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OBSERVATION OF A SLOW-MODE SHOCK IN THE DAYSIDE MAGNETOPAUSE RECONNECTION LAYER

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ABSTRACT

Plasma and magnetic field data from the ISEE 2 spacecraft recorded on 29 Oct 1979 provide evidence for a slow shock (SS) in the reconnection layer of the dayside magnetopause. This layer is bounded on the magnetosheath side by the SS and on the magnetospheric side by a rotational discontinuity (RD). The direction of the accelerated plasma flow, the earthward sense of the normal magnetic field across both discontinuities, and the relative orientation of the SS and the RD all indicate that the reconnection site was located south of the spacecraft. Examination of the substantial pressure anisotropy downstream of the SS explains two unusual properties of the shock: (1) the slow-mode and intermediate-mode phase speeds are inverted downstream of the SS such that the RD propagates behind the SS rather than ahead of it; (2) the magnetic wave polarization reverses such that the SS initially displays a left-handed polarization and then switches to a right-handed polarization inside the shock structure.

INTRODUCTION

A principal feature of the original Petschek MHD model of reconnection /1/ is that the outflow region of the reconnection layer, which consists of two symmetrical narrow wedges with their vertices at the reconnection site, is bounded by two standing slow-mode switch-off shocks which serve to reverse the tangential component of the magnetic field across the reconnection layer. In more general reconnection models, which incorporate asymmetries in the plasma and magnetic fields on opposite sides of the reconnection layer /2,3/, the slow shocks and/or expansion fans are nested around a contact discontinuity and inside a pair of rotational discontinuities. However, despite these theoretical predictions of slow shocks forming part of the reconnection layer structure, in-situ satellite observations of the dayside magnetopause /4,5/ have yet to reveal them; only a single rotational discontinuity has been identified in the reconnection layer.

The purpose of this paper is to report evidence of such a slow shock in the dayside magnetopause reconnection layer recorded by the ISEE 2 satellite on 29 Oct 1979. Herein, we discuss the basic observations of this shock and report a number of unusual properties associated with it which result from a significant pressure anisotropy observed within the reconnection layer. A more detailed analysis may be found in /6/.

OBSERVATIONS

Figure 1 shows the ISEE 2 magnetic field and plasma moment data from 0115 to 0145 UT on 29 Oct 1979 during an outbound pass through the magnetopause/boundary layer region. At this time, the satellite was located at about 0927 LT, 8.5° LAT, and 13.1 R_E. The 2D velocity magnitude trace in the third panel of Figure 1 indicates large accelerated flows (shown shaded in the figure) during the magnetopause crossing, which are interpreted as evidence that reconnection was occurring at this

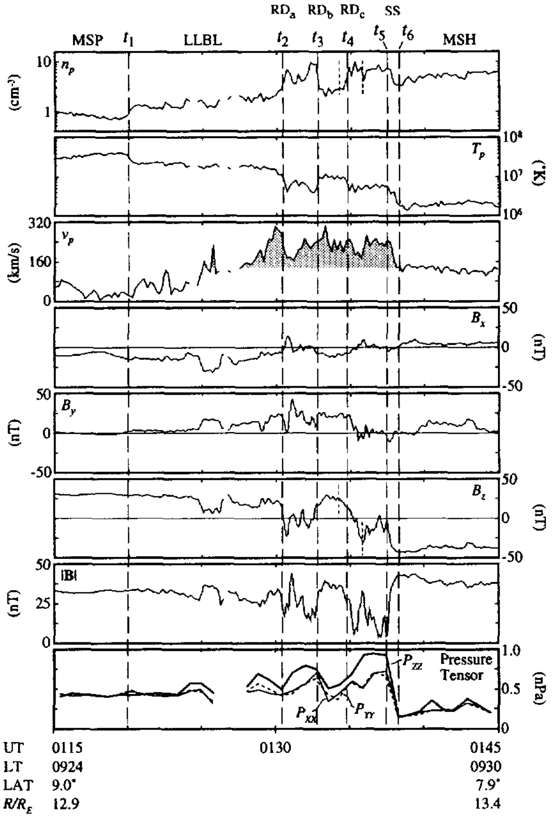

Fig. 1. ISEE 2 observations of magnetopause crossing on 29 Oct 1979. From top to bottom: proton number density (n_p), proton temperature (T_p), magnitude of the 2D plasma velocity (v_p), three components of the magnetic field (B_x, B_y, B_z), magnetic field strength ($|\mathbf{B}|$), and three diagonal components of the pressure tensor.

time. The ISEE 2 observations show that this accelerated plasma was flowing northward, indicating that the reconnection site was located southward (equatorward) of the satellite.

The data in Figure 1 are divided into seven regions, separated by the times denoted by t_1 to t_6. Measurements before time t_1 are in the magnetosphere (MSP), characterized by low-density, high-temperature plasma. During times t_1 to t_2 and t_3 to t_4, ISEE 2 was located in the low latitude boundary layer (LLBL). As one moves outward in the LLBL, the density slowly increases and the temperature slowly decreases; also the satellite begins to observe accelerated plasma at the outer edge of this layer (close to t_2 and from t_3 to t_4). In the intervals t_2 to t_3 and t_4 to t_5, the satellite was in the magnetopause proper, which is characterized by a higher-density, intermediate-temperature, high-speed plasma and an intermediate orientation of the magnetic field. There is evidence /6/ that the structures at t_2, t_3, and t_4 are one and the same rotational discontinuity (RD) which the satellite crosses three times during its traversal of the reconnection layer. The interval from time t_5 to t_6 is the structure we identify as a slow-mode shock (SS), with t_6 representing the upstream region and t_5 the downstream region. Across this structure, the density, temperature, and plasma velocity change to their magnetosheath values and the magnetic field rotates to its final magnetosheath orientation.

The magnetic field in Figure 1 is shown in the coordinate system of the slow-mode shock, where the x axis is the upstream-directed normal to the shock and the z axis (due approximately north) is aligned with the jump in the magnetic field vector across the shock, i.e., along $\mathbf{B}_2 - \mathbf{B}_1$, where the subscripts 1 and 2 indicate conditions upstream, or ahead of the shock, and downstream, or behind the shock, respectively. This coordinate system was identified by finding the best fit to the constraints that the shock normal (x axis) be closely aligned with the magnetic minimum-variance direction and that the plasma and magnetic field measurements satisfy the Rankine-Hugoniot (RH)

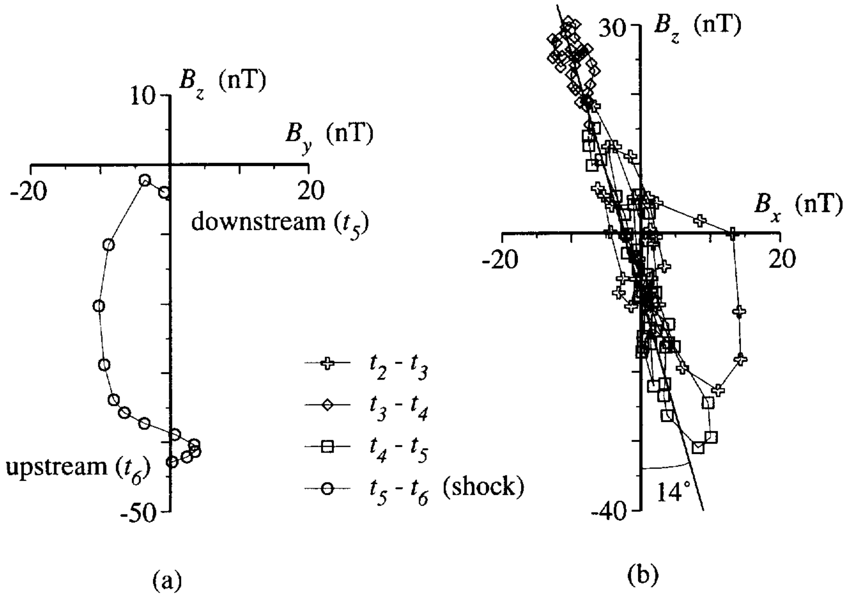

Fig. 2. Magnetic hodograms of (a) the yz plane during the SS (t_5 to t_6), and (b) the xz plane during the time period t_2 to t_5. Both hodograms are in the coordinate system of the SS.

conditions for a shock in an anisotropic plasma /7/. Comparing predictions from the RH conditions to the measured parameters, we find that the predicted downstream tangential field, B_{z2}, of −4.0 nT matches the measured value of −4.0 nT and the predicted downstream perpendicular beta value, $\beta_{\perp 2} \equiv 2\mu_o p_{\perp 2}/B_2^2$, of 94 agrees well with the value of 89 determined from the measurements.

Figure 2 shows magnetic hodograms of (a) the yz plane during the SS (t_5 to t_6), and (b) the xz plane during the time period t_2 to t_5 which encompasses the crossings of the RDs; both of these hodograms are in the coordinate system of the slow shock. A number of features of the magnetic structure become apparent from examining the data in this format. First, the slow shock in Figure 2a satisfies coplanarity, i.e., $B_y \cong 0$ in both the upstream (time t_6) and downstream (time t_5) regions of the slow shock, as expected from the RH conditions. Second, Figure 2b shows that, with the exception of a brief structure during the time interval t_2 to t_3 (open crosses in the figure), the magnetic field vectors during the RD crossings prior to the slow shock lie in a plane tilted at 14° to the shock plane (yz).

This information suggests the structure for the reconnection layer shown schematically in Figure 3. It consists of the RD, which ISEE 2 crosses three times, and the SS lying at 14° to one another such that the reconnection site is located southward of the satellite. ISEE 2 observes both the magnetic field and the plasma flow to be directed Earthward across both discontinuities /6/. Based on the data in Figure 1, the LLBL appears to consist of two regions: one in which accelerated reconnection flows are observed (the dark gray region in Figure 3), and one in which no accelerated flows are observed (the light gray region).

One unusual feature of the slow shock, apparent from the schematic in Figure 3, is that it is found to be propagating ahead of the RD instead of behind it, as one might normally expect. To understand this behavior, the effects of pressure anisotropy must be taken into account. The eighth panel of Figure 1 shows the three diagonal components of the pressure tensor in GSE coordinates as recorded by ISEE 2. Because these data are not available in digital form, they have been transcribed from survey plots. The three off-diagonal components of this tensor are not zero, but are smaller than the diagonal components and have been neglected. Upstream of the SS ($t \geq t_6$), the pressure is essentially isotropic, while downstream of it ($t_4 < t \leq t_5$), the pressure is clearly anisotropic. Noting that downstream, the magnetic field lies within 20° of the GSE Z axis, we can make the approximations $p_\parallel \cong P_{ZZ}$ and $p_\perp \cong \frac{1}{2}(P_{XX} + P_{YY})$.

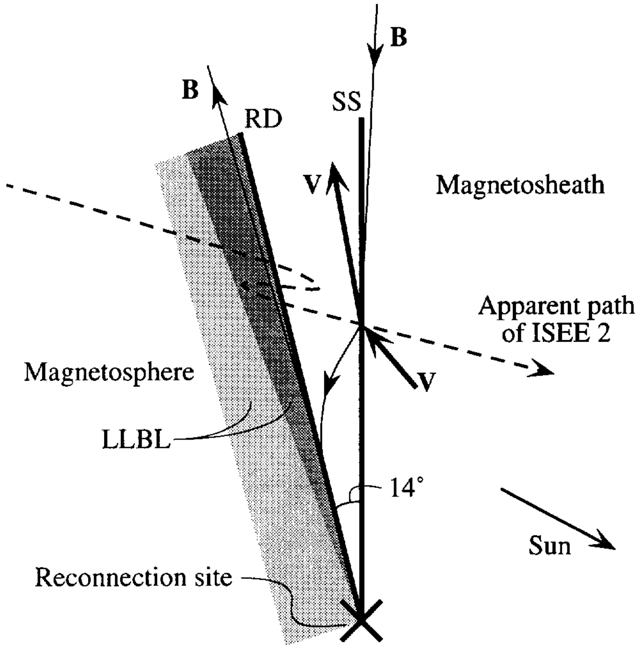

Fig. 3. Schematic of reconnection layer crossing.

Examination of the pressure anisotropy factor, $\alpha \equiv \mu_o(p_\parallel - p_\perp)/B^2$, leads to useful conclusions. In the upstream region (t_6), the magnetic field is strong and the pressure is nearly isotropic, and so $\alpha_1 \cong 0$. However, in the downstream region (t_5) there is a considerable anisotropy ($p_\parallel > p_\perp$) along with a weak magnetic field such that α_2 is large and positive; we infer values for α_2 greater than 1 and possibly as large as 16. This indicates that the intermediate mode in the downstream region is firehose unstable ($\alpha > 1$); thus its phase speed has zero real component, i.e., it is non-propagating.

A second conclusion can be inferred from the RH equation for conservation of tangential momentum across the shock. This equation can be written as

$$\frac{A_{x1}^2 - 1 + \alpha_1}{A_{x2}^2 - 1 + \alpha_2} = \frac{B_{z2}}{B_{z1}} \tag{1}$$

where $A_x^2 = (v_x - u)^2 \mu_o \rho / B_x^2$ is the normal Alfvén number in the shock frame, v_x and u being the x component of the plasma velocity and the shock velocity along the x axis, respectively, both observed in the spacecraft frame. As shown in Figures 1 and 2a, the tangential component of the magnetic field (B_z) does not change sign across the SS; therefore, the right-hand side of equation (1) must be positive. Furthermore, as mentioned above, α_2 is greater than unity; therefore, the denominator of the left-hand side must also be positive. Finally, because $\alpha_1 \cong 0$, we come to the conclusion that A_{x1} must be greater than 1 to satisfy the conservation equation, i.e., that the upstream flow in the shock frame must be greater than the local Alfvén speed. From the data we infer a value for A_{x1} of 1.59.

This conclusion is somewhat unexpected for a slow-mode shock, where one would anticipate that the upstream flow should be subalfvénic. However, it is apparent that the discontinuity cannot be of the intermediate mode: the flow speed in the shock frame exceeds the intermediate-mode phase speed in both the upstream and the downstream regions. Therefore, intermediate-mode waves cannot stand in the flow; they are always convected downstream. The RD then forms downstream of the SS due to an increase, of unknown origin, in magnetic field strength which allows the intermediate-mode phase speed to become real once again.

The conclusion that the discontinuity is in fact a slow-mode shock is supported by calculating the slow-mode phase speed in the downstream region: it is found to substantially exceed the downstream flow speed when using the double-adiabatic (or more generally, double-polytropic /8/) closure relations to compute the phase speed /6/. Thus, the flow speed is super slow upstream and subslow downstream, which allows slow-mode waves to stand in the flow and steepen to form the slow shock.

A second unusual property resulting from the pressure anisotropy concerns the magnetic polarization. As shown in Figure 2a, the magnetic field in the *yz* plane, when viewed by an observer traveling across the SS from the upstream to the downstream side, is first seen to rotate in a left-handed sense and then to switch to a right-handed sense for the remainder of the shock (note that B_x is negative during the SS). This behavior can be understood by examining the polarization condition for small-amplitude waves in the presence of anisotropic pressure:

$$\frac{i\delta B_z}{\delta B_y} = \frac{(1-\alpha)c_A^2\cos^2\theta - \omega^2/k^2}{\omega\lambda_i c_A \cos\theta} \tag{2}$$

Here, the δ indicates perturbed quantities, c_A is the Alfvén speed, ω/k is the phase speed of the wave of interest (in this case, the slow mode), θ is the angle of propagation relative to the background magnetic field, and λ_i is the ion inertial length. When the right side of equation (2) is positive, the phase angle of δB_y leads that of δB_z by 90° resulting in a left-handed polarization when viewed at a fixed point in space; when the right side is negative, δB_y lags δB_z by 90° resulting in a right-handed polarization. Because the term $(1-\alpha)c_A^2\cos^2\theta$ in the numerator of the right side is the intermediate-mode phase speed squared, equation (2) indicates that whenever the phase speed of the slow mode begins to exceed that of the intermediate mode, as it does somewhere within this SS, the polarization of the slow mode will reverse to thus yield behavior of the type observed in Figure 2.

SUMMARY

These observations represent the first quantitative evidence that slow-mode shocks can exist as part of the reconnection structure of the dayside magnetopause. The shock examined herein displays increases in number density, temperature, and plasma flow speed along with a decrease in magnetic field strength with no reversal in the tangential component of the field, as expected for a slow-mode shock. To within experimental uncertainties, which are substantial, it satisfies coplanarity and other Rankine-Hugoniot conditions for slow-mode shocks in an anisotropic plasma and has the required super-slow upstream and sub-slow downstream flow speeds. However, the upstream and downstream states are peculiar in that the upstream flow is superalfvénic while the downstream flow is firehose unstable. This is a result of the large positive anisotropy factor which develops in the downstream region owing to the pressure anisotropy, $p_\parallel > p_\perp$, and small magnetic field strength observed there. This positive pressure anisotropy, which is expected from double-polytropic plasma behavior, also leads to the magnetic polarization reversal observed within the shock structure, from left-handed polarization to right-handed polarization. In support of our findings, recent numerical calculations utilizing kinetic theory /9/ exhibit the same phase speed inversion and polarization reversal for slow-mode waves that is described here.

These observations illustrate the strong influence that pressure anisotropy can exert on the behavior of slow shocks and on the structure of the entire reconnection layer. We suggest that future efforts should be devoted to understanding the fundamental physics underlying these effects through numerical simulation as well as further satellite data analysis.

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