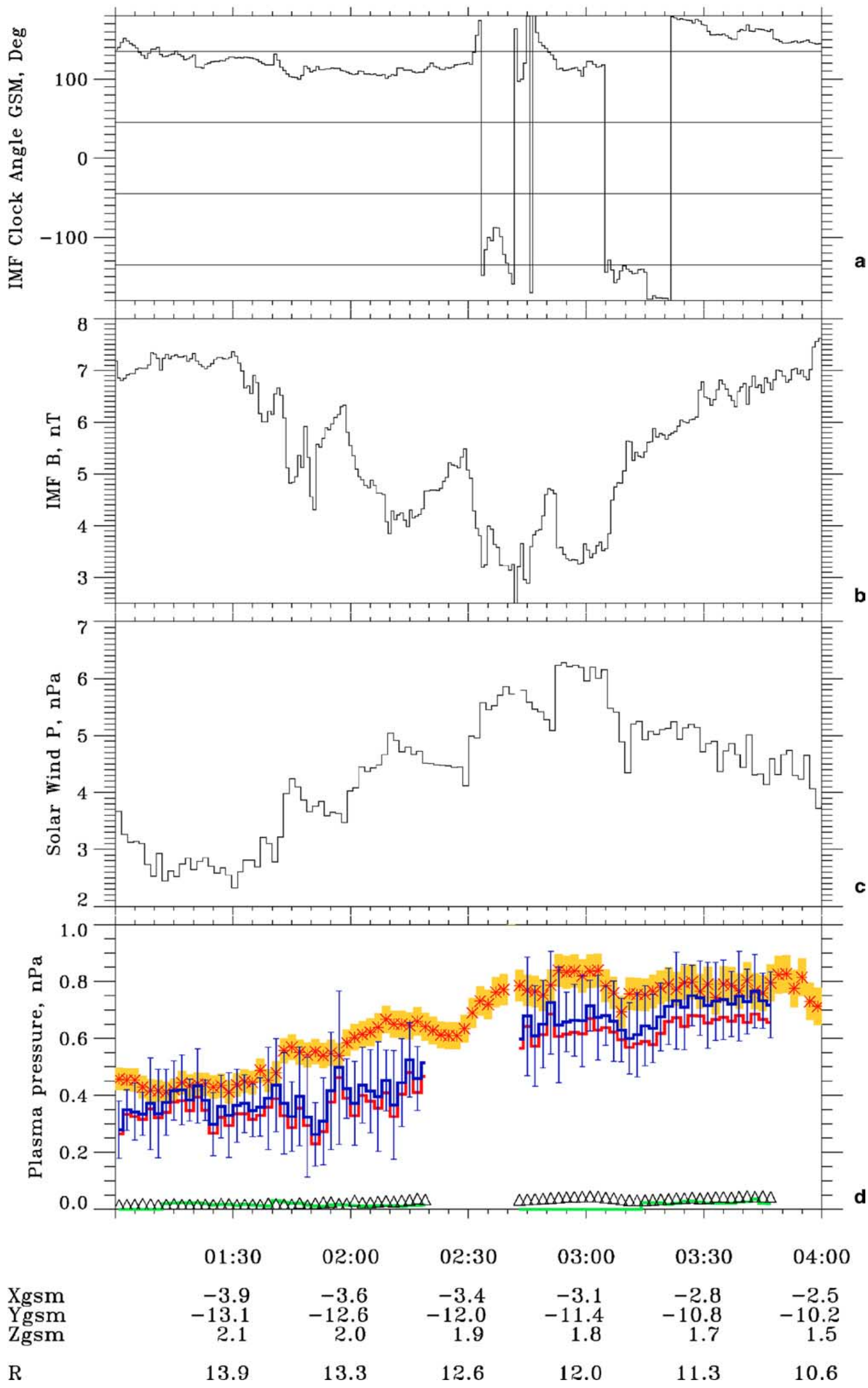

Fig. 3. The results of calculation of plasma pressure. Vertical lines show the values of pressure along the magnetic field line (upper value) and perpendicular to the field line (lower value). □ is the averaged contribution in the plasma pressure produced by ions with energies 0.1–20 keV; Δ is the contribution in the plasma pressure by electrons with energies 0.1–10 keV; × is the contribution measured by ions with energies more than 20 keV; black line is the integral pressure; ∗ is the plasma pressure calculated using Tsyganenko and Mukai (2003) plasma pressure model. First panel shows IMF clock angle, second is IMF value, third is the solar wind dynamic pressure.

The interval 0225–0238 UT is characterized by changes and fluctuations in the magnetic field value and direction, and abrupt increases in the tailward streaming low-energy ions in contrast to sunward streaming ions, demonstrating the presence of fast tailward flow. B_z component of the magnetic field decreases till zero and even briefly becomes negative. From these features, it is inferred that the satellite is repeatedly located in the magnetosheath during these intervals. The data of Electron instrument support this finding. It is necessary to note that during all analyzed period IMF B_z continues to be northward. The changes in the flow conditions are naturally explained by the change of the solar wind dynamic pressure (see panel c in Fig. 3). The jump of the solar wind density produces the magnetospheric compression for time interval about 15 min. The interval 0223–0226 UT is characterized by the presence of plasma with plasma sheet (PS) characteristics. These features are practically restored after 0238 UT. The boundary of particle fluxes of the LLBL-type and PS-type near 0223 UT can be considered as topological boundary or temporal boundary. The first interpretation is traditional view on the sharp LLBL/PS boundary. But such interpretation meets with difficulties due to multiple magnetopause crossings during 0225–0238 UT interval. The flapping of the magnetopause in such conditions must lead to multiple positions of satellite in the thick LLBL region, is not observed. The period 0225–0238 UT is characterized by multiple crossings of the magnetopause when the satellite repeatedly measures the plasma of magnetosheath and PS and practically does not measure plasma characteristics typical for LLBL at northward IMF orientation. The most probable explanation of the observed event in such a case is the change of the regime of plasma flow under the magnetopause after 0223 UT when LLBL practically disappears. Measurements produced by DOK-2 experiments support the discussed findings (see panel a in Fig. 2). DOK-2 data was available only from 00:12 to 02:36 UT and from 03:16 to 03:48 UT, but its measurements give the possibility to restore the shape of the ion distribution function from 20 to 800 keV during these intervals.

3. Variations of the plasma pressure

One of the main feature of Interball/Tail probe measurements is the possibility to calculate plasma pressure with comparatively high accuracy (see Antonova et al., 2002). CORALL, DOK-2 and ELECTRON instruments conduct simultaneous measurements of particle fluxes in overlapped energy ranges. The distribution functions and plasma pressure are anisotropic in LLBL region and have different values along and perpendicular to the direction of the magnetic field. Plasma sheet particles give close to isotropic component; injected magnetosheath component has the high value of anisotropy. Cigar-forms of the ion distribution function suggest the existence of the diagonal form of the ion pressure tensor with different components along and perpendicular to the magnetic field lines. Panel d of Fig. 3 shows the results of plasma pressure calculations on 21 September, 1995. Squares (□) are the averaged contribution in the plasma pressure produced by ions with energies 0.1–20 keV; triangles (Δ) are the contribution in the plasma pressure by electrons with energies 0.1–10 keV; crosses (×) show the contribution measured by ions with energies more than 20 keV; black line shows the integral pressure; star (*) is the plasma pressure calculated using Tsyganenko and Mukai (2003) plasma pressure model. It is possible to see that ions with energies 0.1–20 keV produce the dominant contribution in the plasma pressure. Vertical lines show the values of pressure along the magnetic field line (upper value) and perpendicular to the field line (lower value). The period from 02:20 to 02:40 (gap in calculations of pressure) is the period when due to the magnetopause compression the satellite was in the magnetosheath. It is possible to see that cold fresh injected particles introduce the considerable contribution in the plasma pressure anisotropy in LLBL. Magnetic pressure is smaller than plasma pressure and close to pressure perpendicular to field line. It is possible to see also good correlation of the solar wind dynamic pressure and plasma pressure inside LLBL. Plasma pressure after 3 h when the satellite was inside the plasma sheet practically coincide with the values given by Tsyganenko and Mukai (2003) model. This model is developed on the basis of GEOTAIL observations in the regions of isotropic plasma pressure. But it is possible to see that the model values describe the results of Interball/Tail probe measurements with comparatively high accuracy. Values of measured $B_x \sim 0$ show the position of satellite near the equatorial plane. Magnetic field pressure is lower or comparable with the plasma pressure. This means that LLBL plasma pressure can produce the dominant contribution in the total pressure (plasma pressure plus magnetic pressure) inside the magnetosphere.

4. Conclusions and discussion

On the basis of Interball/Tail probe observations, we investigate the ion and electron behavior in the morningside low-latitude magnetosphere just inside the magnetopause for the event on 21 September, 1995 in order to investigate the LLBL formation mechanisms. The compression of the magnetopause by the increase of the solar wind dynamic pressure leads to the change of the flow regime. It is abruptly changed from typical LLBL with the mixing of magnetosheath and plasma sheet plasmas to the conditions of the absence of LLBL. The observed phenomenon is difficult to explain without modification of the developed theories of LLBL formation. Magnetosheath is a very turbulent region. The magnetic configuration in the magnetosheath can vary in the conditions of stable solar wind parameters. The influence of the variations of the magnetosheath magnetic field on the magnetopause stress balance can help to explain the observed picture of LLBL plasma flow containing mixture of localized jets of magnetosheath plasma and plasma sheet plasma.

The condition of pressure balance across the magnetopause requires the analysis of the values of dynamic, static and magnetic pressures. Fresh injected magnetosheath plasma leads to the anisotropy of plasma pressure. Tangential to the magnetopause component of the plasma pressure participates in the magnetopause stress balance. The obtained preliminary results show that plasma pressure on the earthward side of the magnetopause can produce the considerable contribution in the magnetopause stress balance.

Acknowledgments

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