MAGNETOSPHERES

Structure, force balance, and topology of Earth's magnetopause

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The magnetopause deflects the solar wind plasma and confines Earth's magnetic field. We combine measurements made by the four spacecraft of the Magnetospheric Multiscale mission to demonstrate how the plasma and magnetic forces at the boundary affect the interaction between the shocked solar wind and Earth's magnetosphere. We compare these forces with the plasma pressure and examine the electron distribution function. We find that the magnetopause has sublayers with thickness comparable to the ion scale. Small pockets of low magnetic field strength, small radius of curvature, and high electric current mark the electron diffusion region. The flow of electrons, parallel and antiparallel to the magnetic field, reveals a complex topology with the creation of magnetic ropes at the boundary.

he Sun produces a supersonic stream of magnetized plasma whose properties are controlled in part by the ever-changing magnetic configuration of its photosphere (1). When this solar wind reaches Earth's magnetosphere, it is deflected by the pressure forces exerted on the magnetized solar wind (2). Because the solar wind is moving supersonically before the encounter, it must undergo a transition to the subsonically flowing state before it can be deflected by pressure gradients associated with its interaction with the magnetosphere. This occurs at a bow shock that stands in front of the magnetosphere, producing the subsonic, magnetosheath flow that interacts with Earth's magnetopause (3). The strength of this bow shock affects the temperature of the downstream plasma and the relative balance between magnetic and plasma forces, and it influences how the solar wind interacts with the magnetopause. Understanding the physics at the magnetopause has been the objective of many missions launched over the last half-century. The high cadence and close spacing of the Magnetospheric Multiscale (MMS) mission (4) enables further advances in that understanding.

Studies of the macroscopic behavior of the magnetosphere, the control of its shape by the direction of the interplanetary magnetic field (5), the control of geomagnetic activity by its direction and Mach number of the solar wind (6-8), and the control of plasma acceleration at

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the magnetopause (9) indicated that, as proposed by J. W. Dungey (10), magnetic reconnection is responsible for the energy transfer across this magnetic barrier. However, although plasma data showed the magnetic deflection of the flow as predicted (9), the previous sample rates of the plasma and magnetic fields were too slow to obtain the necessary diagnostics of the plasma to address the nature of the interaction in this thin layer. Further, conventional theory is based on a regular geometry with laminar flows in all but the ion and electron diffusion regions.

The European Space Agency's (ESA) Cluster mission (11) had the requisite four spacecraft needed to determine speeds, boundary orientations, and electric current. However, its orbit had been chosen for polar region studies and not the equatorial region where reconnection is thought to be initiated. Moreover, the separation distances between the spacecraft were large, from 100 to 1000 km or more. By contrast, MMS mission was launched into a near-equatorial orbit, with separations down to 7 km and high sample rates (4). Initial MMS studies focused on identifying a reconnecting magnetopause (12). This study presents a different approach by examining the behavior and structure of the boundary, with varied magnetosheath conditions. We limit our discussion to the measurements of two instruments, the Flux Gate Magnetometer (FGM) (13) and the Fast Plasma Instrument (FPI) (14).

We adopt a standard format for all presentations of data, to aid in understanding the control of the magnetopause by the magnetized magnetosheath plasma. Data are shown for time periods of 20 s in Figs. 1 to 4. The figures are divided into three panels (A, B, and C), showing the magnetic field and relevant scale sizes; forces and currents; and electron pitch angle and energy distributions. In each panel A, the measurements of the magnetic field, B, are plotted at the top in the LMN coordinate system explained below, together with the magnetic field magnitude. The four spacecraft, numbered 1 to 4, are represented by the colors black, gold, green, and blue. The N direction is that with the minimum change in current during the crossing of the magnetopause. The current, J, is expected to flow mainly on the magnetopause surface, not across it. The L direction is perpendicular to N in the direction most aligned with the measured magnetic field in the magnetosphere. The M direction completes the right-handed LMN orthogonal triad. Three important sizes are given in Earth radii $(R_{\rm E})$: (i) The magnetic field is used to calculate the radius of curvature of the magnetic field passing through the tetrahedron formed by the spacecraft, plotted in black; (ii) The radius of gyration of an ion of the temperature measured by the FPI instrument is plotted in green; and (iii) The spacecraft separation is plotted in gold. In this example, the interplanetary magnetic field (IMF) is 0.6 nT in the northward direction, and the solar wind Mach number is 5.6.

The radius of curvature, $R_{\rm C}$, exceeds the proton thermal gyroradius, ρ^+ , and the separation between spacecraft of 14 km. There are pulses in the magnetic field as the spacecraft traverse the boundary. Panel B in each figure shows in black the magnetic pressure, $B^2/2 \mu_0$, where μ_0 is the permeability of the free space, $4\pi \times 10^{-7}$, and the magnetic field B is in teslas. The ion plasma pressure, $n_{\rm D}kT_{\rm D}$, is added to the magnetic pressure to give the total pressure and is plotted in gold, where $n_{\rm p}$ and $T_{\rm p}$ are the proton number density and temperature, and k is Boltzmann's constant. Despite the pulses in the magnetic field, the pressure here is relatively steady. The next set of traces shows the outward $(J \times B)$ magnetic force in black along the magnetopause normal given above. This is calculated from the vector cross-product of the electric current flowing through the tetrahedron formed by the four spacecraft and the average magnetic field observed at the four spacecraft. The gold trace is the outward force exerted by the plasma, which changes in approximate balance with the magnetic force as we expect. This is consistent with the observed constancy of the total pressure. The multiple sublayers have a thickness of ~110 km (~1.5 ion gyroradii). The final traces are the currents along the magnetopause normal in gold, the current along the magnetic field in green, and the magnitude of the current flowing perpendicular to the magnetic field in blue. The current is calculated by the curlometer technique (15), which integrates the magnetic field along the edges of each face of the tetrahedron to obtain the current flowing through the face (following Ampere's law). The current along the normal direction is small, especially within the magnetosphere (on the right in each case). The parallel current is the component that rotates the magnetic field, and the perpendicular current applies the magnetic force. Panel B reveals that even a quiet magnetopause boundary with

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balanced magnetic and pressure forces has temporally and/or spatially varying contributions to the force balance. This is an important distinction from the usual assumption that away from the diffusion region, the boundary is regular. The model of a single extended X-line may not be correct.

Panel C of each figure shows electron measurements made by the FPI instrument every 30 ms. The top segment shows the energy spectrum in color ranging from 10 to 20,000 eV. The flux decreases as the magnetosphere (on the right) is entered. The next segment shows the pitch angle distribution of the low-electron spectrum, from 10 to 200 eV. The bottom plot is the pitch angle distribution of the middle of the energy band, from 200 to 2000 eV. The low energies are generally nearly isotropic and the higher energies are peaked at right angles to the field, shown in panel A. The magnetosheath electron spectrum shows that these electrons extend into the magnetosphere, providing a boundary layer just inside the region of dynamic currents. The average velocities of the crossing are determined by timing events at the four spacecraft (16). This magnetopause is 700 km thick, or 10 thermal proton gyroradii. More details on the construction of these figures can be found in the supplementary materials.

In the second year of operation in mid-2016, the spacecraft were brought closer together. In the example in Fig. 2, they are an average of 7 km apart, half the separation in Fig. 1. As in the first example, the magnetic fields on the two sides of the current layer lie at an acute angle to each other. Such an orientation is believed to minimize the rate of reconnection locally (10). The total pressure again is constant across the boundary. The outward forces of the field and plasma in Fig. 2B approximately balance each other. The forces seem noisier than in Fig. 1B, as we expect, because the instrument accuracies are the same. but the baselines for the gradient measurements are now halved. Figure 2C shows the electron spectrum, which is similar to the previous example; however, the pitch angle distributions differ from those of the previous example. Both the low-energy electrons (middle) and the mediumenergy electrons (bottom) are usually streaming parallel (bottom of each subpanel) and antiparallel (top of each subpanel) to the magnetic field. Occasionally, such as on the low-energy electron panel at 1614:51, the electrons stream in predominantly one of the directions. As judged from the speed of the magnetopause and its duration in the magnetic field profile, the thickness here is about 200 km, or about 1.4 thermal ion gyroradii.

Figure 2D shows our interpretation of these electron distributions. Reconnection has taken place at X-points, to which the broad arrows are pointing. The solid lines are magnetic field lines whose directions are indicated by solid black arrowheads. They are upward in the magnetosphere and downward in the magnetosheath. The reconnection process populates these field lines, and electrons stream away from the re-



Fig. 1. Measurements of the magnetic field and plasma at the magnetopause from 1107:48 to 1108:08 on 24 November 2015. (**A**) Magnetic field and scale sizes. M_{ms} is the magnetosonic Mach number of the solar wind flow relative to Earth. GSM is the Geocentric Solar Magnetospheric coordinate system. (**B**) Pressure, force, and currents. j_n , current along the normal direction; j_{\parallel} , parallel current; j_{\perp} , perpendicular current. (**C**) Electron pitch angle and energy spectrum. Time resolution of data used is 62.5 ms for the magnetometer, 30 ms for the electrons, and 150 ms for the protons. All data have been interpolated to a common 62.5-ms time cadence across instruments and spacecraft for this display and analysis. Labels and traces are color coded for identification. See supplementary materials for further details.

connection sites along the paths shown by the thin arrowheads. In magnetic islands, such as in the center of the figure, the electrons flow both parallel and antiparallel to the field. In locations away from the islands, they are unidirectional, either parallel or antiparallel to the magnetic field according to whether they are above or below the region of reconnection and if they are on the magnetosphere or magnetosheath side of the boundary. The motion of the magnetopause carries it across the spacecraft, allowing us to probe the region of electron anisotropy.

The magnetic fields on either side of the boundary are not antiparallel. There is a sizable component of the magnetic field into and out of the plane of the diagram. The islands represented by the circular magnetic field line must be magnetic ropes. They may have been formed elsewhere where the fields were more nearly antiparallel, but they are at an acute angle here.

Fig. 2. Measurements of the magnetic field and plasma at the magnetopause from 1614:40 to 1615:00 on 29 September 2016.

(A) Magnetic field and scale sizes. (B) Pressure, force, and currents. (C) Electron pitch angle and energy spectrum. (D) Magnetic field line topology and electron anisotropy. Simple arrowheads denote electron flow along magnetic field. Solid arrowheads denote magnetic field direction. Open arrows denote flow of magnetized plasma.



When the magnetosheath magnetic field is nearly antiparallel to the magnetospheric field, the opposing pressure forces grow and new phenomena arise (Fig. 3). We return to the first year of operation when the spacecraft were further separated and the gradient more accurate. We take the magnetosheath conditions as those existing at 10:33:38 UT, when the magnetic field is quiet and nearly antiparallel to the magnetospheric field. Between the magnetosphere on the left and the magnetosheath to the right is a region of irregular but nearly horizontal and weak magnetic field. In the previous examples, the radius of curvature of the magnetic field was larger than the ion gyroradius and the separation between the spacecraft, but the radius of curvature of the magnetic field is small-exactly how small is not possible to calculate once it is comparable to the spacecraft separation. Nevertheless, the electron distributions became isotropic at this time (17), consistent with the radius of curvature (~3 km) being comparable to the electron gyroradius (~5 km). The magnetic forces are squeezing the plasma in the current layer near

the magnetic hole that is associated with the small radius of curvature. As in the previous example, currents flow both up and down the field line. The total pressure here shows some variability.

Figure 3C again shows the electron spectrum and the pitch angle distributions. There are strong flows along the field and antiparallel to it, as in the previous example, which was much less antiparallel. There are also occasions such as 10:33:27 and from 10:33:31 to 10:33:36 when the electrons become isotropic even at low energies. These occasions correspond with times for which the radius of curvature of the magnetic field is small, as shown in the size plot of Fig. 3A. On these occasions, the magnetic field is weak, so the gyroradii are larger than at other times. We expect more isotropy of the electrons under these conditions, because they cannot be guided by the field. Here the magnetic field is no longer "frozen" to the plasma, allowing the field to reconnect with a different element of plasma.

Figure 4 shows another example of a small radius of curvature event when the magnetic

field in the magnetosheath made an angle greater than 90° to that in the magnetosphere. There is a strong outward force in the magnetopause current layer. Where the outward force is weakening on the magnetosheath side is another region of small radius of curvature. On the magnetosheath side of this structure, at 0117:39, low-energy electrons move both parallel and antiparallel to the magnetic field. The strong perpendicular current, the small radius of curvature, and the antiparallel electron beams indicate that this region is close to the electron diffusion region. On the magnetospheric side, oppositely directed electrons occur at medium energies. Again, the region near the magnetopause behaves as if there were a flux rope, conducting electrons in both directions along the magnetic field.

Our four examples of MMS observations of the magnetic field and ions across the magnetopause illustrate that the small-scale structure on the boundary is ubiquitous. The net reconnection rate is a result of the summation over many localized sites. Examining the radius



Fig. 3. Measurements of the magnetic field and plasma at the magnetopause from 1033:20 to 1033:40 on 16 October 2015. (A) Magnetic field and scale sizes. (B) Pressure, force, and currents. (C) Electron pitch angle distribution and energy spectrum.



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Fig. 4. Measurements of the magnetic field and plasma at the magnetopause from 0117:30 to 0117:50 on 14 December 2015. (A) Magnetic field and scale sizes. (B) Pressure, force, and currents. (C) Electron pitch angle and energy spectrum.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/356/6341/960/suppl/DC1 Materials and Methods Figs. S1 and S2 References (18–20)

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Probing the structure of the magnetopause

The magnetopause is the boundary in space that separates the region dominated by Earth's magnetic field (the magnetosphere) from the surrounding solar wind. The four spacecraft of NASA's Magnetospheric Multiscale (MMS) mission have repeatedly flown in formation through the magnetopause, measuring the properties of the plasma and magnetic fields in the region. Russell *et al.* used MMS measurements to study the magnetopause's structure and force balance. They identified small-scale dynamic features that form a complex topology and evidence for magnetic flux ropes at the boundary. The results aid our understanding of Earth's space environment and magnetospheres around other planets.

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