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Magnetosheath interaction with high latitude magnetopause: Dynamic flow chaotization

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Abstract

Exploration of plasma–plasma interactions at the high-latitude magnetopause versus a simulated sheared current sheet with strong fluctuations of realistic spectral shape, revealed a new type of dynamic equilibrium, in which nonlinear disturbances serve as an effective obstacle for 80% of the incident magnetosheath ions, providing also the exchange by ~10% of plasma particles with the stagnant high-beta boundary layer in the minimum field region over the polar cusps. The measured waves, reflected upstream by the boundary, interact in the 3-wave manner with the magnetosonic (MS) fluctuations of the incident flow, resulting in their amplification and then decay into accelerated MS-jets and Alfven waves, driving decelerated flows at the Alfven speed. This impulsive momentum loss via the MS-jets contributes in the average flow bend around the magnetosphere. The leading jet appearance is suggested to be phase-synchronized with both the initial MS fluctuations and nonlinear cascades upstream at the magnetopause, which constitutes the wavy obstacle with multiple decays into the smaller MS-jets and Alfvenic flows.

High dynamic pressure in the MS-jets does not fit their acceleration by a reconnection; instead the jets are able to initiate the driven reconnection in the process of interaction with a downstream magnetopause. The acceleration of the MS-jets is consistent with a Fermi-type mechanism, in which electric wave-trains play the role of a moving non-continuous 'wall'. Estimations of the jet scales from the approach of a nonlinear Cherenkov resonance conforms 2–3 reflections of the jet from the 'wall' before overcoming the 'wall' potential barrier.

We demonstrate quantitative agreement of the acceleration of the leading MS-jet in the process of inertial ion drift in variable electric fields. Current sheets, generated due to opposite sign of the ion and electron inertial drift, can account for the intermittency of the TBL fluctuations.

Keywords: Magnetopause; Magnetosheath; Turbulent boundary layer; Cusp

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1. Introduction

We study plasma–plasma interactions at the high-latitude boundary of the magnetopause (MP), where the incident solar plasma flow is separated from the pre-existing boundary layer plasma in the outer cusp throat mainly by a zone of a strong turbulence—a turbulent boundary layer (TBL). A substantial difference of the present work from previous TBL studies (Haerendel, 1978; Savin et al., 1998, 2001) is that in the reported case of high ion beta (β), magnetic forces are negligible. Thus, only the high-amplitude disturbances decline and scatter the major incident flow (Savin et al., 2002, 2004b). Such an interaction supports dynamic source-sink equilibrium versus the static one at the MP current sheet between the incident plasma and magnetic barriers (Savin et al., 1998, 2001). In the latter case, the energy stored in the compressed barrier can be released via magnetic reconnection, either global or secondary (Haerendel, 1978; Hultqvist et al., 1999). In the case under study, an amplification of the upstream fluctuations in the process of interaction with sunward back-scattered waves causes their nonlinear decay representing a manner of direct transformation of the laminar flow energy into a chaotic plasma motion (Savin et al., 2001, 2004b). Similar direct interactions and plasma inter-penetration could control also much of the topology and energetics of laboratory plasmas, different magnetospheres, stars and all of astrophysics.

In this paper, we carry out a detailed analysis of the TBL on June 19, 1998 (Savin et al., 2002, 2004b) including a new data on the ion-velocity bi-coherence in the TBL just upstream the MP. This constitutes a necessary background for testing the Fermi-type acceleration mechanism by moving non-continuous 'wall', i.e., by electric wave-trains at the outer border of the MP boundary layer. The extremely high dynamic pressure in the jets occurred as a result of conversion of the ion thermal energy (cf. Laval nozzle approach in (Yamauchi et al., 2003)), being about an order of magnitude larger than the energy from any reconnection mechanism (Hultqvist et al., 1999) in this case. We concentrate on a quantitative comparison of the presented data with the jet acceleration in the process of the inertial drift of MHS ions in the varying electric field. The mechanism of inertial drift also predicts generating of current sheets that can explain the intermittency of the TBL fluctuations (Savin et al., 2002).

Finally, we compare our data with a simulated turbulent current sheet (Taktakishvili et al., 2003) for which in simulations the spectral shape and magnitude of magnetic fluctuations from our data have been used (e.g., Savin et al., 2001, 2002). To our knowledge this comparison provides, for the first time, a quantitative estimate of the role of high-amplitude disturbances in the high-β case: in zero order (80% particles in simulations), the turbulence serves as a separator of two plasmas, while in the first order (10% particles in simulations), the turbulence provides an exchange across the separator. In Taktakishvili et al. (2003), the authors have not done a detail comparison with high-resolution data and have not outlined that reflection of ~80% of the external ions by nonlinear TBL fluctuations can be regarded as the presence of an effective obstacle for the incident plasma.

2. Interball-1 inbound magnetopause crossing on June 19, 1998

On June 19, 1998, Interball-1 crossed the inbound magnetopause (MP) at a critical region—outer cusp, where the Earth's magnetic field is bifurcated and the heated magnetosheath (MSH) plasma penetrates down to the ionosphere from diamagnetic cavity called a 'plasma ball' (Savin et al., 2002, 2004b). This is namely the location of the direct plasma–plasma interaction, while at lower latitudes, the plasma interacts with the magnetic barrier. This case differs by the anti-sunward dipole tilt from that of Savin et al. (2001), where the dipole is inclined sunward and the disturbed MSH flow penetrates the cusp throat creating the TBL both over the indented MP and at the flow boundary. Strong fluctuations between the stagnant MSH and the outer cusp in the case of Savin et al. (2001) isolate them (see discussion below), while in our case, the 'plasma ball' represents a large-scale reservoir for the magnetospheric plasma (Savin et al., 2002, 2004b). Interball-1 moved from a laminar flow to the randomized stream adjacent to the MP. The MP is manifested here by the loss of control over the magnetic field direction from the solar wind (SW) magnetic field (Savin et al., 2002, 2004b). In Fig. 1a, the MP terminates strong perturbations at the ion density $N_{\rm i}$ and ion kinetic energy density $W_{\rm kin}$ (Savin et al., 2004b). At ~09 UT, the wideband spectral spike is seen in the wavelet spectrograms (Savin et al., 2001, 2002, 2004b) of the ion velocity $V_{\rm ix}$ (panel b) and in the electric field perpendicular to the jet at 09 UT ($E_{\rm perp}$ in the panel f, see Fig. 4a), which corresponds to the maximum in $W_{\rm kin}$ in Fig. 1e. The maximum in $W_{\rm kin}$ reaches the magnitude of the ion thermal energy density $nT_{\rm i}$ (a product of the ion density and temperature, see also Fig. 3a), i.e., the velocity in this narrow plasma jet is of the order of magnetosonic speed $V_{\rm MS}$ (Savin et al., 2001) (highlighted by bars over panel e). The latter is a direct indication of the magnetosonic nature of the disturbance as an alternative Alfvenic wave should have comparable kinetic and magnetic energy densities ($W_{\rm kin} \sim W_{\rm b}$, see respective gray bars at the bottom of the panel e), i.e., the speed is about twice less. This is namely the case at 09:03–09:15 UT (with interrupts). To confirm that those disturbances are not SW-driven, we