Detection of bi-directional plasma jets and extended magnetic reconnection line at Earth's magnetopause

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Magnetic reconnection, a universal plasma process which converts magnetic energy into bi-directional plasma jets, is believed to be one of the dominant processes by which the solar wind energy enters the Earth's magnetosphere[1,2]. This energy is subsequently dissipated in auroras and magnetic storms[3,4]. Due to the single-spacecraft nature of past observations, however, only single jets have been reported at the magnetopause[5,6,7]. The existence of the counterstreaming jet, i.e., the other half of the reconnection picture, has always been assumed but never confirmed. Furthermore, single-point detection of reconnection could not reveal the overall solar wind entry rate via this process. Here we report an *in-situ* two-spacecraft observation of bi-directional jets at the magnetopause, thereby completing the magnetopause reconnection picture. Our observations also reveal evidence for a stable and extended reconnection line implying substantial solar wind entry. The existence of such a

line indicates that reconnection is determined by large-scale interactions between the solar wind and the magnetosphere rather than by conditions at the local magnetopause.

The Equator-S, Geotail, and Wind satellites are members of a fleet of spacecraft designed to study solar-terrestrial interactions by providing simultaneous multi-point measurements of the Earth's magnetosphere and the surrounding interplanetary medium. For more than one hour on February 11, 1998, the trajectories of both Equator-S and Geotail skimmed the dawn flank magnetopause at low latitudes in the relative positions shown in Figure 1. Continuous solar wind measurements were made by the Wind spacecraft at ~ 230 R_E upstream of the magnetopause.

Figure 2a-f shows Equator-S and Geotail plasma and magnetic field data for the 13:05 UT - 14:12 UT interval which reveal the presence of bi-directional jets. During this entire interval, the solar wind magnetic field was persistently southward (Fig. 2g). This field convects to the dayside magnetopause to form an anti-parallel field configuration favored to induce reconnection (see Figure 1). Figure 2a-c shows multiple crossings of the magnetopause as the Equator-S orbit skimmed the magnetopause. High speed northward directed plasma flows ($V_L > 0$) were observed in many of these crossings. The Geotail spacecraft, located ~ 4 R_E southward and ~ 3 R_E tailward of Equator-S, also crossed the magnetopause multiple times (Fig. 2d-f). But in contrast to the jets encountered by Equator-S, those detected by Geotail were mostly in the southward direction. The flow speeds detected by the two spacecraft at the magnetopause were enhanced by 200-300 km/s relative to the solar wind flow right next to the magnetopause. To highlight the opposite flow directions detected by the two spacecraft, northward (southward) flow speed enhancements of greater than 150 km/s are shaded blue (red). Nine of the 11 Equator-S high-speed flow events are northward directed while 14 of 16 Geotail events are southward directed. Thus for the majority of cases, the reconnection site was located south of Equator-S and north of Geotail. The 4 exceptions

(2 from each spacecraft) presumably correspond to instances when the reconnection site was either north or south of both spacecraft.

While Equator-S was mostly in the solar wind during this period and made only brief excursions into the magnetosphere, Geotail was in the reversed situation. This implies that, except for small short-term inward or outward motions, the magnetopause position was relatively stable. The observed brief encounters with plasma jets are due to such motions causing the spacecraft to enter briefly into a region of longer duration jets, which also explains why the northward and southward jets do not appear simultaneously in Figure 2.

To establish quantitatively that the bi-directional jets are the result of reconnection between solar wind and magnetospheric magnetic fields, we compare the plasma velocity enhancements observed in the magnetopause crossings with quantitative theoretical predictions[5]. To simplify the analysis, we select only crossings in which the magnetic field exhibited a complete transition from its solar wind to its magnetospheric orientation. In total, there are 8 such crossings by Equator-S and 5 by Geotail. The results of the analysis are illustrated in detail in Figure 3 for four crossings - two from each spacecraft. The agreement between theory and observations is remarkable: The magnitude of the velocity increase is 88% of the predicted values, or better, while the flow direction agrees to better than 10^{o} for these cases. The other crossings also show good quantitative agreements with theory (see Caption of Fig. 3).

The combined Equator-S and Geotail observations of reconnection jets allow the deduction of the location, orientation, and minimum length of the reconnection line as illustrated in Figure 1. With few exceptions, the two spacecraft detected oppositely directed jets which implies that the reconnection site (or X-line) must have been between the spacecraft, and therefore somewhat north of but not far from the equatorial plane. The X-line was oriented along the east-west direction because the jets were directed mainly in the north-south direction (Fig. 3). The repeated encounters of the jets over more than one hour imply that reconnection was active much of the time with its site remaining quasi-stationary. The occurrence of a stable equatorial reconnection line for southward solar wind magnetic field implies that reconnection occurs in a large-scale[1,8,9,10,11] rather than patchy manner and that its sites are determined by the large-scale interaction between the solar wind and the magnetosphere as opposed to local conditions at the magnetopause. Control by local conditions would result in patchy reconnection, distributed in a less well-organized fashion over the magnetopause surface.

The length of the X-line must have been at least 3 R_E along the flank magnetopause because of the spacecraft separation in the east-west direction. Although the full extent of the X-line is not directly measured, we infer from its persistent presence on the dawn flank, and from the frequent detection of quasisteady reconnection jets in the subsolar region when the solar wind magnetic field is southward[6,12], that the X-line extended all the way across the subsolar region to the dusk flank. The alternative scenario in which persistent reconnection occurs on the dawn flank but not in the subsolar region is unlikely because the subsolar magnetopause is maximally driven by the solar-wind ram pressure. Reconnection occurs on the dusk flank because, for symmetry reasons, the conditions for reconnection there would be the same as on the dawn flank.

Such a long reconnection line implies that reconnection is the dominant process by which the solar wind is transferred into the magnetosphere: The dawn-to-dusk potential difference across the magnetosphere, imposed by the solar wind via the reconnection process, is the electric field E_t along the reconnection line times the length of that line. The length of a dawn to dusk reconnection line along the dayside magnetopause amounts to some 40 R_E. The electric field is not measured by the two spacecraft and cannot be reliably inferred from measured magnetic fields and plasma flow. However, previous *in-situ* measurements[13] of this field during some 200 dayside reconnection events have led to an average value for E_t of 0.4 mV/m, from which a reconnection-produced potential difference over 40 R_E of about 100 kV is obtained. This value should be compared to the polar cap potential measured by low-altitude spacecraft, which represents the total magnetic flux transported from the dayside to the nightside magnetosphere by all processes, including viscous interaction[14] and reconnection. For the solar wind conditions at hand (from Wind spacecraft: V_{SW} = 550 km/s and B_{SW} = 7 nT, due south) the polar cap potential can be calculated[15], from a large assembly of low-altitude satellite data, to be about 105 kV. Thus this analysis indicates that, as has been hinted by indirect evidence[16,17] but never confirmed by *in-situ* measurements, reconnection is indeed the dominant solar wind entry process when the solar wind magnetic field is persistently southward, with other processes playing at most a minor role.

The reconnection electric field together with the length of the reconnection line determine what fraction of the solar wind particle flux and energy impinging on the magnetopause actually enters the magnetosphere. The presence of a 0.4 mV/m electric field across a dawn-to-dusk reconnection line implies ~10% entry rate[13]. This translate to ~10^{28} particles per second crossing the magnetopause from a flux of ~10^{29}/s (based on solar wind density of 4 cm^{-3} and speed of 550 km/s) impinging on a magnetopause cross-sectional area of 40 R_E in diameter. The corresponding total energy transfer into the magnetosphere is 2.5×10^{12} W.

The observations presented in this paper were made under the simple purely southward solar wind magnetic field geometry where most large-scale models of magnetopause reconnection[1,8,9,10,11] predict an equatorial reconnection line, as observed. For other field orientations, the location and extent of the reconnection region are presently not known. Their predictions are model dependent. To evaluate which of the models (e.g., "component reconnection"[8,9] versus "anti-parallel reconnection"[10]) best represents the global reconnection configuration requires the identifications of the reconnection sites for a variety of field orientations, a task that will be performed by the upcoming four-spacecraft Cluster II mission.

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Acknowledgments. We thank Ron Lepping and Bob Lin for making the Wind spacecraft data available. We are grateful to Harald Kucharek, Dimple Patel, and Peter Schroeder for their help in the processing of Equator-S plasma data. We also thank Säm Krucker for his helpful comments on the manuscript.

Figure Legends

Figure 1. Three-dimensional cutaway view of the magnetosphere showing the spacecraft positions and the presence of an extended reconnection line. The spacecraft separation was ~ 4 R_E in the north-south and ~ 3 R_E in the east-west direction. Bi-directional reconnection jets detected at both spacecraft locations imply a reconnection X-line (yellow solid line) along the dawn flank magnetopause and slightly north of the equatorial plane. The inferred X-line (yellow dashed line) extends to the subsolar point and over to the dusk flank. The boundary normal (LMN) coordinate system is defined such that the N axis points outward along the magnetopause normal and the (L, M) plane is tangential to the magnetopause with L oriented due north and M due west.

Figure 2. Overview of Equator-S and Geotail encounters of bi-directional jets. Multiple magnetopause crossings are caused by inward-outward magnetopause motions. Panels a-c show the plasma density, the north-south (L) component of the magnetic field and flow velocity in the LMN coordinate system (see Fig. 1) measured by Equator-S. Panels d-f display the L component of velocity and magnetic field, and the density measured by Geotail. The magnetopause is identified by a transition from high density and southward field (B_L<0) in the solar wind to low density and northward field in the magnetosphere, or vice versa. Panel g shows the clock angle of the solar wind magnetic field, measured by Wind. A forward time-shift of 45 minutes has been applied to this data to take into account the solar wind convection time from the Wind position to the flank magnetopause. The field was purely southward ($\tan^{-1} (B_z/B_y) \sim \pm 180^o$) during this interval.

Figure 3. Quantitative comparison with reconnection prediction. The observed ($\Delta\mathbf{V}_{obs}$) and theoretical prediction ($\Delta\mathbf{V}_{th}$) of tangential (L, M) flow acceleration across the magnetopause are shown for Equator-S crossings 6 and 8 (left panels) and Geotail crossings 2 and 5 (right panels). The crossing times are indicated in Figure 2 by green (purple) numbers and bars for the Equator-S

(Geotail) events. According to magnetohydrodynamic models of the dayside magnetopause reconnection, the solar wind plasma is accelerated by the magnetic tension force according to: $\Delta\mathbf{V}_{th} = \mathbf{v}_{t2} - \mathbf{v}_{t1} = \pm (\mu_0\rho_1)^{-1/2}(\mathbf{B}_{t2} - \mathbf{B}_{t1})$**,** where **B**, **v**, and ρ are the magnetic field, flow velocity, and mass density, respectively. Subscript t denotes the component tangential to the magnetopause surface. Subscript pair (1, 2) refers to the solar wind side and the magnetospheric side of the magnetopause. The positive or negative sign of the equation depends on whether the observation point is north or south of the reconnection site. This relation is derived for a 1-D time stationary magnetopause, whereas the actual magnetopause exhibits 3-D time-varying structures. Nevertheless, the agreement between predicted and observed flow enhancements for these 4 events is excellent. With all crossings included, the average magnitude of the velocity increase is 78% of the prediction for the 8 Equator-S events and 74% of the prediction for the 5 Geotail events. The corresponding average flow direction is within 3.8^o (Equator-S) and 6.1^o (Geotail) of the prediction. There is one event (Equator-S Crossing 5) where the observed flow increase $\Delta v_L < 100$ km/s was substantially below the prediction of $\Delta v_L \sim 380$ km/s. All other crossings displayed flow enhancements whose magnitudes were at least 50% of the prediction, and whose directions agreed to better than 10^o. We conclude that flows consistent with reconnection were detected in all but one crossing.