MULTI-SPACECRAFT TRACING OF TURBULENT BOUNDARY LAYER

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ABSTRACT

Multi-spacecraft tracing of the high latitude magnetopause (MP) and boundary layers and Interball-1 statistics indicate that:
(a) The turbulent boundary layer (TBL) is a persistent feature in the region of the cusp and 'sash', a noticeable part of the disturbances weakly depends on the interplanetary magnetic field By component; TBL is a major site for the magnetosheath (MSH) plasma penetration inside the magnetosphere through percolation and local reconnection.
(b) The TBL disturbances are mainly inherent with the characteristic kinked double-slope spectra and, most probably, 3-wave cascading. The bi-spectral phase coupling indicates self-organization of the TBL as the entire region with features of the non-equilibrium multi-scale and multi-phase system in the near-critical state.
(c) We've found the different outer cusp topologies in summer/ winter periods: the summer cusp throat is open for the decelerated MSH flows, the winter one is closed by the distant MP with large-scale (~several Re) diamagnetic 'plasma ball' inside the MP; the 'ball' is filled from MSH through the patchy merging rather than large-scale one.
(d) A mechanism for the energy release and mass inflow is the local TBL reconnection, which operates at the larger scales for the average anti-parallel fields and at the smaller scales for the nonlinear fluctuating fields; the latter is operative throughout the TBL. The remote from TBL anti-parallel reconnection seems to happen independently.

INTRODUCTION

Turbulent boundary layer (TBL) studies are proceeding within the framework of the Inter-Agency Consultative Group's (IACG) Campaign #2 on boundaries and boundary layers (Campaign #2 Web homepage: http://www-ssc.igpp.ucla.edu/IACG/).
At the cusp the magnetopause is indented. The indentation was first predicted by Spreiter and Briggs (1962) and then detected by HEOS-2 (Haerendel, Paschmann, 1975). For a synopsis of measurements and models of the high altitude cusp, the reader is referred to the papers by Savin *et al.* (2002a,b). The different regions at the

cusp/magnetosheath (MSH) interface are the outer and inner cusp, the outer cusp throat (OT) and the turbulent boundary layer (TBL, see Figure 1, left upper corner). The OT is the disturbed, sometimes stagnant, region with MSH plasma outside the indented MP, the outer cusp is just inside the MP, and the inner cusp is deeper inside the magnetosphere. Here we identify the MP as the innermost current sheet where the magnetic field turns from Earth-controlled to magnetosheath-controlled (Haerendel and Paschmann, 1975). The difference between our outer cusp throat and the "stagnation region" defined by Haerendel *et al.* (1978) is that the stagnation region has no specific relation to the magnetopause. The outer cusp is a region with three different particle populations: newly injected magnetosheath ions, MSH ions reflected from the ionosphere, and quasi-perpendicular ions trapped in the local magnetic field minimum near the cusp. The outer cusp consists of the entry layer and the portion of the plasma mantle adjoining the entry layer (Haerendel, 1978). The TBL is a region dominated by irregular magnetic fields and plasma flows. It is located just outside and/or at the near-cusp magnetopause and has recently been found to be a permanent feature (see Figure 1, Savin *et al.*, 1998b, 1999, Klimov *et al.*, 1997). Here the fluctuation energy density is comparable to the ion kinetic, thermal, and DC magnetic field densities, and the AC power is usually several times larger than in the MSH, and one or two orders of magnitude larger than inside the MP.

Haerendel (1978) introduced the turbulent boundary layer in cusp physics in a discussion on the interaction of the magnetosheath flow with the MP indentation. Recent studies demonstrate that in TBL the kinetic energy transforms into the thermal energy of the random fluctuations. Local reconnection features, that look to contribute to the TBL energetics, have commonly been reported over cusps and in the 'sash' (see Savin, 2002b, Romanov *et al.*, 1999, Maynard *et al.*, 2001, Sandahl *et al.*, 2000, Fedorov *et al.*, 2000, Safrankova *et al.*, 2001, Onsager *et al.*, 2001 and references therein). The TBL energetic particles occur to correlate with the 'diamagnetic bubbles', i.e. sites of vanishing magnetic field (Fritz *et al.*, 2000, Savin *et al.*, 1998b, 2002a).

In this paper we illustrate the wide spatial extent of the TBL determined from the Interball-1 crossings during 3 years (extended from the 1-year statistics used in Savin *et al.*, 1999, Romanov *et al.*, 1999) and for the first time discuss the IMF By dependence in the light of the 'sash' predictions (Maynard *et al.*, 2001). The case study on June 19, 1998 displays the general TBL features and demonstrates the TBL/MP summer/winter asymmetry. We concentrate on the intrinsic spectral properties of the TBL fluctuations deduced from wavelet analysis of the Interball-1 and Polar magnetic field in TBL and that of Geotail in solar wind (SW). Finally, we discuss the MSH plasma transport inward MP through the reconnection and the plasma percolation through the TBL/MP nonlinear network (cf. Kuznetsova and Zelenyi, 1991). We then summarize the TBL features presented here and published elsewhere.

TBL SPREAD FROM 3-YEAR INTERBALL-1 DATA

We start by displaying the TBL distribution during 1995-1998 years as observed by Interball-1 magnetometer MIF-M (for the experiment description see Klimov *et al.*, 1997). The extension of the 1-year statistics (see Savin *et al.*, 1999 and Romanov *et al.*, 1999) shed a new light on the TBL distribution in summer/winter periods. Figure 2a- 2c show projections of the TBL encounters onto the three GSM planes (XY, XZ, and YZ) for different value of the IMF By component: –2 nT< By< 2 nT, By < -2 nT and By> 2 nT, respectively. For the analysis we use the routinely calculated over 20 s intervals standard deviation of the variations (dBx) of the magnetic field sunward component, sampled at 4 Hz rate. We multiply dBx by the factor $3^{1/2}$ to evaluate the full standard deviation (RMS), assuming statistical equality of the AC power of the 3 components; this equality has been checked in ~ 20 case studies. For an interval to be included in the TBL we have set the threshold by requiring the maximum RMS to exceed 6 nT and the maximum RMS being at least 150% of the average MSH RMS during a 10 minute interval. An event is regarded as the continuous if the RMS exceeds the threshold with interruptions less than 10 minutes. We further spatially limit our study outward from the magnetosphere by minimum of two values: (a) half the distance between most distant from the Earth MP and closest to the Earth bow shock (BS) on the same orbit, or (b) 3 Re outward from the most distant MP. We exclude single RMS spikes clearly corresponding to the main magnetic field rotations at MP itself. In the period of March 1997 through March 1998 (see Savin *et al.*, 1999 for details) the average value of the RMS maximum in 150 events near MP equals 15 nT, the absolute RMS maximum is over 30 nT. The near-cusp indentation in the Northern Hemisphere is visible in the upper half of the YZ plane of Figure 2 (this is driven by northern summer data). This indentation follows the MP location in the outer throat reported by Savin *et al.* (1998b). Note also the TBL 'wings', most visible in the XY plane, which range from the near-cusp TBL down the tail to X ~ -(15-20) Re. These 'wings' are in the vicinity of the boundary between the open mantle lines and closed lines. The TBL wings are believed in part to correspond to the 'sash' predictions

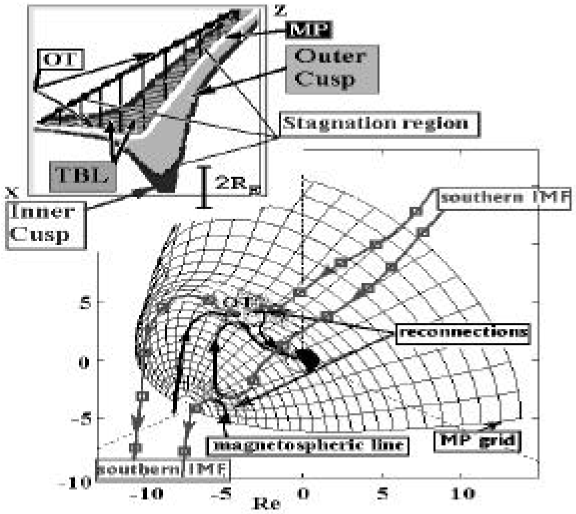

Fig. 1. Sketch of MP grid and reconnected Earth (green) and MSH (red) lines for IMF Bz <0 (bottom). Note two anti-parallel reconnection sites: near equator and in the northern cusp vicinity.Upper insert: characteristic regions in the noon meridian plane, see text for details.

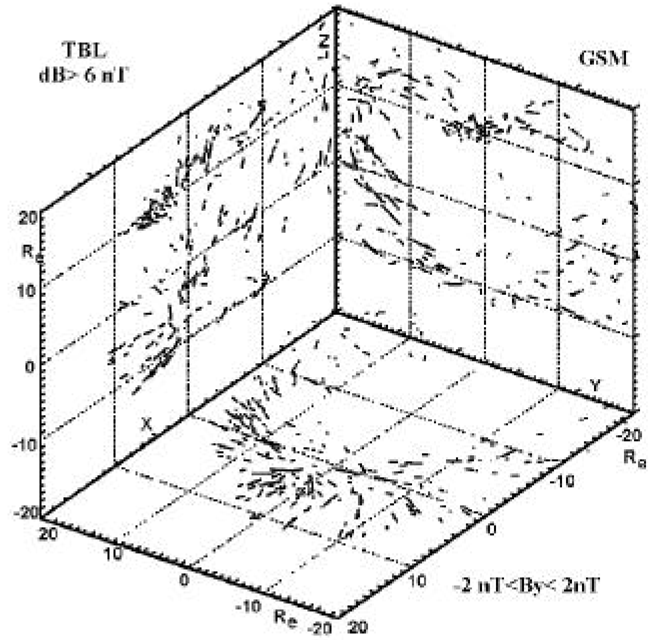

Fig. 2a. Interball-1 TBL in 1995-1998 IMF |By|<2 nT

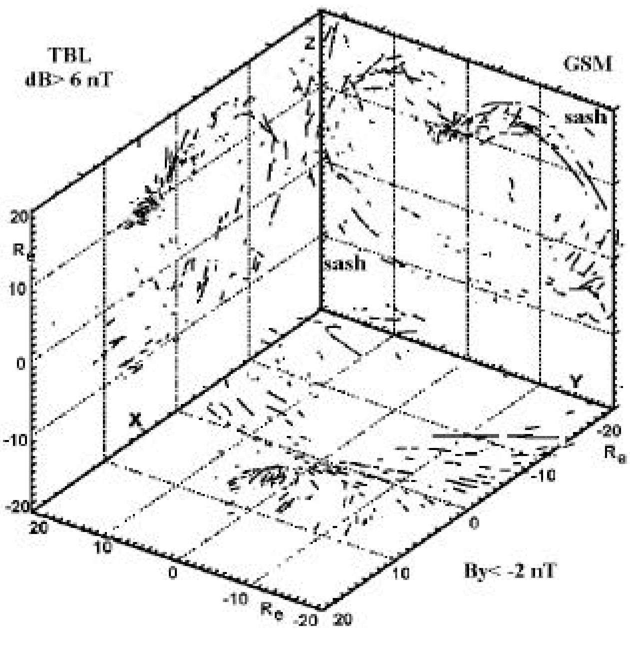

Fig. 2b. Interball-1 TBL in 1995-1998 IMF By< -2 nT

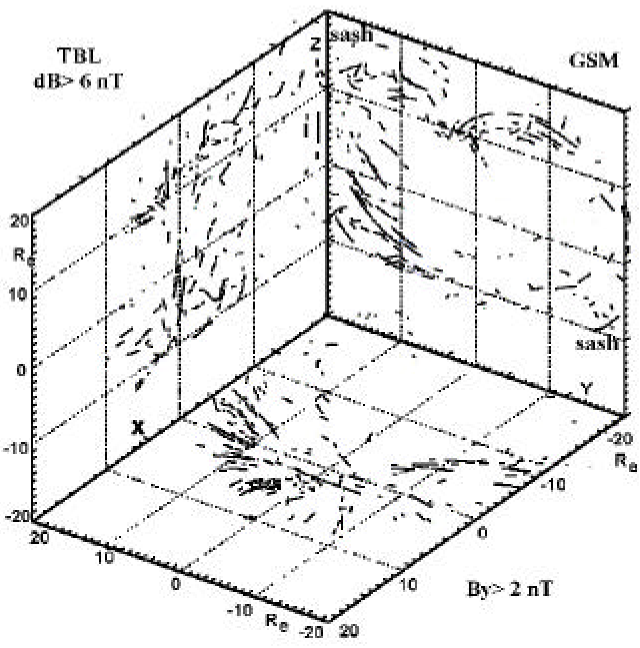

Fig. 2c. Interball-1 TBL in 1995-1998 IMF By> 2 nT

(cf. Maynard *et al.* 2001; Siscoe *et al.* , 2001) or to dynamic features near reconnection sites (cf. Safrankova *et al.*, 2001 and Fedorov *et al.*, 2000). At high latitudes (|Z|> 4 Re) the TBL power and occurrence rate are higher. In the cusp vicinities the 'sash' model predicts for Z> 0 the reconnection shift to the positive Y for By> 0 and to the negative Y for By< 0 and the reverse situation for Z<0, that is labeled in Figure 2b and 2c (Maynard *et al.*, 2001). One can see in the YZ plane of Figure 2c tendencies for the TBL at Z> 0 to be located more often in the 'sash'-predicted quadrant, however, it is obvious that is not true for Z< 0. Moreover, in this quadrant (Z< 0; Y< 0) in Figure 2a and 2b the TBL is encountered more often. Figure 2b displays similar features to the Figure 2c with even less visible 'sash' effect at Z> 0. It suggests that other processes than 'sash'-related are involved. Another source of TBL generation is through the interaction of the MSH flow with the obstacle, i.e. MP indentation over northern cusp. The southern (winter) cusp seems to be asymmetric in the sense of TBL. We address this issue to the following case study. The summer MSH interaction with the cusp throat results in the core downstream TBL and the By-dependent 'sash' effects could be superimposed on that (cf. Maynard *et al.*, 2001). In the XY plane of

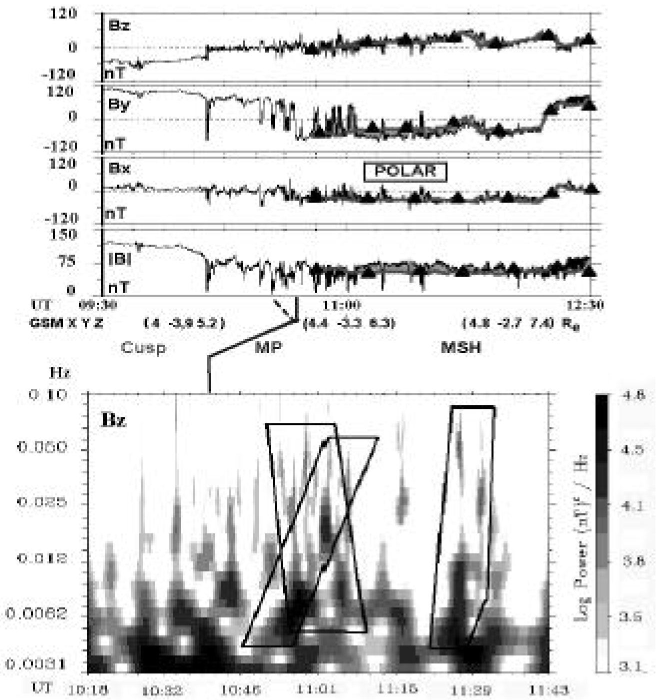

Fig. 3a. Wavelet spectrogram (bottom) and GSM magnetic field for Polar outbound MP/TBL on June 19, 1998. Gray thick line with triangles – GDCFM model with Geotail magnetic field in SW as input (see text for details).

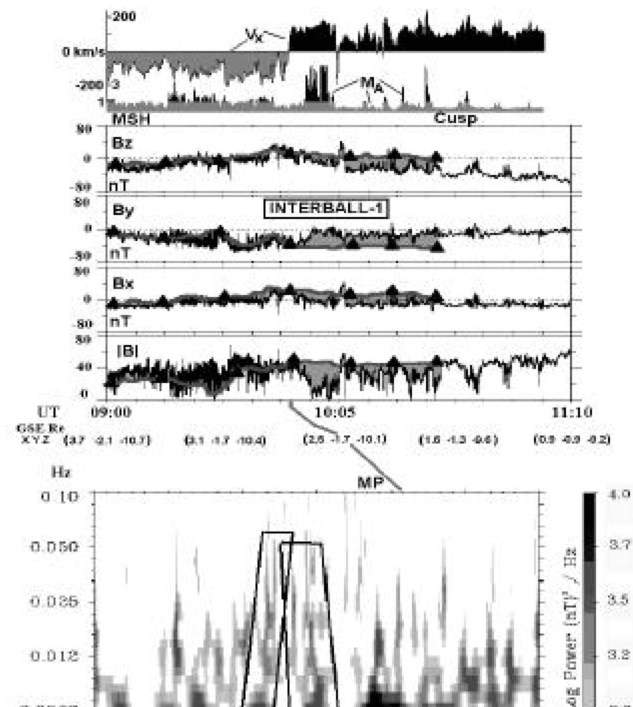

Fig. 3b. The same as in Figure 3A for Interball-1 inbound TBL/MP on June 19, 1998; two extra top panels: ion speed Vx (+/- black/gray shadowed) and Alfven Mach number M_A (M_A>1 black-shadowed).

Figures 2b and 2c this superposition looks asymmetrically with domination of the possible summer 'sash' effects over the winter ones.

SIMULTANEOUS POLAR AND INTERBALL-1 TBL TRACING

On June 19, 1998, near simultaneous passes through of the northern TBL by Polar and the southern TBL by Interball-1 occurred. The respective plasma data are given in Dubinin *et al.* (2001) and Savin *et al.* (2000), here we concentrate on the turbulence properties.

In Figures 3a and 3b we present magnetic field data and wavelet spectrograms for passes through the MP/TBL, by Polar (outbound – northern) and Interball-1 (inbound – southern), respectively. Thick gray lines with triangles display the Gasdynamic Convected Field Model (GDCFM) predictions for the magnetic field in the MSH, using Geotail magnetic field in the solar wind (SW) as input (see Dubinin *et al.* , 2001 and references therein). In Figure 3a we identify the time, which separates average MSH and magnetospheric fields as the MP (the MSH region is where the data are close to the model). Traverses of MP current sheet may be multiple, as indicated by the dashed line. Subsequent apparent traversals of current sheets (see By jumps) at ~ 10:50-11:05 UT resemble the MP ones, but their spectra are different, being similar to that of Interball in TBL (see Figures 3b - 5 and discussions below). We attribute these intense fluctuations to TBL. The comparison with the model strongly supports that Polar crossed the MP and entered the stagnant MSH. In Figure 3b the data-model comparison provides unexpected evidence that Interball crossed MP at almost double GSM Z, compared to the Polar crossing, and the AC power level stays high for ~half an hour inside MP. Another strange feature is the large-scale magnetic field depletion at 09:57-10:05 UT, which is clearly just inside MP (cf. Vx sign change and shadowed systematic difference in the model and measured By and Bx on 1, 4, 5 top panels in Figure 3b). The heated MSH plasma and plasma sheet ions are mixed in the 'ball' (Savin *et al.*, 2000). A future paper will provide statistics of this rather common phenomenon in the winter outer cusp. To estimate the scale of this diamagnetic 'plasma ball' we have found de Hoffman-Teller frame (dHT, see e.g. Fedorov *et al* , 2000) at 09:56:54- 10:00:02 UT with GSE velocity $\mathbf{V}_{HT}$ = (139, -45, 18) km/s, regression coefficient of [$\mathbf{V}$x$\mathbf{B}$] versus [$\mathbf{V}_{HT}$x$\mathbf{B}$] R= 0.999, and small acceleration $\mathbf{a}_{HT}$ =(-0.06, -0.06, 0.14) km/s^2. Existence of such a good dHT frame implies that the 'ball' passes Interball with ~$\mathbf{V}_{HT}$ and thus its scale can be estimated at ~ 5 Re. While the 'ball' moves sunward it cannot be accounted for unique large-scale reconnection as the stress balance fails on this interval.

Wavelet analysis is a powerful tool to investigate turbulent signals and short-lived structures. In order to examine transient nonlinear signals in the TBL we have performed the wavelet transform with the Morlet wavelet:

$$W(a, t)= C \Sigma \{f(t_i) \exp[i\, 2\pi(t_i-t)/a - (t_i-t)^2/2a^2]\} \qquad \text{(Eq. 1)}$$

where 'C' has been chosen so that the wavelet transform amplitude |W(a,t)| is equal to the Fourier one (see Consolini and Lui, 2000 and references therein for details). When this wavelet shows the single peak at the frequency f = 1/a, a wavelet characteristic scale may be read as representing a frequency f = 1/a $\pm$ f/8. Figures 3 and 4 display the power spectra from the wavelet transform in the TBL intervals on Polar and Interball-1. The wavelet spectrograms in Figure 3 clearly outline wave trains at different frequencies simultaneously, which suggest multi-scale intermittent processes. These effects can be seen up to several Hz (not shown). The linkage between the maximums represents a feature of cascade processes. Direct/ reverse (i.e. high or low frequency fluctuations appear first) cascades can be recognized. Representative examples are highlighted in Figure 3 by black frames. The reverse cascade from 0.025 to 0.00625 Hz at ~ 10:52 UT in Figure 3a might converge with the direct one from 0.004 Hz. Several high frequency branches are frequently seen.

Note the similarities in the spectrograms in Figures 3: namely, the intensification of the waves at 0.01-0.1 Hz in front of MP and the existence of intense lower frequency fluctuations upstream and downstream. In the sense of the Figure 2 criteria the TBL is seen with interruptions in Figure 3b between 09:00- 11:00 UT, while it is most prominent for 09:10- 10:30 UT. We have chosen the By and Bz components measured by Interball and Polar, respectively, for displaying the wavelet transform. In front of the MP these components have the most fluctuations in the higher frequencies and the fluctuations do not resemble those seen in magnetosphere or MSH, but are typical of the inherent TBL ones. The MP-like transitions are best seen in Bz at 10-11 UT on Interball and in By on Polar. For the quantitative comparison of the TBL properties we present characteristic spectra in Figure 4 from the core TBL Polar/Interball intervals at 10:50 – 11:10 (crosses) and 09:10- 10:00 UT (asterisks), which exhibit similar higher frequency fluctuations. The maximums at 0.002/ 0.0014 Hz correspond to the MP-like transitions in By/Bz, which are close to the inverse Alfven transition times for traversing the magnetopause between the cusp regions or for MP to the ionosphere. Two characteristic negative slopes are actually seen: ranging between 2.1 to 2.3 at 0.1-0.5 Hz and between 1 to 1.1 at 0.004-0.05 Hz. The different slope of -1.9, seen by Geotail in SW, and the absence of any maximum in the Geotail data demonstrate that the dominant processes in the TBL in this event are local and inherent, in spite of the average field following the SW as demonstrated by the model to data comparisons in Figure 3. In the inner region 10:18- 10:45 UT Bz spectra on Polar have a different slope ~1.6 (not shown) and a minimum occurs in place of the 0.002 Hz peak. The strong MP current with nearly anti-parallel fields prevents penetration of the fluctuations from the TBL. In contrast to Polar, Interball-1 magnetic spectra for 0.004-0.5 Hz in the outer cusp at 09:53- 11:00 UT (curve without asterisks) have similar shape to that of the core TBL, while the slope at 0.004-0.05 Hz of 1.3 is slightly higher. At 09:55- 10:30 UT the slope from Interball-1 at 0.1- 0.5 Hz is the same as in the TBL just outside MP. The characteristic power at low frequencies just outside MP is about twice that in the core region (the difference is shadowed in Figure 4). Shifting the interval to 09:56-10:08 UT reduces the peak at ~ 0.0013 Hz by factors of 2 to 3 but doesn't change much the rest of the spectrum. This is in strong contrast to that seen in the summer TBL where the power drops by the order of magnitude in the outer cusp (see Figure 1 and cf. Savin *et al.* , 1998b, 1999). Thus the southern MP with nearly perpendicular fields appears to reduce the fluctuation power. The Bx spectra (not shown) are similar to that of Figure

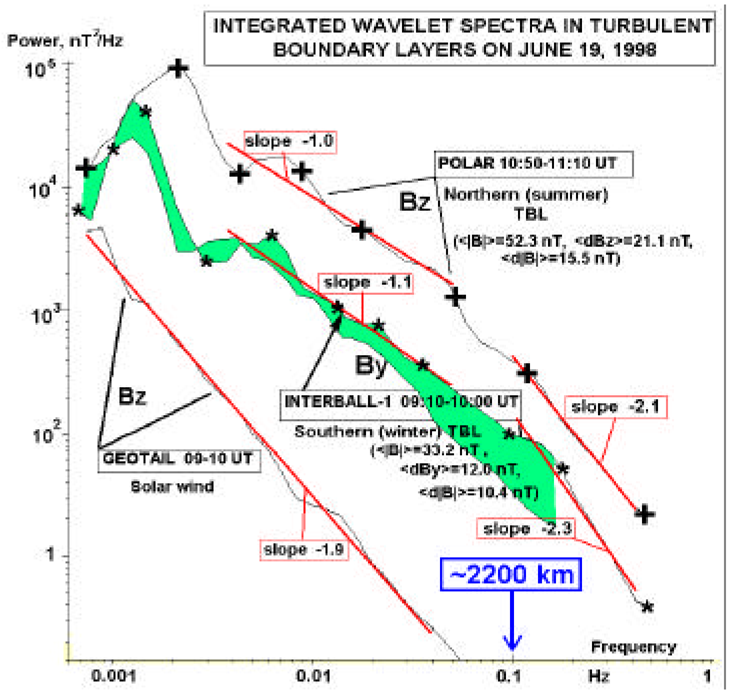

Fig. 4. Wavelet integrated spectra in the northern/ southern TBL (crosses and asterisks, see also text) and in the SW.

4 on both Polar and Interball. Interball Bz and Polar By (main components inside MP) have steeper spectra at lower frequencies (slopes of 1.45 and 1.75) and more gradual slopes at the higher ones. Interball Bz spectrum from 09:53 to 11:00 UT in the cusp has a maximum at 0.0016 Hz that is close to that of Polar in Figure 4. Thus Alfvenic resonance between hemispheres could account for the major spike separations in TBL/cusp (see Figure 3). The difference of the power for Polar and Interball spectra in Figure 4 of about one order of magnitude can't be attributed to the higher average magnetic field on Polar (~ in 1.6 times). We suggest that the power excess may be due to intermittent reconnection of the nearly anti-parallel fields on Polar. The reconnection of the average nearly perpendicular fields in the Interball case is hardly operative, but fluctuating fields can still reconnect as the ion speed Vx and M_A spikes infer (see 2 top panels in Figure 3b). In the latter case the average field is not annihilated and the energy input into turbulence is thus lower. Another characteristic TBL feature is the fact that the standard variances <dBz> and < dBy> are higher than that of the field magnitude <d|B|> (see text in Figure 4). It implies that the transverse magnetic fluctuations dominate over the compressible ones (cf. Savin *et al.* , 1998b, 1999). To estimate the scale of the kink in Figure 4 we have found dHT frame with GSE velocity $\mathbf{V}_{HT}$ = (-156, 82, -121) km/s and regression R= 0.993 at 09:35:31- 09:39:03 UT. That gives for the kink L~ 2200 km.

To investigate if the wave trains in TBL are really coupled by the cascade-like nonlinear processes, we have studied the magnetic spectral bicoherence using a wavelet approach, which is able to resolve phase coupling in short-lived events and pulses (see e.g. Sagdeev and Galeev 1969, Lagoutte *et al.* 1989 and Consolini and Lui 2000). We use SWAN software from LPCE/CNRS in Orleans for the wavelet analysis, that defines the bicoherence as:

$$b^2(a_1,a_2) = |B(a_1,a_2)|^2 / \{\Sigma\, |W(a_1,t_i)\, W(a_2,t_i)|^2\, \Sigma\, |W(a,t_i)|^2\} \qquad \text{(Eq. 2)}$$

with $B(a_1,a_2)$ being the normalized squared wavelet bi-spectrum:

$$B(a_1,a_2) = \Sigma\;\; W^*(a,t_i)\, W(a_1,t_i)\, W(a_2,t_i) \qquad \text{(Eq. 3)}$$

the W(a,t) is wavelet transform according (Eq. 1) and the sum is performed satisfying the following rule:

$$1/a = 1/a_1 + 1/a_2 \qquad \text{(Eq. 4)}$$

which correspond to a frequency sum rule for the 3-wave process, $f = f_1 + f_2$.
The bicoherence has substantial value only if three processes, with the highest frequency being the sum of the rest two, are phase-coupled (cf. Consolini and Lui, 2000). The simplest such case is the harmonic generation due to quadratic nonlinearity, namely the second and third harmonic generation with 2f = f + f , and with 3f = 2f + f . As the harmonics are present in any nonlinear wave pulse and do not represent phase coupling of the different waves, we will ignore them in the future analysis. We assume that the most-powerful nonlinear 3-wave process (excluding the harmonics) in the TBL is decays (or junction), which requires the third-order nonlinearity in the system. The weaker, higher-order nonlinear effects, which also might contribute in the TBL physics, are beyond the scope of this paper and will be addressed in future studies.

In Figures 5a and 5b we present, respectively, Polar and Interball bicoherence spectrograms from nearly the same core TBL intervals as the spectra shown in Figure 4. We have chosen the exact time and frequency intervals, and spatial components, which display characteristic maximums from third and higher order nonlinearity. All features, visible in the Figure 5 are present in the bi-spectra of another components, but not all together in one plot. The

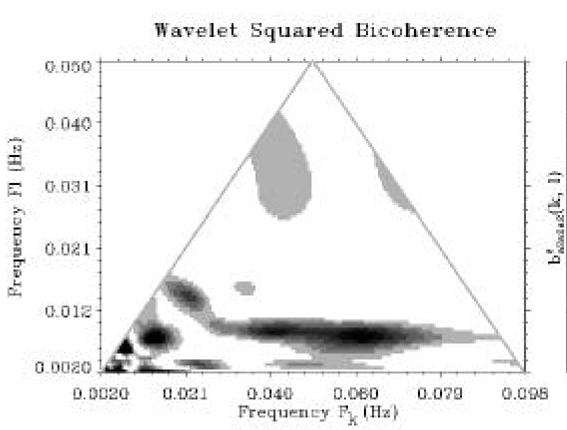

Fig. 5a. Wavelet bicoherence module for Polar By GSM, 10:45-11:10 UT, 0.002-0.1 Hz.

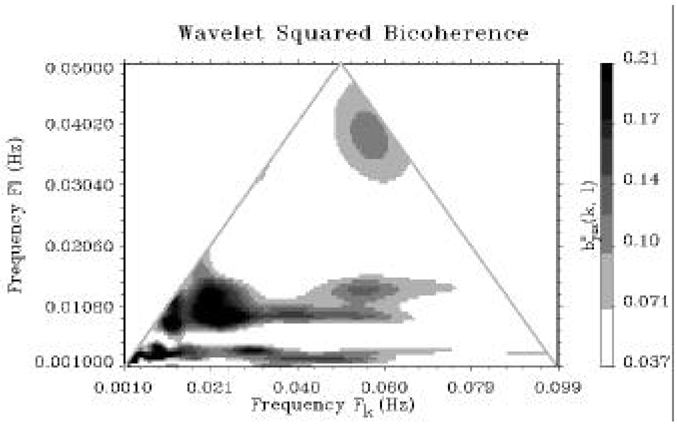

Fig. 5b. Wavelet bicoherence module for Interball-1 By/Bz/Bz GSM, 09:10-09:59 UT, 0.002-0.1 Hz.

frequency plane (f_1, f_2) is limited by the signal symmetry considerations and by the frequency interval of the most characteristic TBL slope of about 1 in the Figure 4. The bicoherence spectra in Figure 5 displays, in addition to the second and third harmonic nonlinear generation, 3-wave processes with the cascade-like features, that are centered at ~ 0.006 Hz on Polar (cf. By transitions in Figure 3a at 10:45- 11:00 UT) and at ~0.009 Hz on Interball. We assume the cascade signatures in the Figure 5 when at the sum frequency, $f = f_1 + f_2$, the bicoherence has comparable value with that at the point (f_1, f_2). In the case of the horizontal-spread maximum, it implies that the wave at sum frequency interacts with the same initial wave at frequency f_1 in the following 3-wave process: $f_3 = f_1 + f$ etc., the initial wave spectrum can be smooth resulting in the continuous bi-spectral maximum. Returning to the Figure 5b, the higher frequency (on the vertical axes) cascade-like maximum also is seen in parallel with the main horizontal one. In the exterior southern TBL (Interball) plasma velocity is ~ 200 km/s, while in the northern TBL (Polar) the average speed < 50 km/s. Thus the frequency difference could be attributed to the higher Doppler shift in the Interball case. As we mentioned above, the cascading features are also seen as multiple spectral maximums in Figure 3. We suggest that in general the energy flows from the lower to higher frequency regions with the slope ~2.3, which is characteristic for the developed MHD turbulence (cf. Zelenyi and Milovanov, 1999). Assuming that the cascade origin corresponds to the highest bicoherence amplitude, one could find the main cascade from (0.006 + 0.06) Hz towards the low frequencies in Figure 5a. Unlike Polar, Interball data displays a maximum at (0.009 + 0.022) Hz, which looks to decays on two X-aligned cascades with the growing higher frequency and the fixed second one. We have checked that the three-wave like processes are present also at the lower and higher frequencies, e.g. at ~ 0.0004 and 0.15 Hz, the former also displays cascading features.

DISCUSSION AND CONCLUSIONS

We have demonstrated that the TBL is a persistent feature for the high latitude MP (cf. Sandahl *et al.* , 2000). The noticeable fraction of disturbances, weakly dependent on the IMF By component, indicates the significance of the MSH flow direct interaction with the high latitude obstacle – the outer cusp throat. The summer/winter TBL asymmetry (mentioned but not demonstrated in Savin *et al.* , 2000) visible in Figures 2 and 3, invokes different geometry of the MSH/MP high latitude interface for the positive and negative dipole tilt angles, i.e. for the throat open for the MSH penetration and closed by the distant MP. In the case study presented above a large scale 'plasma ball' just inside the MP have been observed. Inspection of the 5 consecutive Interball-1 orbits in the June 19 to July 3 period shows the presence of similar features on 4 inbound (winter/southern) MP crossings (cf. Savin *et al.* , 2000). That supports quasi-stationary of the 'plasma ball' in contrast to random smaller scale 'diamagnetic bubbles' (see spiky |**B**| drops in Figure 3, cf. Savin *et al.* , 1998a,b, 1999). We propose that for the future a simple instrument for the MSH/MP studies could be developed based on GDCFM-like models using an asymmetric obstacle.

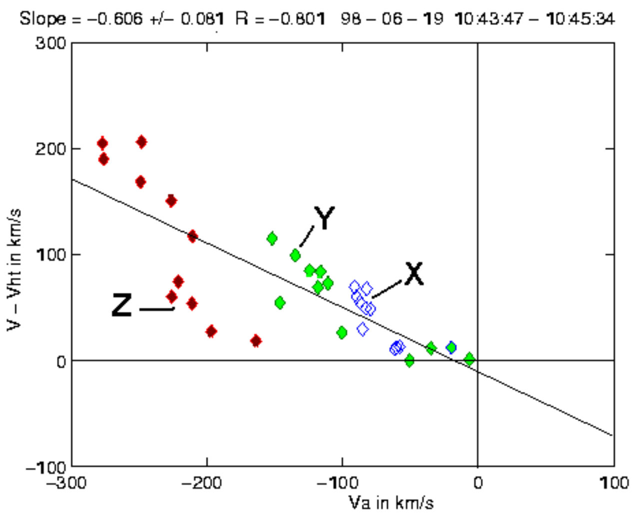

Fig.6 . *Stress balance test for Interball-1 injection in cusp at 10:43:47- 10:45:44 UT (see Figure 3b and text)*

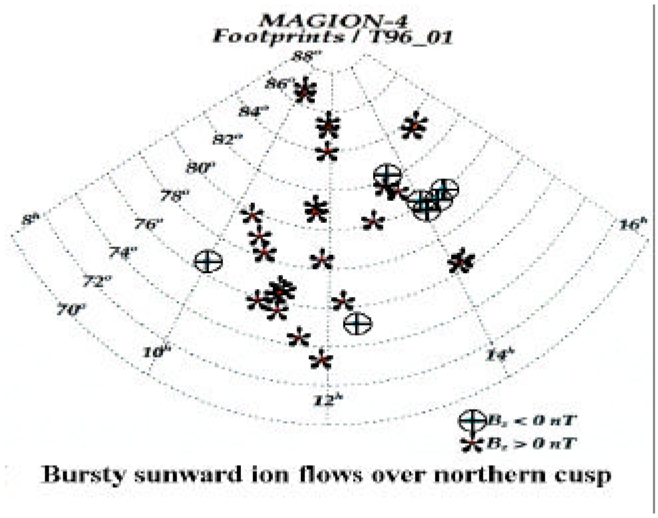

Fig. 7. Ionospheric projections of the exterior cusp reconnections.

We have mentioned above that the 'plasma ball' of ~5 Re in the winter cusp could not result from unique large-scale reconnection. The super-Alfvenic flows in front of MP (black-shadowed in 2 upper panel of Figure 3b) also indicate that the steady merging is hardly possible (La Belle-Hamer *et al.* , 1995). Instead we assume that the quasi-regular jets at 10-11 UT in Figure 3b can represent cusp counterparts of patchy merging (cf. Dubinin *et al.* , 2001), which can contribute into the 'ball' filling by MSH plasma. In Figure 6 we depict results of the stress balance test for one of the Interball-1 injections at 10:43:47- 10:45:44 UT: the dependence of ion speed in dHT frame (**V- V**$_{\mathbf{HT}}$) versus vector $\mathbf{V_A} = \mathbf{B} \mid \mathbf{V_A}| / |\mathbf{B}|$ for different vector components (marked by X, Y, Z). The average slope of -0.6 (+/- 0.08) with regression of 0.8 satisfactory fits plasma flowing anti-parallel magnetic field in dHT frame (i.e. from the MP towards the southern pole) at velocity ~ 0.6 of the local V_A. It agrees with locating of Interball on the cusp part of the line, reconnected at the tailward MP, taking into account the lower V_A in MSH and possible deceleration of the reconnected kink, pushed sunward, by the MSH flow. The 'quality' of the dHT frame for this interval is high enough: $\mathbf{V_{HT}}$ = (134, -39, 22) km/s, $\mathbf{a_{HT}}$ =(-0.08, 0.05, 0.03) km/s^2 with main deceleration in X, Y directions and regression coefficient R= 0.994. Remember that the spiky cusp jets in Figure 3b constitute a part of the flow coherent interactions, discussed above. In particular, the flow repetition quasi-periodicity corresponds to the spectral maximums at 1-3 mHz in Figures 4, 5. The difference between $\mathbf{V_{HT}}$ and average ion bulk velocity in the jet vicinity is in the limit of the bulk velocity variations (deviation < 16 degrees) that should be a characteristic feature for standing structures in the cusp plasma frame. So, we could infer the space rather than time resonance pattern at the MSH/ cusp interface. $\mathbf{V_{HT}}$ is at 107 degrees to the surrounding magnetic field, then one can get an estimate of transverse scale of the jet of ~ 2 Re.

These small-scale reconnections not only supply the MSH plasma in the 'plasma balls', its contribute in creation of the nonlinear network across MP, resulting in percolation of the plasma through this network inside the MP. The estimates for the plasma transport through the entire TBL walls, eroded by reconnection, can be done in the frame of the percolation model by Kuznetsova and Zeleny (1991): effective diffusion coefficient D_P ~ (5-10) 10^9 m^2/ s for typical MP parameters results in particle influx of (1-2) 10^{27} particles /s. Such influx already might account for the population of the dayside cusp and the low latitude boundary layer through the dayside TBL (Savin *et al.* , 1999).

The characteristic scales of the TBL turbulence are shown to spread from several thousand to few km, i.e. to a few electron inertial lengths c/ω_{pe} (Savin *et al.* , 1998b). This infers violation of the frozen-in condition and could be treated as a feature of the local reconnection near the cusp. The vertical/sunward ion flows support that too (Merka *et al.* , 2000, Dubinin *et al.* , 2001, Maynard *et al.* , 2001). Especially suggestive are the sunward/vertical flows in the cusp vicinity during negative IMF Bz. We reproduce the respective Magion-4 statistics from Safrankova *et al.* , (2001) in Figure 7. We would like to outline that events with Bz > 0 do not concentrate at the high latitudes nor do the events with Bz <0 tend to be at the low latitude cusp border. Such shifts are anticipated when the stretched by the MSH flow field lines are situated along the indent MP in the cusp vicinity. This is schematically shown for negative Bz in Figure 1, where in general the MP nearly anti-parallel fields will be nearer the equator and at the equatorial cusp border. Thus, one expects favorable for the reconnection situation at these places, both of which map to the cusp equatorial border in the ionosphere. The operation of the bursty reconnection for the locally anti-parallel fields over the cusp is in agreement with a number of studies, while the experimental evidences for the permanent by-product reconnection of the TBL strongly fluctuating fields are seen as well (see e.g. Savin *et al.* , 1998b, 2002a,b, Merka *et al.* , 2000, Onsager *et al.* , 2001, Dubinin *et al.* , 2001). Figure 7 also confirms a widespread of the reconnection features in the cusp throat. On the other hand we propose to account for the much higher level of the TBL wave power on Polar (Figure 4) by the simultaneous operation of multiple processes including the by-products of anti-parallel reconnections (cf. Savin *et al.* , 2002b). As a result of the multi-scale and partially intermittent reconnection, field lines are connected through the TBL in statistical sense (Savin *et al.* , 1998b), without opportunity to trace individual field lines in the inhomogeneous non-equilibrium 2-phase medium, one phase being the frozen-in 'MHD' plasma another one representing by unmagnetized 'diamagnetic bubbles'. We would like to note also that, as can be seen from the Figure 1, the remote from cusp reconnection should take place independently. The same is valid for Bz >0 and By dominating cases (cf. Figure 3b and Dubinin *et al.* , 2001, Savin *et al.* , 2002b, Maynard *et al.* , 2001).

The TBL plasma may be double heated and accelerated to a few 100 keV for ions or few 10 keV for electrons (Chen *et al.* , 1997, Chen and Fritz, 1998, Fritz *et al.* , 2000, Savin *et al.* , 1998b, 1999, 2002a). The TBL magnetic fluctuation energy density is closer to that of the MSH kinetic energy than that of the MP, which is suggestive for the conversion of the kinetic energy into the AC random energy and plasma heating/acceleration. Another valuable TBL-related feature is the deceleration and heating of the MSH flow downstream of the TBL/cusp. Using Interball data, Savin *et al.* (1998c, 1999) showed that on January 12 and 27, 1997 the ion thermal energy density in the

TBL is close to that seen downstream of the TBL. On January 27, 1997 at the same time near equator Geotail registered MSH flow with several times higher velocity and lower temperature. The sum of the thermal and kinetic energies were of the order of that on Interball with the strong dominance of the kinetic energy density (see Figure 2 in Savin *et al.* , 1998c). That outlines the significance of the flow interaction with the obstacle (indented outer cusp throat) at least in the summer/ northern hemisphere. Further study is foreseen to clarify how common and valuable is this type of streamline and if it present over the winter cusp.

In spite of different positions, MSH velocities, and behavior of the main magnetospheric components, the spectral characteristics of the summer/winter TBL just outside MP are very similar. The spectral shapes demonstrate inherent character of the TBL fluctuations, which have no counterpart in SW. The power-law spectra imply translation symmetry of the fluctuations. The cascade-like wavelet and bicoherence spectrograms infer coherent interaction between wave trains, while the disturbances seem to be random in waveforms. Quasi-coherent large-scale structures, which organize phase coupling throughout the entire TBL, can result from the inverse cascades of the local wave trains (see Figure 3). The local wave trains originate from interaction of the disturbed MSH flows with the MP, the interaction includes local reconnection as a part. The TBL disturbances modulate the incident MSH flow in a self-consistent manner, being globally organized by the phase coupling with the long-scale variations. So, the round is closed: TBL seems to be multi-scale multi-phase self-organized system of interacting nonlinear waves. It infers qualitative difference from the traditional approach when the MSH/cusp interaction is regarded as additive sum of magnetospheric reactions on the solar wind or MSH disturbances. Note also that the long-term correlation is suggestive for systems out of equilibrium near the critical point (cf. Consolini and Lui, 2000). The kinked TBL spectra with characteristic slopes remarkably resemble that in the near-Earth neutral sheet in the state of the self-organized criticality (see e.g. Zelenyi and Milovanov, 1999).

The above properties of the turbulent boundary layer demonstrate that it is a significant region of the magnetosphere through which the solar wind plasma is transported inside, and partially heated and accelerated. A valuable future task is further detailed study of this region especially in comparison with the lager scale remote reconnection and the low latitude diffusion on the tail flanks.

ACKNOWLEDGMENTS

Work was partially supported by International Space Science Institution, and by grants INTAS/ESA 99-1006, INTAS-2000-465, EST.CLG 975277, KBN 8T12E04721 and by Humbolt Foundation.. We appreciate D. Lagoutte and his colleagues from LPCE/CNRS in Orleans for providing the SWAN software and V. Romanov, I. Dobrovolsky and A.B. Belikova for help in the data processing.

REFERENCES

Chen, J, T.A. Fritz, R.B. Sheldon, H.E. Spencer, W.N. Spjeldvik *et al.* , Temporary confinedpopulation in the polar cap during the August27, 1996 geomagnetic field distortion period, *Geophys. Res. Lett.*, **24**, 1447, 1997

Chen, J. and T.A. Fritz, Correlation of cusp MeV helium with turbulent ULF power spectra and its implications, *Geophys. Res. Lett.* **25**, 4113, 1998

Consolini, G. and A. T. Lui, Symmetry breaking and nonlinear wave-wave interaction in current disruption: possible evidence for a phase transition, in *Magnetospheric Current Systems*, , Geophysical Monograph **118**, American Geophysical Union, Washington D.C., 395-401, 2000

Dubinin, E., A. Skalsky, P. Song, S. Savin, J. Kozyra *et al.* , Polar-Interball coordinated observations of plasma characteristics in the region of the northen and southern distant cusps, *J. Geophys Res.*, accepted, 2001

Fedorov , A., E. Dubinin, P. Song, E. Budnick, P. Larson, J.A. Sauvaud, Characteristics of the exterior cusp for steady southward IMF: Interball observations, *J. Geophys. Res.*, **105**, 15,945- 15,957, 2000

Fritz, T.A., J. Chen, R.B. Sheldon, The role of the cusp as a source for magnetospheric particles: a new paradigm? *Adv. Space Res.*, 25, 1445-1457, 2000

Haerendel, G. and G. Paschmann, Entry of solar wind plasma into the magnetosphere, in *Physics of the Hot Plasma in the Magnetosphere*, edited by B. Hultqvist and L. Stenflo, p. 23, Plenum, NY, 1975

Haerendel, G., Microscopic plasma processes related to reconnection, *J. Atmos. Terr. Phys.*, **40**, 343-353, 1978

Klimov, S. *et al.* , ASPI Experiment: Measurements of Fields and Waves Onboard the INTERBALL-1 Spacecraft, *Ann. Geophys.*, **15**, 514-527, 1997

Kuznetsova, M. M., and L. M. Zelenyi, The theory of FTE: Stochastic percolation model, *in Physics of Magnetic Flux Ropes*, edited by C. T. Russell, E. R. Priest, L.C. Lee, *American Geophysical Union*, 473-488, 1990

La Belle-Hamer, A.L., A. Otto, L.C. Lee, Magnetic reconnection in the presence of sheared flow and density asymmetry: application to the Earth's magnetopause, *J. Geophys. Res.*, **100**, 11,875- 11,889, 1995

Lagoutte, D., F. Lefeuvre and J. Hanasz, Application of bi-coherence analysis in study of wave interactions in space plasma, J. Geophys. Res., 94, 435, 1989

Maynard, N. C., S. Savin, G. A. Erickson, H. Kawano, *et al.* , Observations of fluxes of magnetosheath origin by Polar and Interball at high latitudes behind the terminator – relationships to the magnetospheric "sash". *J. Geophys. Res*, **104**, 6097- 6122, 2001

Merka, J., J. Safrankova, Z. Nemecek, A. Fedorov, N. Borodkova, S. Savin, A. Skalsky, HIGH ALTITUDE CUSP: INTERBALL OBSERVATIONS, Adv. Space Res., **25**, 1425-1434, 2000

Onsager, T.G., J. Scudder, M. Lockwood, C.T. Russell, Reconnection at the high latitude magnetopause during northward IMF conditions, *J. Geophys. Res.*, in press, 2001

Romanov V., S.Savin, S.Klimov, S.Romanov, Yu.Yermolaev, J.Blecki, R.Wronowski, Magnetic turbulence at the magnetopause: plasma penetration, J. Tech. Phys. (Poland), **40**, 1, 329-332, 1999

Safrankova, J., Z. Nemecek, L. Prech, J.-A. Sauvaud, and S. Wing, The structure of the magnetopause layers at magnetospheric flanks, Proceedings of COSPAR/ESA, Colloquium, Warsaw, February 6-10, 2001

Sagdeev, R.Z., A.A. Galeev, Nonlinear plasma theory, p.6 Benjamin, White Plains, N.Y., 1969

Sandahl, I., B Popielavska, E. Yu. Budnick, A. Fedorov, S. Savin, J. Safrankova, Z. Nemecek, THE CUSP AS SEEN FROM INTERBALL, Proceedings of 'Cluster II Workshop. Multiscale/Multipoint Plasma Measurements., Imperial College, London, Sept. 22-24, 1999, ESA/ SP-499, 39-45, 2000

Savin, S. P., S. A. Romanov, A. O. Fedorov, L. Zelenyi, S. I. Klimov, *et al.* ,The cusp/magnetosheath interface on May 29, 1996: Integball-1 and Polar observations, *Geoph. Res.Lett.*, **25,** 2963-2966, 1998a

Savin, S. P., N. L. Borodkova, E. Yu. Budnik, A. O. Fedorov, S. I. Klimov, *et al.* , Interball tail probe measurements in outer cusp and boundary layers, in *Geospace Mass and Energy Flow: Results from the International Solar-Terrestrial Physics Program*, edited by J.L. Horwitz, D.L. Gallagher and W.K. Peterson, Geophysical Monograph 104, American Geophysical Union, Washington D.C., 25-44, 1998b

Savin, S., L. Zelenyi, L. Budnik, N. Borodkova, A. Fedorov, *et al.* , Manifestations of Boundary Layer Dynamics in Substorm Activity. Multi Spacecraft Study, in *SUBSTORM-4, 'Conf. on Substorms-4', Lake Hamana, Japan: March 9-13, 1998*, ed. S. Kokubun and Y. Kamide, Terra Scientific Publ. Co., Tokyo, 125-130, 1998c

Savin, S., E. Budnik, M. Nozdrachev, V. Romanov *et al.* , ON THE PLASMA TURBULENCE AND TRANSPORT AT THE POLAR CUSP OUTER BORDER, Chekhoslovak J. Phys., **49**, 4a, 679-693, 1999

Savin, S., A. Skalsky, S. Romanov, E. Budnick, N. Borodkova, L. Zelenyi, *et al.* , Outer cusp boundary layer: summer/ winter asymmetry, Proceedings of Symposium 'From solar corona through interplanetary space into magnetosphere and ionosphere', Kyiv University, Kyiv, Febr. 1-4, 2000, 229-232, 2000

Savin, S., J. Blecki , N. Pissarenko, V. Lutsenko, I. Kirpichev *et al.* , Accelerated particles from turbulent boundary layer, Proc. of INTERBALL/COSPAR Colloquium 'ACCELERATION AND HEATING IN THE MAGNETOSPHERE', 6-10 February 2001, Konstancin, Poland, in press, 2002a

Savin, S., N. Maynard, I. Sandahl, H. Kawano, C. T. Russell, S. Romanov, L. Zelenyi *et al.* , Magnetosheath/ Cusp Interface, *Ann. Geophys.*, submitted, 2002b

Siscoe, G. L., G. M. Erickson, B. U. Ö. Sonnerup, N. C. Maynard, K. D. Siebert. D. R. Weimer, and W. W. White, Magnetospheric sash dependence on IMF direction, *Geophys. Res. Lett.*, in press, 2001

Spreiter, J. R., B. R. Briggs, Theoretical determination of the form of the boundary of the solar corpuscular stream produced by interaction with the magnetic dipole field of the Earth, *J. Geophys. Res.*, **67**, 37-51, 1962

Zelenyi, L.M., A.V. Milovanov, Multiscale magnetic structure of the distant tail: self-consistent fractal approach, in *New Perspectives on the Earth Magnetotail*, Geophys. Monograph **105**, AGU, Washington DC, 321-338, 1998