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Evidence of high-latitude reconnecting during northward IMF: Hawkeye observations

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Abstract. Reconnection is accepted as an important process for driving the solar wind/magnetospheric interaction although it is not fully understood. In particular, reconnection for northward interplanetary magnetic field (IMF) at high-latitudes tailward of the cusp, has received little attention in comparison with equatorial reconnection for southward IMF. Using Hawkeye data we present the first direct observations of reconnection at the high-latitude magnetopause (75°) during northward IMF in the form of sunward flowing protons. This flow is nearly field aligned, approximately Alfvénic, and roughly obeys tangential momentum balance. The magnetic field shear is large at the magnetopause and there is a non-zero B_N component suggesting the existence of a rotational discontinuity and reconnection. The Hawkeye observations support several recent simulations at least qualitatively in terms of flow directions expected for high-latitude reconnection during northward IMF.

Introduction

Reconnection of magnetosheath and magnetospheric magnetic field lines at the dayside magnetopause is generally accepted as the single most important process driving the solar wind-magnetosphere interaction. It provides a natural explanation for many in situ magnetopause and remote ionospheric observations [e.g., [*Reiff*, 1984; *Lundin*, 1988]. However, many details of magnetic reconnection remain to be determined. For example, different models for reconnection predict different locations for magnetic merging. In antiparallel reconnection models, merging occurs on portions of the magnetopause where magnetosheath and magnetospheric magnetic field lines point in nearly opposite directions. During periods of southward IMF, merging should take place on the equatorial magnetopause [*Dungey*, 1961]. During periods of northward IMF, merging should move poleward of the cusps to the high-latitude magnetopause [*Dungey*, 1963]. *Crooker* [1979] and *Luhmann et al.* [1984] are more recent advocates of antiparallel merging. By contrast, component reconnection models predict merging along a line passing through the subsolar point whose tilt depends upon the IMF orientation [e.g., *Sonnerup*, 1974; *Gonzales and Mozer*, 1974]. In these models, reconnection diminishes or terminates altogether for northward IMF.

In situ observations provide conflicting results concerning the occurrence patterns of magnetic reconnection on the magnetopause. *Russell et al.* [1985], using magnetic field measurements from ISEE-1 and -2, show evidence of bursty merging occurring along a tilted subsolar line, supporting the component merging model. Statistical studies of accelerated flows appear to indicate that merging is closely confined to the subsolar point [*Scurry et al.*, 1994]. *Gosling et al.* [1990] show that subsolar reconnection occurred not only for antiparallel magnetic field orientations, but rather for magnetic shear angles between 60° and 180°.

Recently, attention has focused on the possibility of reconnection at the high-latitude magnetopause, especially during periods of northward IMF. *Berchem et al.* [1994], using a 3D global MHD simulation of the solar wind interaction with the Earth's magnetosphere for strictly northward IMF, found that most field lines sunward of the reconnection site became closed through a symmetrical reconnection process occurring in both hemispheres, while the lobe field lines tailward of the reconnection site became unconnected resulting in the erosion of the plasma mantle. Simulations by *Richard et al.* [1994] indicated that the dominant mechanism of magnetosheath plasma entry into the magnetosphere was convection on reconnecting field lines. For northward IMF, they found that particles entered the magnetosphere when the field lines on which they were convecting became closed by cusp reconnection.

This paper presents the first direct observations of reconnection at the high-latitude magnetopause (75°) during a period of northward IMF. *Rosenbauer et al.* [1975] using Heos 2 data discussed mantle observations in terms of merging but did not show specific observations of reconnection. The previously reported "high-latitude" ISEE observations of reconnection presented by *Gosling et al.* [1991] are for a magnetopause crossing near the dawn-dusk terminator plane at 38° GSM latitude and during a time when the IMF had a southward component. *Berchem et al.* [1994] showed Hawkeye magnetometer data which are fairly consistent with the expected signature of twisted flux ropes at a location which they suggest is far from the reconnection region.

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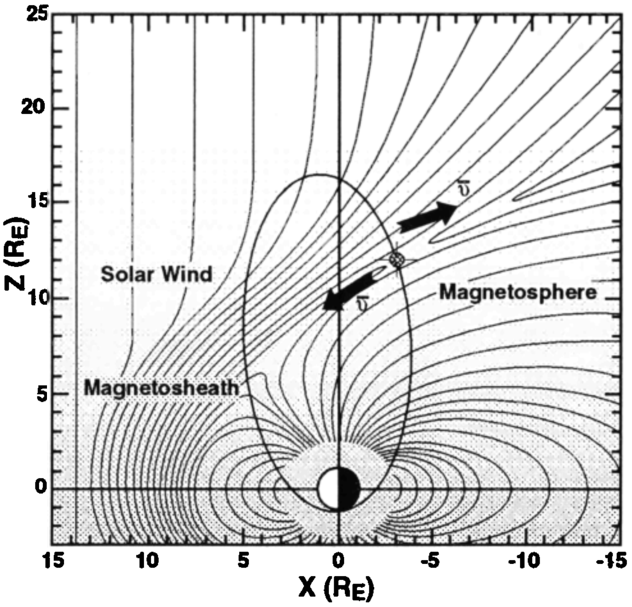

Figure 1. The near-Earth magnetic field during northward IMF when high-latitude reconnection is occurring tailward of the cusp with a full Hawkeye orbit. The arrows indicate flows near the reconnection region. (Magnetic field lines sketched after *Berchem et al.* [1994].)

Using the Hawkeye satellite we present observations of accelerated, sunward flowing protons in the reconnection outflow region, large shear in the magnetic field across the magnetopause, and a magnetic field depression in the reconnection region. These observations are consistent with the scenario of magnetic reconnection tailward of the cusp.

Hawkeye Orbit and Instrumentation

The Hawkeye satellite collected data from June 3, 1974 until April 28, 1978. Hawkeye flew in a polar orbit with an inclination to the Earth's equator of nearly 90°, an apogee of 20-21 R_E, and a period of 51.3 hours (see Figure 1). During each orbit, Hawkeye crossed the magnetopause boundary. Hawkeye carried three scientific instruments: a low energy proton-electron differential energy analyzer (LEPEDEA), a fluxgate magnetometer (MAG), and a very low frequency plasma wave instrument (VLF). As the satellite rotated, LEPEDEA swept out a 30° band of the surrounding space. A full energy sweep (40 keV to 100 eV) took 1.44 s and was obtained once every 11.52 s. Since the satellite spin period was approximately 11 s, each energy sweep was offset in angular direction from the previous one such that a full 2D energy-angle distribution was obtained in approximately 3.5 min. The Hawkeye magnetometer was a triaxial fluxgate system with a time resolution of 2 s. More detailed information on the satellite and instrumentation can be found in *Gurnett and Frank* [1978] and *Farrell and Van Allen* [1990].

Observations

For the reconnection event observed on September 19, 1974 (day 262), Hawkeye crossed the magnetopause at approximately $x_{GSM}, y_{GSM}, z_{GSM} = (-2, 3, 11)\ R_E$, at a geomagnetic latitude of 75°. IMP-8 was in the solar wind on the dawnward side at ~7 hrs magnetic local time and -30° geomagnetic latitude. The IMF is northward from the beginning of this day until about 0600 UT when it turns southward, the solar wind speed is 635 km/s and the density is 8.5 cm^{-3}. Figure 2 shows one hour of IMP-8 (top panel) and Hawkeye data on day 262 from 0110 UT to 0210 UT. Hawkeye observations are from top to bottom: the plasma density and bulk flow speed (running moments of the full measured distribution functions calculated every 51 s), and the three components and magnitude of the magnetic field in boundary normal (LMN) coordinates. The LMN coordinates are determined from minimum variance assuming that $B_N = 0$ and a time interval large enough to include background fields both in the magnetosheath and in the magnetosphere (01:34:45-01:40:49). (Using

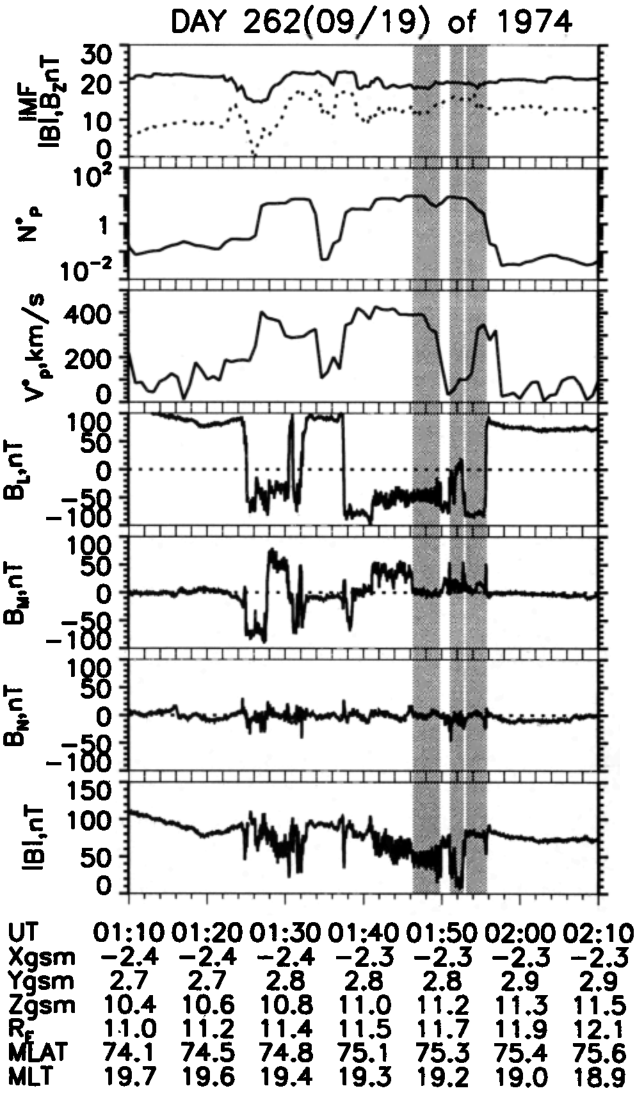

Figure 2. One hour of Hawkeye and IMP-8 data on September 19, 1974. Top panel shows IMF magnitude and z-component (IMP-8). Hawkeye observations top to bottom: plasma density, bulk flow speed, and three components and magnitude of magnetic field.

a scheme which determines B_N as a non-zero constant produces an almost identical set of LMN coordinates for this time period; the angles between LL*, MM*, and NN*, each being less than 3°.) The eigenvalues corresponding to the eigenvectors, L, M, N, are 6570, 271, and 35, respectively. The normal direction determined from minimum variance is (0.57, 0.14, 0.81) GSM, which is in approximate agreement with the normal to the magnetopause surface as illustrated in Figure 1.

Multiple Hawkeye magnetopause crossings can be identified in this hour long plot by the large magnetic shear in the B_L component with a non-zero B_N component at each crossing. At 0110 UT Hawkeye is in the magnetosphere and first crosses the magnetopause at about 0125 UT. We look in more detail at the time period between 0146 UT and 0156 UT which in Figure 2 is shown as three consecutive shaded regions, which correspond to a magnetosheath region from approximately 0146 UT to 0150 UT, a depression in magnetic field strength from 0151 UT to 0153 UT, and another magnetosheath region from 0153 UT until approximately 0155 UT. The lag time between IMP-8 and Hawkeye ($\sim 3-5$ minutes based on a longer time comparison between the two spacecraft not shown) suggests that the depression region is not simply a temporal feature swept through the magnetosheath, but represents a magnetopause region in that vicinity. The ten minute interval is shown in more detail in Figure 3. The top three panels display Hawkeye magnetic field: B_L, B_N, and the magnitude. Each of the three regions exhibits a distinctly different magnetic field magnitude and orientation (identified most strongly in the B_L component). The shear between regions is large, e.g., between the depression region and the latter magnetosheath region it is 119°, and between the magnetosheath and the magnetosphere it is nearly 180°. This large magnetic shear along with the non-zero B_N component strongly suggests the presence of an RD.

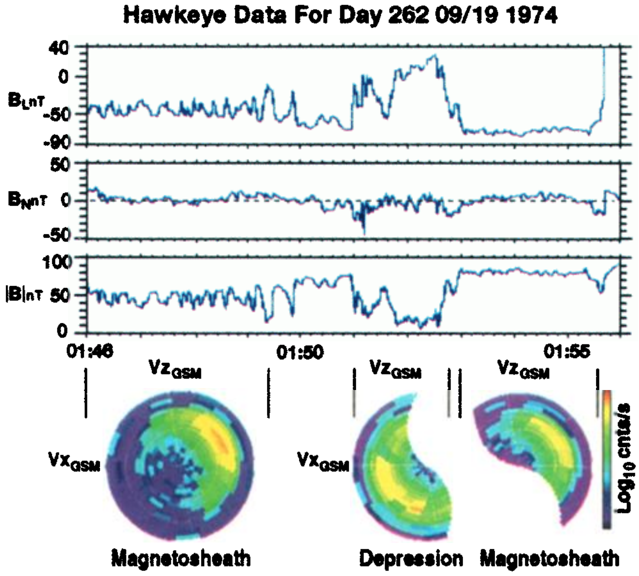

Figure 3. Hawkeye magnetic field from top to bottom: B_L, B_N, and the magnitude. Partial LEPEDEA proton distributions are shown below these panels and correspond to magnetosheath, depression, and magnetosheath regions. The radial direction represents energy from 100 eV at the center to 40 keV at the edges, and the angular direction coincides with measured plasma flux in that direction.

Partial LEPEDEA proton distributions are shown below these panels and correspond to the three identified regions. The magnetosheath distributions in Figure 3 show plasma flowing roughly tailward and northward. The center distribution shows large numbers of sunward and southward flowing protons during the observed depression in magnetic field strength. The latter two distributions are not full distributions so we calculated partial moments in each region, i.e., densities and flow speeds: 3.5 cm^{-3} and 331 km/s for the center distribution, and 9.8 cm^{-3} and 394 km/s for the latter distribution. However, the distribution shown in the depression region exhibits a more-or-less isotropic "background". In order to more accurately estimate the bulk flow speed this background was extended through the angles that are not viewed.The flow speed then slows down significantly to between 90 km/s and 140 km/s (depending on the chosen background) in essentially the same direction, and the density increases to $\sim 8.5\ \text{cm}^{-3}$.

Discussion

In a closed magnetosphere, magnetic field lines of the interplanetary medium do not connect to the Earth's field and the magnetopause is a tangential MHD discontinuity (TD). A TD separates two regions with different flows which can only interact through diffusion. A pressure balance is maintained but there is no component of the magnetic field normal to the magnetopause. If reconnection takes place and the magnetosphere is open, the magnetopause becomes a rotational discontinuity (RD). It is difficult to determine if a magnetopause crossing is a TD or RD on the basis of magnetic field data alone because the fit may not be good or the B_N component may not be greater than the noise. *Paschmann et al.* [1990] suggest also using plasma data to check for the existence of a moving frame of reference (deHoffman-Teller frame) in which plasma flow is aligned with B. If the flow is Alfvénic in the HT frame, then the discontinuity is a RD. This is the so-called Walén relation: $\mathbf{v} = \mathbf{v}_{\mathbf{HT}} \pm \mathbf{B}/\sqrt{\mu_0 \rho}$ based on tangential momentum balance, and predicts a linear relationship between the velocity and the magnetic field.

Figure 2 shows a large shear between the magnetosheath and the magnetosphere with smaller shears separating the depression region and the magnetosheath. In addition there is a non-zero B_N component at these boundaries and $B_N < 0$ for most of the depression region indicating that Hawkeye was located sunward of the reconnection site. The Hawkeye LEPEDEA instrument provides only 2D measurements of particle distributions so we cannot make definitive statements about the plasma flow component out of the spin plane. However, for this event the magnetic field component out of the spin plane in the depression region is also nearly zero (only 8.5% of the overall field). If we assume that we have measured the bulk of the proton distribution, then the plasma flow is within 14° of being aligned with the magnetic field. The Alfvén speed based on the magnetic field and density in the depression region is approximately 110 km/s and is, given the uncertainty in the measurements of density and velocity, roughly equivalent to the flow speed calculated in the depression region (with background, 90–140 km/s). This makes the plasma flow approximately field aligned and Alfvénic, thereby suggesting that reconnection is occurring at the high-latitude magnetopause, possibly very close to the depression region. If we further predict a velocity for the depression region based on the Walén relation, $\Delta \mathbf{v} = \pm \Delta \mathbf{B}/\sqrt{\mu_0 \rho}$, we get a sunward and southward flow of 130 km/s compared to 90-140 km/s above. Hawkeye is not sampling from the tailward flowing direction within the depression region so no definitive statements can be made about the existence of accelerated tailward flows there.

The presence of sunward flowing protons in Figure 3 is difficult to account for except as a direct consequence of reconnection. Moreover, this flow is nearly field aligned, approximately Alfvénic, and roughly obeys tangential momentum balance. The magnetic field shear is large at the magnetopause and there is a non-zero B_N component suggesting the existence of a rotational discontinuity. The Hawkeye observations support the simulations of *Richard et al.* [1994] and *Berchem et al.* [1994] at least qualitatively in terms of flow directions expected for high-latitude reconnection during northward IMF. However, the long time required to obtain a full proton distribution and the limitation to 2D suggests that some features may be missed. Hawkeye clearly is a key data source for high-latitude magnetosphere observations.

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References

Berchem, Jean, Joachim Raeder, Maha Ashour-Abdalla, Reconnection at the magnetospheric boundary: Results from global magnetohydrodynamic simulations, in **Physics of the Magnetopause**, AGU, 1994.

Crooker, N. U. Dayside Merging and Cusp Geometry, *J. Geophys. Res.*, 84, 951–959, 1979.

Dungey, J. W., Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, 47–48, 1961.

Dungey, J. W., The structure of the exosphere or adventures in velocity space, in **Geophysics: The Earth's Environment**, ed. C. DeWitt, J. Hiebolt, and A. Lebeau, 526–536, Gordon and Breach, New York, 1963.

Farrell, W. M. and J. A. Van Allen, Observations of the Earth's polar cleft at large radial distances with the Hawkeye 1 magnetometer, *J. Geophys. Res.*, 95, 20945, 1990.

Gonzales, W. D. and F. S. Mozer, A quantitative model for the potential resulting from reconnection with an arbitrary interplanetary magnetic field, *J. Geophys. Res.*, 79, 4186–4194, 1974.

Gosling, J. T., et al., Plasma flow reversals at the dayside magnetopause and the origin of asymmetric polar cap convection, *J. Geophys. Res.*, 95, 8073, 1990.

Gosling, J. T., et al., Observations of reconnection of interplanetary and lobe magnetic field lines at the high-latitude magnetopause, *J. Geophys. Res.*, 96, 14097, 1991.

Gurnett, D. A., and L. A. Frank, Plasma Waves in the Polar Cusp: Observations From Hawkeye 1, *J. Geophys. Res.*, 83, 1447, 1978.

Luhmann, J. G., et al., Patterns of potential magnetic field merging sites on the dayside magnetopause, *J. Geophys. Res.*, 89, 1739–1742, 1984.

Lundin, Rickard, On the magnetospheric boundary layer and solar wind energy transfer into the magnetosphere, *Space Sci. Rev.*, 48, 263-320, 1988.

Paschmann, G., et al., The magnetopause and boundary layer for small magnetic shear: convection electric fields and reconnection, *Geophys. Res. Lett.*, 17, 18239, 1990.

Reiff, P. H., Evidence of magnetic merging from low-altitude spacecraft and ground-based experiments, in **Magnetic Reconnection in Space and Laboratory Plasmas**, ed. E. W. Hones, AGU, Washington, D. C., 1984.

Richard, Robert L., Raymond J. Walker Maha Ashour-Abdalla, The population of the magnetosphere by solar wind ions when the interplanetary magnetic field is northward, *Geophys. Res. Lett.*, 21, 2455-2458, 1994.

Rosenbauer, H., et al., Heos 2 Plasma Observations in the distant Polar Magnetosphere: The Plasma Mantle, *J. Geophys. Res.*, 80, 2723, 1975.

Sonnerup, B. U. Ö., Magnetopause Reconnection Rate, *J. Geophys. Res.*, 79, 1546–1549, 1974.

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