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Dynamic Interaction of Plasma Flow with the Hot Boundary Layer of a Geomagnetic Trap

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The study of the interaction between collisionless plasma flow and stagnant plasma revealed the presence of an outer boundary layer at the border of a geomagnetic trap, where the super-Alfvén subsonic laminar flow changes over to the dynamic regime characterized by the formation of accelerated magnetosonic jets and decelerated Alfvén flows with characteristic relaxation times of 10–20 min. The nonlinear interaction of fluctuations in the initial flow with the waves reflected from an obstacle explains the observed flow chaotization. The Cherenkov resonance of the magnetosonic jet with the fluctuation beats between the boundary layer and the incoming flow is the possible mechanism of its formation. In the flow reference system, the incoming particles are accelerated by the electric fields at the border of boundary layer that arise self-consistently as a result of the preceding wave–particle interactions; the inertial drift of the incoming ions in a transverse electric field increasing toward the border explains quantitatively the observed ion acceleration. The magnetosonic jets may carry away downstream up to a half of the unperturbed flow momentum, and their dynamic pressure is an order of magnitude higher than the magnetic pressure at the obstacle border. The appearance of nonequilibrium jets and the boundary-layer fluctuations are synchronized by the magnetosonic oscillations of the incoming flow at frequencies of 1–2 mHz. © *2004 MAIK “Nauka/Interperiodica”.*

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This work is devoted to the experimental study of the dynamic interaction of plasma flow with a local obstacle in which the transverse pressure of hot plasma dominates: $\beta_i = nT_i/W_b > 2$ ($W_b = B^2/8\pi$ is the magnetic pressure, n is the ion density, and T_i is temperature; all energy quantities are in eV/cm^3 (Fig. 1)). This occurs over the magnetic poles of traps in the regions, where the absolute value of magnetic field is minimal and which are filled with external (originally) plasma (Fig. 1b). This work is the continuation of our work [1], where the opposite limiting case of plasma deceleration and chaotization by a “rigid” magnetic barrier was considered. The main distinction is that the flow regime considered in this work is inhomogeneous and nonstationary, in which the flow kinetic energy does not fully transform into nonlinear wave cascades in the stagnation region ahead of the obstacle [1], but first is “released” downstream in the accelerated magnetosonic jets. The plasma–plasma interaction proceeds through large-amplitude waves. It is anticipated that the dynamic flow regime considered in this work will throw light on the mass- and energy-transfer processes at the borders of astrophysical objects and laboratory traps and allow the study of plasma–plasma interaction remotely using secondary radiations in accelerated inhomogeneous jets.

We illustrate the interaction between the incident and stagnant plasmas by the example of the Interball-1 satellite data on June 19, 1998 (Fig. 1). In Fig. 1a, the spectrogram of the intensity of ion kinetic-energy fluctuations is given for $W_{\text{kin}} = 0.5nM_iV_i^2$ (M_i and V_i are the proton mass and velocity, respectively) and the main waves are shown (see also Fig. 2 and [2]). The transition from the unperturbed equilibrium flow (from the left in Fig. 1b) to the boundary layer near the trap border (magnetopuase (MP)) is shown in Fig. 1b. The satellite was brought into the trap near the magnetic-field bifurcation over the trap magnetic pole (the field had a nonzero upward projection at the top of the border and a nonzero downward projection at the bottom), where the magnetic density is low and an inner boundary layer (cusp) filled with a heated solar plasma (“plasma ball” [2]) is formed. The flow, on average, is subsonic, and the ion pressure nT_i dominates; the domains with $W_{\text{kin}} > W_b$ (Fig. 1c) correspond to the super-Alfvén flow [2]. In

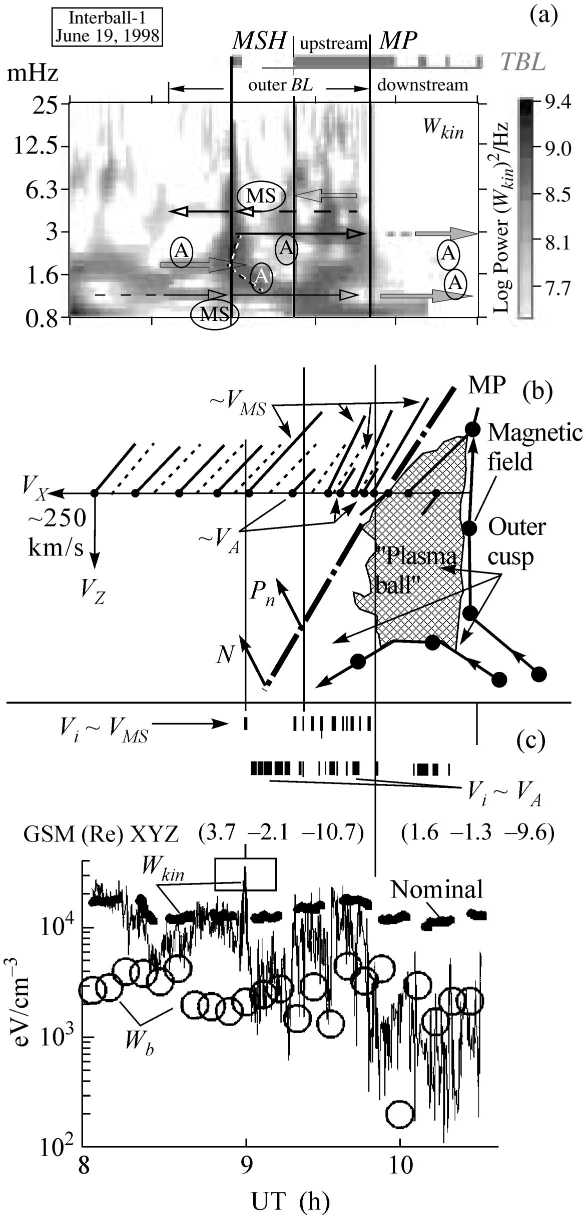

Fig. 1. (a) Morlet wavelet transformation [1, 2] of the ion kinetic-energy density $W_{\rm kin}$ on June 19, 1998. Arrows indicate the propagation directions of the Alfvén (A) and magnetosonic (MS) waves. (b) Vectors of plasma velocity along the Interball-1 satellite orbit in the *XZ* plane of the geocentric solar ecliptic (GSE) coordinate system (dashes: nominal values [2]); *N* is the normal to the magnetopause (MP) ~ (0.7, 0.07, –0.71) [2]; the MP is denoted by a heavy line with discontinuities; and the magnetic field **B** is shown by the arrowed curves with circles. (c) Energy densities $W_{\rm kin}$ (nominal value is shown by bold dashes; see [2]) and (circles) W_b in eV/cm^3. The first MS jet is indicated by the rectangle, and the instants of time at which the ion velocity (V_i) was close to the magnetosonic (V_{MS}) and Alfvén (V_A) velocities are shown at the top of Fig. 1c.

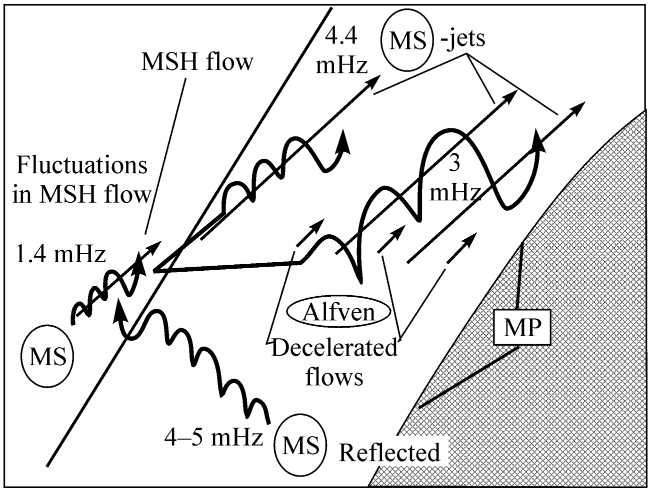

Fig. 2. Scheme of interaction between the magnetosonic waves in magnetosheath (MSH; 1.4 mHz; see Fig. 1a) and the reflected MS waves (4–5 mHz), and the decay into the accelerated MS jet (4.4 mHz) and decelerated Alfvén waves (Alfvén; 3 mHz).

contrast to [1], W_b rapidly drops immediately under the MP (β_i ~ 15). At 09:00 UT, the measured $W_{\rm kin}$ exceeds the nominal value by a factor of 2.5, which corresponds to the appearance of the first accelerated plasma jet with a velocity close to V_{MS} ~ $(2T_i/M_i)^{1/2}$, i.e., a magnetosonic (MS) velocity at high β_i (MS jet at 09:00 UT). Thereafter, a decelerated Alfvén flow (A) arises, as follows from the fact that $W_{\rm kin}$ ~ W_b, i.e., V_i ~ V_A = $B/(nM_i)^{1/2}$, where V_A is the Alfvén velocity. The relaxation time of the slow jet is on the order of 10–20 min. The MS and A domains are marked off by black rectangles at the top of Fig. 1c. Since the dynamic pressure of the first MS jet is as high as its value in solar wind and, hence, far exceeds the magnetic pressure even deep inside the obstacle (Fig. 1c), such jets, when flowing around complex magnetic configurations, can distort the boundary and even penetrate it (cf. "impulsive penetration" in [3]) at large angles of incidence relative to the average flow (as in [1]). Hence, the phenomenon discussed here should have an appreciable effect on the flow process and on the local shape of the obstacle.

At 09:00 UT, the projection of the Poynting's vector onto the normal to MP (**N** in Fig. 1b; see [2]) is $P_n < 0$, indicating that the corresponding perturbation approaches the MP (i.e., the reconnection of magnetic fields at the MP cannot be its source). The average flow $n|\mathbf{V}_i|$ at 08:55–09:55 UT decreases by more than 40% with respect to its nominal value (cf. $W_{\rm kin}$ in Fig. 1c), which, at first glance, points to the fact that the momentum conservation law is violated (after time averaging). However, the MS jet formed in the unperturbed flow moves in the **N** direction with the velocity of the surrounding flow, while the rest of the boundary layer moves together with the MP. Inasmuch as the velocity of the unperturbed flow is, approximately, an order of magnitude higher than the MP velocity [2, 3], the momentum conservation law is obeyed after averaging over the distance along **N**.

The reliable detection of the waves reflected from the obstacle with the use of the Poynting's vector is one of our main experimental results. After 09:00 UT, reflected waves with $P_n > 0$ are repeatedly seen [2]. From 08:35 UT, intense bursts with $P_n < 0$ (downstream) appear, which are unrelated to the perturbations in the external flow (cf. the nominal value of $W_{\rm kin}$ in Fig. 1c and [2]); i.e., they correspond to the downstream momentum release.

At low frequencies, only the MS wave can propagate counter to the super-Alfvén flow (the Alfvén Mach number is >2) [3, 4]. By comparing the ion-density N_i and velocity V_{ix} spectrograms with allowance for the Poynting's vector [2], we determined the wave types in the essentially nonlinear situation: the reflected MS waves with a weak maximum at 4–6 mHz (marked "MS" and "Reflected" and by the leftward arrow in Figs. 1a and 2; for them, $P_n > 0$) interact at 1.4 mHz with the MS wave in the incoming flow. This results in the oscillation amplification and gives rise to an A wave at 1.7–2.2 mHz. The process ends at 09:00 UT in the MS jet generation, shown in Fig. 1a as a decay of the initial oscillations into the MS-jet and Alfvén waves (3 mHz, Alfvén). At 09:15–09:45 UT, the reflected waves at 5–6 mHz initiate multiple MS/A decays.

Three periods $T_1 \sim 13$ min corresponding to a frequency of 1.4 mHz cover the entire outer boundary layer. This frequency modulates the spectral maxima at 3–10 mHz. This fact conforms with a "thick" turbulent boundary layer (TBL) [1] (rather than with a thin shock front), where equilibrium is attained within several periods (T_1) of the main oscillation that synchronizes the phases of all the interactions, from the unperturbed flow to the TBL and plasma ball. The phase synchronization is evident from the bicoherent character of V_{ix}, which sets off the processes with frequencies $f_s = f_l + f_k$ (see [1, 2]): the bicoherence is appreciable only if the phases of the three processes are synchronized. We assign the bicoherence maximum at 1.4 mHz + 3 mHz = $f_l + f_k = f_s$ = 4.4 mHz with an amplitude of ~75% to the decay of the stationary flow into the nonstationary MS/A flows. The phase synchronization at these frequencies provides the interplay between the processes prior to the jet formation in the boundary layer. The most intriguing experimental fact is that the initial flow decays precisely into the MS/A flows. It is likely that this is one of the most prominent examples of three-wave decay in plasma; each of the secondary waves consists of flows propagating with the corresponding characteristic velocity. So far, the presence of accelerated plasma in the boundary layer was regarded as evidence that the energy accumulated in a magnetic field compressed by an external flow transforms during the process of reconnection of the flow and trap magnetic fields in a hypothetically small region, where the plasma freezing-in breaks down due to the efficient conduction [3]. In the case of the initially antiparallel magnetic fields, the acceleration to the Alfvén velocity is due to the magnetic tension. However, the Alfvén Mach number in the MS jet is higher than 3, which, with allowance for the fact that the mean $\beta_i > 2$, excludes the local magnetic-field reconnection as a cause of jet acceleration. To reveal the acceleration mechanism for the jets near the magnetopause, it is convenient to compare their dynamic pressure with the magnetic pressure inside the obstacle, because the upper limit for $W_{\rm kin}$ upon the reconnection is $0.5nM_iV_A^2 \sim W_b$; i.e., it depends only on $|\mathbf{B}|$. In the case of $W_{\rm kin} \gg W_b$ (as in Fig. 1c), an alternative plasma-acceleration mechanism based on the direct flow-energy transformation without the intermediate energy accumulation in the distorted magnetic field is expected to be operative. This mechanism (the structurization of nonlinear oscillations) is the opposite of the flow thermalization in the shock wave, as regards the increase in the ordered MS-jet velocity. For plasma, it turns out to be energetically more profitable to "release" downstream the excess of its momentum through the acceleration of its small portion and pass to the decelerated Alfvén flow closer to the obstacle border (Fig. 2). This process can be described using the formalism corresponding to the maser-type mechanism of formation of magnetosonic solitons ([5]): the system radiates a coherent magnetosonic packet (MS jet) and turns to the stable state with the Alfvén flow. If the fast and slow flows are spatially separated, the slow flow starts to interact with the newly incoming super-Alfvén flow to relax to its nominal level or initiate oscillations in the outer boundary layer.

Thus, the study of the plasma-flow interaction with a geomagnetic trap gives evidence that the laminar flow transforms into nonstationary magnetosonic jets and decelerated Alfvén flows behind the shock wave. They are involved in a unified synchronized process of interaction in the outer boundary layer ("outer BL" in Fig. 1a), whose thickness is estimated at 1–2 Earth radii R_E for a distance of $\sim 10R_E$ between the MP and the Earth. The characteristic (synchronizing) frequency of ~1.4 mHz can be assigned to the resonance plasma oscillations between the dayside magnetopause and the shock wave (Yu.I. Gal'perin, private communication, 2001).

The frequencies f_l and f_k (1.4 and 3 mHz in Fig. 2) relate to the time domain in the MP system, because the corresponding maxima are seen at practically the same frequencies over a wide range of flow velocities (and, hence, Doppler shifts; see Fig. 1 and [2]).

Neglecting the MS-jet oscillation frequency compared to the Doppler shift and using the frequency summation rule $f_l + f_k = f_s$ in bi-spectra, we obtain the condition for the Cherenkov resonance of the jet with the fluctuation beats between the incoming flow and the boundary layer in the case of interacting media moving relative to each other (cf. [4]):

$$f_l + f_k = \mathbf{k}\mathbf{V}/2\pi, \qquad (1)$$

where **V** is the mean velocity of the unperturbed plasma in the MP system, where the interaction takes place, and **k** is the wave vector. The characteristic MS-jet size along the flow can be estimated as $L = |\mathbf{V}|/(f_l + f_k) \sim 5R_E$, in compliance with the above assumption that the MS jet and the corresponding A flow are spatially separated if the characteristic transverse size of the streamlining zone is $\sim 20R_E$.

We now consider quantitatively the plasma acceleration in a nonuniform external transverse electric field encountered by the unperturbed flow at the border of the outer boundary layer. This interaction is similar to the Fermi acceleration induced by the boundary-layer border (inclined "wall") moving toward the $+X$ axis in the plasma reference system (MSH; Fig. 2). The magnetosonic velocity V_{MS} is the asymptotic value of mean velocity of an initially subsonic jet. For the mean plasma velocity $\mathbf{V} \sim (-170, -70, -80)$ km/s at 08:54–08:58 UT, we calculated the electric field in the plasma reference system; it increased to 8 mV/m in the MS-jet region. Since the time resolution (10 s) is smaller than the proton gyroperiod (2–3 s), while the lower estimate of the jet width (300 km for the projection of the boundary-layer velocity behind the jet onto the normal to MP) exceeds the proton gyroradius (~100 km), we use the inertial-drift approximation [6] with the drift velocity

$$\mathbf{V}_d^{(1)} = 1/(M\omega_H^2)d\mathbf{F}/dt = Ze/(M\omega_H^2)d\mathbf{E}/dt, \qquad (2)$$

where M, ω_H, and Ze are the particle mass, cyclotron frequency, and charge, respectively, and **F** and **E** are the transverse force and electric field, respectively. The upper index (1) denotes first order in the small parameter, as compared to the zero-order drift approximation for uniform fields. Then, the energy increment is defined as [6]

$$\delta W_{\text{kin}} \sim \delta(nM(\mathbf{V}_d^{(0)})^2/2), \qquad (3)$$

where the gradient-drift velocity in an electric field is $\mathbf{V}_d^{(0)} = c[\mathbf{E} \times \mathbf{B}]$ (c is the speed of light and **B** is the magnetic vector). The value $\delta W_{\text{kin}} \sim 30$ keV/cm^3 obtained from Eq. (3) for the measured parameters agrees well with the maximal density $W_{\max} \sim 35$ keV/cm^3 of the jet kinetic energy and with the mean value $W_{\text{kin}} \sim 7$ keV/cm^3 immediately ahead of the jet (Fig. 1c). Moreover, it follows from Eq. (2) that the ions and electrons drift in different directions. This explains the appearance of "intermittent" current layers with anomalously high statistic of large magnetic-field rotation angles in the turbulent boundary layer [2].

We note in conclusion that the process of streamlining nearby the plasma–plasma boundary is nonequilibrium on a time scale comparable with the characteristic observation time of Alfvén flows (10–20 min). Instead of a gradual plasma acceleration near the side walls of the obstacle, accelerated and decelerated jets are observed. The accelerated jets carry away downstream the difference in momenta of the unperturbed flow and the flow decelerated in the outer boundary layer. The dynamic pressure of the jets is so high that they can distort the local boundary of the obstacle and penetrate into it at large angles of incidence.

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