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Turbulent Boundary Layer at the Border of Geomagnetic Trap

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A new phenomenon was discovered on the basis of analysis of the Interball project data. A hot plasma flow is thermalized through the formation of "long-operating" vortex streets and local discontinuities and solitons in a distributed region over polar cusps. Plasma percolation through the structured boundary and secondary reconnection of fluctuating magnetic fields in a high-latitude turbulent boundary layer account for the main part of solar wind plasma inflow into the magnetospheric trap. Unlike local shocks, the ion thermalization is accompanied by the generation of coherent Alfvén waves on the scales ranging from ion gyroradius to the radius of curvature of the averaged magnetic field, as well as by the generation of diamagnetic bubbles with a demagnetized heated plasma inside. This "boiling" plasma has a frequency region where the spectrum is different from the Kolmogorov law (with slopes 1.2 and 2.4 instead of 5/3 or 3/2). The fluctuation self-organization in the boundary layer (synchronization of three-wave decays) was observed on certain frequency scales.

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This work is devoted to the experimental study of singular regions at the high-latitude boundary of a geomagnetic trap, where the incoming solar plasma flow forms a zone of strong turbulence—a turbulent boundary layer (TBL). In the TBL, magnetic field fluctuations are on the order of field magnitude, while their total energy density (W_b) in the range from 0.1 to 1 Hz amounts to 10–30% of the density of ion thermal energy $E_{\rm th}$ [1]. The possible formation of TBL was predicted by Haerendel in [2]. More recently, a number of groups continued studying the region of the outer polar cusp in a high-latitude region of the magnetic-field minimum at the boundary between the nightside and dayside magnetic field lines. However, much of the effort was focused on the reconnection of field lines at low latitudes. In [3], it was shown that the TBL is virtually constantly present and that its fluctuations have an essentially nonlinear character. It is the purpose of this work to discuss the properties and nature of fluctuations in the TBL on the basis of the Interball-1 satellite data,

Turbulent boundary layer at April 2, 1996. A typical exit of the Interball-1 satellite from the polar cusp and its entry into the magnetosheath (MSH) between the collisionless shock in the solar wind and the magnetopause (MP) which occurred April 2, 1996, is shown in Fig. 1 (see also Fig. 4). The MP manifests itself by a transition of the magnetic field component B_x from large negative values to small (on average) values and by the predominance of E_{th} over the magnetic pressure $B^2/8\pi$ in the TBL and MSH. The region of transition to the plasma flow (PF), where $E_{th} \sim E_{kin}$ (ion kinetic energy density), is separated from the MP by the zone of enhanced turbulence (i.e., TBL), which is shown by black shadowing under the trace of the total energy

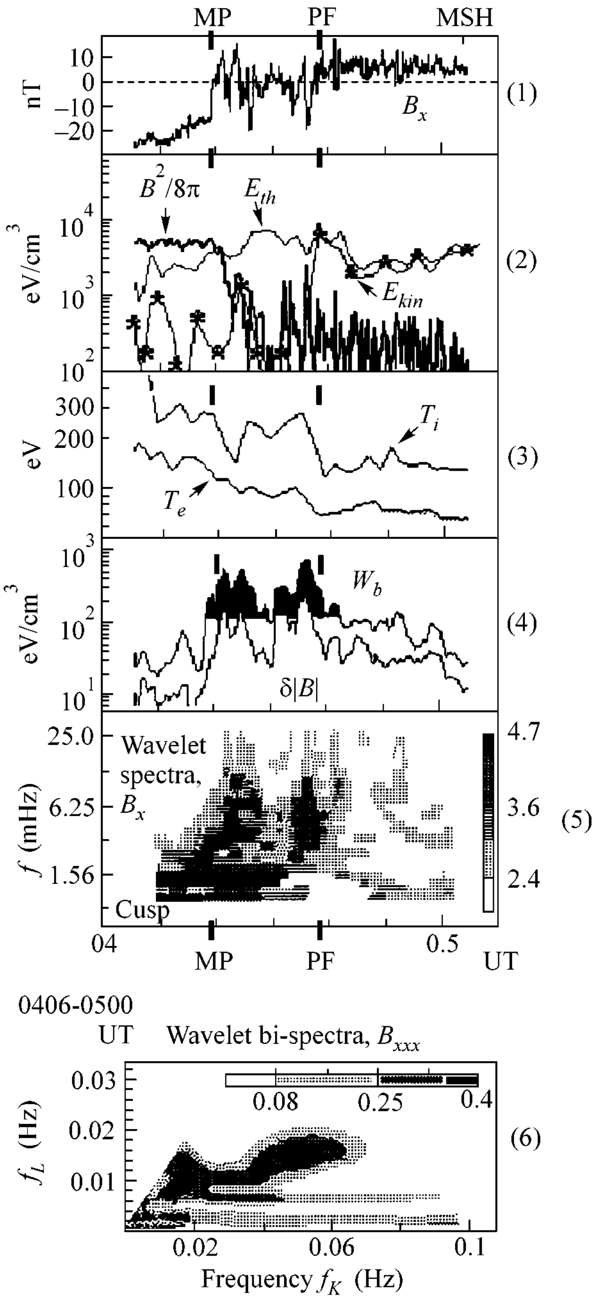

Fig. 1. The Interball-1 exit from the cusp and its entry into the MSH at April 2, 1996 (for details, see text). From top to bottom: (1) B_x is the magnetic field component, (2) ion and magnetic field energy densities, (3) ion and electron temperatures, (4) magnetic fluctuation power, (5) wavelet spectrum of B_x, and (6) wavelet bi-spectrum of B_x.

density W_b of magnetic field fluctuations. The W_b quantity includes the variations of field magnitude and its angular oscillations. A comparison of W_b with the fluctuation energy $\delta|\mathbf{B}|$ of the absolute value of magnetic field in the same energy range and with E_{th} indicates that, in this zone, W_b attains $3.5\delta|\mathbf{B}|$ and $0.1E_{th}$ (i.e., incompressible oscillations dominate). In this zone, the ion temperature T_i increases by a factor of 2.2 and the electron temperature T_e increases by a factor of 1.3, while the magnetic energy density $B^2/8\pi$ drops to low values corresponding to "diamagnetic bubbles" (DB; see [1, 3]). One can see in the lower left corner of the lower panel in Fig. 2 that $|\mathbf{B}| \sim 1$ nT inside DB; i.e., the magnetic field is expelled by hot plasma. The structure of the PF boundary differs substantially from the shock by the presence of a magnetic barrier with $B^2/8\pi \sim E_{th} \sim E_{kin}$ at its maximum in the MSH. This magnetic barrier is a soliton with scale ~130 km (on the order of the ion gyroradius in the MSH) along the direction of minimal magnetic variations (normal to the front) and trapped gyrotropic ions with energy <300 eV (this region is separated by vertical lines in the upper panel of Fig. 2). As for the ions with the gyroradius exceeding barrier size (>170 km), they freely overcome it. The scale was estimated from the delay between the satellite and the subsatellite; the estimate gave a value of ~12 km/s for the plasma velocity along the normal in the satellite coordinate system. Figure 3a shows the ion velocity hodograph (V_x, V_y) in the Sun–Earth ecliptic coordinate system for the transition from TBL to MSH. The velocity vector has a constant direction in the MSH, and the transition is characterized by a decrease in velocity from (–175; 75) to (–60; 0) km/s and the appearance of "loops," which are most naturally explained by the presence of a vortex street in the TBL (cf. [2, 1]). The maximal vortex scale, as estimated from the delay between the satellite and subsatellite transverse to the PF boundary, equals several thousand kilometers, while the estimation from the mean loop velocity (i.e., along the PF) gives ~10 000 km. For the smallest velocity vortices, the scale is ~1000 km. In Fig. 3b, the magnetic field vector at the PF barrier also displays vortex-like transition on a mean scale of 1000 km, together with the presence of small vortices with a size of ~100 km. High-resolution data suggest that the turbulent cascade in the TBL extends to several kilometers (to the electron inertial length). This indicates that field-line freezing in the TBL is broken. However, a considerably weaker electron heating is an indicator of the most intense energy dissipation in the ion gyroradius region (Figs. 2 and 3a). The wavelet spectrogram (see [3]) in Fig. 1 (panel 5) demonstrates a cascade-like development of the perturbations in the TBL; mutually related spectral maxima appear at several frequencies, and the transitions are observed both from low to high frequencies (direct cascade) and in the opposite direction (reverse cascade). Attention should also be given to the maximum at ~1.5 mHz, which is seen both in the TBL and in the MSH and cusp; judging from its intensity, it appears in the TBL near the MP. The cascade-like perturbations correspond to a slope of 1.18 for the B_x power spectrum at frequencies 1–45 mHz and to 2.4 at 0.05–0.4 Hz. Both are different from the slopes of the Kolmogorov spectra of hydrodynamic or Alfvén turbulence (5/3 or 3/2; see [4]). A slope of 1.18 is typical of

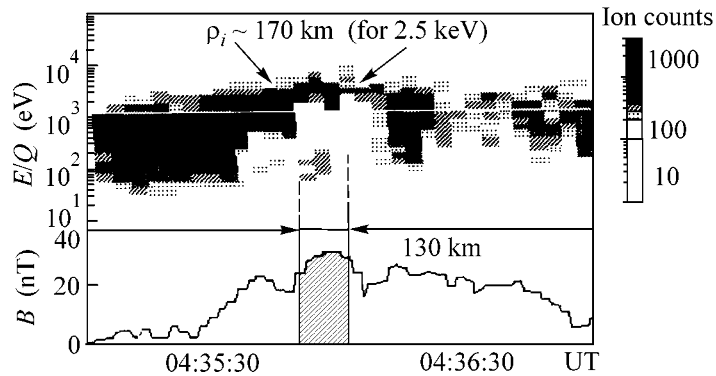

Fig. 2. Structure of the PF boundary; (top) energy distribution per a charge of ions flying from the Sun and (bottom) |**B**|.

a current layer in the critical self-organization state [5]. The detection of fluctuations with different properties indicates the presence of a two-phase (in the statistical meaning) plasma in the TBL; the DB inclusions are analogous to the formation of air bubbles in a boiling fluid.

Influence of turbulence properties on the transport processes. The process of plasma flow (double thick arrows) past the region of geomagnetic field-line divergence (thin lines with arrows) in the vicinity of the polar cusp is schematically illustrated in Fig. 4. The magnetopause MP is concave in this region (thick black line); the solar wind field lines (marked squares) are deformed and run along the MP; at April 2, 1996, the Interball-1 orbit passed over approximately along the diagonal from the bottom right to the top left; the boundary of regular flow is shown by thick dashes. In more than 80% of the cases (of ~400 crossings from 1995 to 2000), the magnetic field and the plasma flows inside the PF were irregular and display the features of vortex cascades [1, 3]. The TBL is adjacent to the MP (shown by vertical hatching). As in Fig. 1, the PF at the center of the region of interest is usually separated from the TBL by the region with reduced W_b and irregular plasma velocity. The average field direction in the TBL is controlled by the interplanetary magnetic field (IMF). Inside the MP, the field is controlled by the Earth dipole, whereas plasma enters the MP (into the cusp; shown by horizontal hatching in Fig. 4) with a slight decrease in E_{th} and an increase in T_i; i.e., the boundary is, in actuality, transparent with clearly seen current layers (cf. B_x in Fig. 1). This picture depends weakly on the IMF, which is important for the penetration of plasma inside the "foreign" magnetic field. The reconnection of the antiparallel field lines at the smooth laminar MP was assumed to be the major mechanism of plasma penetration inside the MP. However, the weak dependence of the cusp and TBL on the IMF direction and the observation of strong perturbations up to the electron inertial length indicate that there may also be different mechanisms. The author of [2] has assumed that the flow into the MSH is broken by an obstacle in the form of a step at the MP to form the TBL, where the ion kinetic energy transforms into heat. Indeed, on the large scales shown in Fig. 1 (for example, at 0430 and

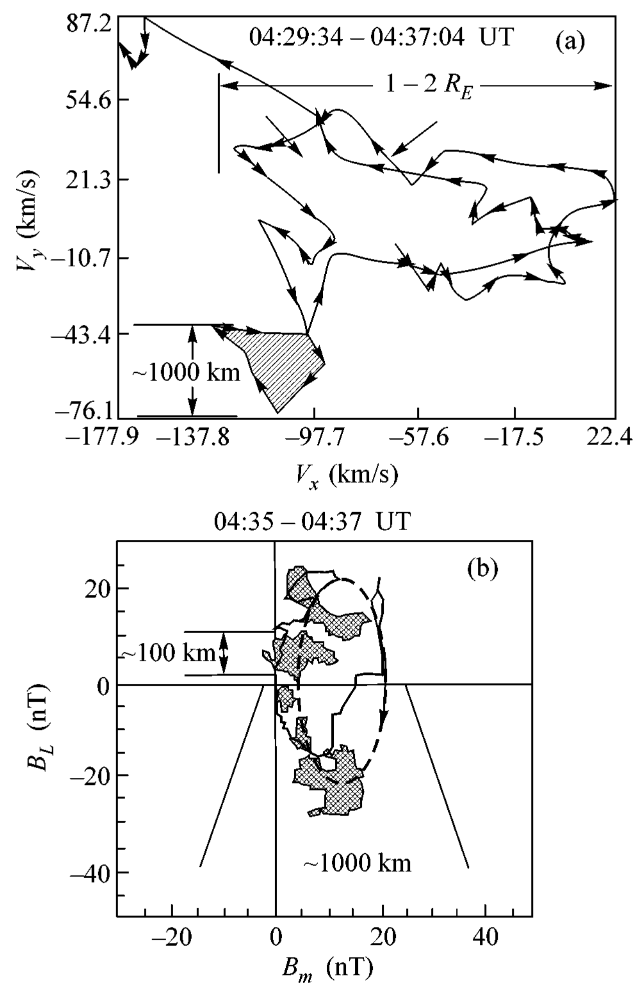

Fig. 3. (a) Ion velocity for the TBL and (b) magnetic-field hodograph for the PF.

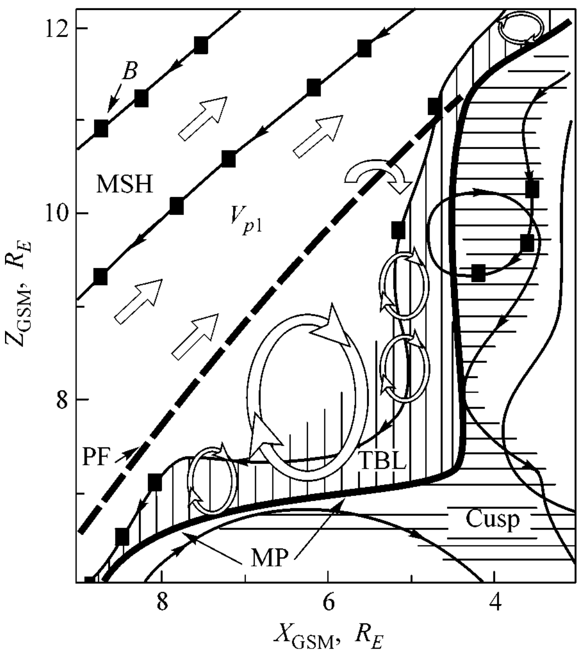

Fig. 4. Scheme of plasma flow along the high-latitude MP over the cusp (for details, see text).

0500 UT), $E_{th} + E_{kin} \sim$ const, with $E_{th} \gg E_{kin}$ inside the PF. Near the PF the flow is locally accelerated to the energies E_{kin} higher than in the MSH. This can really be explained by the acceleration due to the reconnected magnetic-field tension. The reconnection is possible both near the geomagnetic equator and in the cusp locality (an example of reconnection is illustrated in Fig. 4 by the field-line loop with squares). The small-scale fluctuating fields are reconnected efficiently in the TBL as well, as is evident from the breakdown of field-line freezing-in (by virtue of fluctuations on the electron inertial length scale). This allows plasma to penetrate inside the MP and provides efficient magnetic-flux transfer from the dayside of the magnetosphere to its nightside. Nevertheless, we assume that, in the essentially nonlinear situation occurring in the TBL, plasma percolation through the structured boundary makes the main contribution to the local mass transfer inside the MP. Taking the appropriate estimate of diffusion coefficient from [6], one obtains $D_p \sim 0.66\ (\delta B/B_0)\rho_i\Omega_i \sim (5\text{–}10) \times 10^9\ \mathrm{m^2/s}$ for the typical MP parameters, where $\delta B/B_0$ is the ratio of the perturbed magnetic field to its average value, and ρ_i and Ω_i are the ion gyroradius and gyrofrequency, respectively. The resulting value; of (1–2) $\times\ 10^{27}$ particles/s obtained for the flow through the northern and southern TBL is sufficient for filling the magnetosphere with solar plasma.

Let us now turn to the nature of oscillations in TBL. Phase velocity is one of the properties that allows the low-frequency perturbations to be identified with the kinetic Alfvén waves (KAWs). We used the Interball-1 and Polar satellite data on the electric (E) and magnetic (B) fields in the TBL at August 26, 1995, May 5, 1996, June 19, 1998, and June 23, 1998 to verify that (a) like on April 2, 1996, the magnetic spectrum has two characteristic slopes and (b) the low-frequency phase velocity $V_{ph} = E/B$ is close to the Alfvén velocity V_A and shows, on the average, a tendency toward the frequency dependence characteristic of the satellite flight through the KAW spatial structures, up to a frequency of several hertz (which is several times lower than the hybrid frequency). This dependence is expressed by the formula [3]

$$(E/B)^2 \sim V_A^2(1 + (\rho_i\omega/V)^2) \qquad (1)$$

where ω is the frequency, V is the velocity of KAW structures relative to the satellite, and $(\rho_i\omega/V)^2$ is the kinetic addition allowing for the finiteness of the ion gyroradius (KAW takes its name precisely from this fact). In most cases, the asymptotic behavior of (E/B) had the form $\sim\omega$, i.e., corresponded to Eq. (1). This, however, cannot be distinguished from the detection of waves with a constant wave vector **k**, because the Fourier transform of plane waves obeys the Maxwell equation $kE \sim \omega B$. Therefore, Eq. (1) does not allow the identification of KAW in the asymptotic region. The TBL is also characterized by the three-wave decay processes satisfying the condition $f = f_L + f_K$ (for more detail, see [3]). In the frequency range of interest, the products of the appropriate three amplitudes show maxima up to 40% at frequencies $f_L \sim 1.5$, 5, and 15 mHz (vertical axis in the lower panel for the wavelet bi-spectrum in Fig. 1) and over a continuous range of 1.5–80 mHz for f_K. This signifies that the phase–frequency relations are fulfilled for the three-wave process (if the higher-order nonlinear processes are ignored) and the structures with the indicated frequencies f_L decay in a broad range of frequencies f_K and f. That is, the processes at these frequencies (on the vertical axis) synchronize cascades in a broad frequency range (along the horizontal axis). A well-defined maximum at (f_L, f_K) $\sim$ (15, 50) mHz indicates that the reverse cascade can be pumped at high KAW frequencies. We thus assume that the inhomogeneities in the incoming flow interact with the current layer of MP to generate KAWs, a part of which are reflected back, focused by the concave MP, and interact with the incoming flow. As a result, a number of cascades synchronized at the above-mentioned frequencies f_L arise self-consistently. If the estimate of the upper limit of the characteristic scale at 1.5 mHz is carried out using V_A, then $L \sim V_A/f_L \sim (3\text{–}7)R_E$ (Earth radii) is comparable with the TBL length, and L is also on the order of the radius of curvature of the unperturbed MP or the MSH thickness at the dayside. On the other hand, the presence of a maximum at 1.5 mHz both in the MSH and in the cusp inside the MP (Fig. 1) also suggests that the observed process is global. To understand the nature of this resonance in more detail, it is necessary to carry out additional measurements at several points and at distances of both several thousand kilometers and several Earth radii. We used the magnetosonic Mach number M_m in MSH, the Alfvén number, for either the ion velocity projection normal to the PF ($M_{An} \sim M_m \sim 1.2$) or the total velocity ($M_A \sim 3.5$) to compare the ion heating in the TBL with the Rankine–Hugoniot relations at the shock and arrived, respectively, at the following results: $T_i/T_{\rm MSH} \sim 1 + (\gamma - 1)M^2 \sim 1.6$ or ~5 for the adiabatic exponent $\gamma \sim 5/3$ (remembering that $E_{\rm th} \gg E_{\rm kin}$ in the TBL). The observed ion heating in the TBL (~2.2) is greater than at the oblique shock and considerably less than its maximum possible value. Therefore, the observed process of energy transformation differs substantially from the one in the collisionless shock; the entire perturbed region (Fig. 4) should be considered as a whole with long-operating KAW cascades and vortex streets, as well as with local discontinuities and solitons (MP and PF).

To conclude, we would like to note that the investigation into the role and properties of turbulence at the critical point of a geomagnetic trap (turbulent boundary layer) allows the revelation of the key role of turbulent microprocesses accompanying the interaction of plasma flows with magnetic obstacles, be it the fields of planers, starts, black holes, or laboratory traps, and demonstrates real mechanisms of energy transformation in collisionless plasmas.

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