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Magnetic flux ropes at the high-latitude magnetopause

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Abstract. We examine the consequences of magnetic reconnection at the high-latitude magnetopause using a three-dimensional global magnetohydrodynamic simulation of the solar wind interaction with the Earth's magnetosphere. Magnetic field lines from the simulation reveal the formation of magnetic flux ropes during periods with northward interplanetary magnetic field. These flux ropes result from multiple reconnection processes between the lobes field lines and draped magnetosheath field lines that are convected around the flank of the magnetosphere. The flux ropes identified in the simulation are consistent with features observed in the magnetic field measured by Hawkeye-1 during some high-latitude magnetopause crossings.

Introduction

Magnetic field reconnection for northward interplanetary magnetic field (IMF) was first postulated by Dungey [1963]. In his scenario, the IMF reconnects nearly simultaneously with both southern and northern tail lobes forming conjugate merging sites tailward of the cusps. Since then, several phenomenological models of the magnetic field topology of the merging region for northward IMF have been developed [*Russell*, 1972; *Maezawa*, 1976, *Crooker*, 1979; *Cowley*, 1982, *Reiff and Burch*, 1985]. Although three-dimensional (3D) magnetohydrodynamic (MHD) models have been used to examine the global interaction between the solar wind with Earth's magnetosphere [*Leboeuf et al.*, 1981; *Wu et al.*, 1981; *Brecht et al.*, 1982; *Ogino*, 1986; *Fedder and Lyon*, 1987; *Watanabe and Sato*, 1990; *Raeder et al.*, 1995], only a few attempts have been made to use these simulation models to investigate mesoscale aspects of magnetic reconnection at the magnetospheric boundary. Most previous efforts [*Sato et al.*, 1986; *Shi et al.*, 1988; *Ogino et al.*, 1989] focused on the formation of flux transfer events (FTEs) [*Russell and Elphic*, 1978] at the dayside magnetopause for southward IMF. Recent advances in computer technology and improvements in numerical techniques allow us to use simulation systems that not only are large enough to render properly the global configuration of the magnetosphere, but also have sufficient spatial resolution to let us investigate mesoscale aspects of magnetic reconnection at the magnetospheric boundary. In this letter, we present simulation results that reveal the complex magnetic field topology of the high-latitude magnetopause region during periods of northward IMF. As we describe below, the simulation shows that the occurrence of multiple reconnection leads to the formation of magnetic flux ropes.

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Simulation Model

The simulation code solves the one-fluid resistive MHD equations [e.g. *Raeder et al.*, 1994] using an explicit conservative predictor-corrector scheme for time stepping, and fourth-order fluxes hybridized with first-order fluxes for spatial differencing. The resistivity η used in Ohm's law, $\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \eta\mathbf{j}$, is a nonlinear function of the local current density $\mathbf{j}$ such that $\eta = \alpha j^2$, where α is a parameter being determined empirically. To avoid spurious dissipation we have included a threshold that is a function of the local current density. This threshold has been calibrated such that the explicit resistivity is switched on only at a very few grid points in strong current sheets. Similar models have been used in local MHD simulations [e.g. *Sato and Hayashi*, 1979] and are based on the assumption that current driven instabilities are responsible for the anomalous resistivity that produces reconnection.

A spherical boundary with a radius of 3.7 R_E is placed around the Earth to exclude the region where the Alfvén velocity becomes too large to use a reasonable time step. Closure of the field aligned currents (FACs) is ensured by solving self-consistently the ionospheric potential equation using three ionization sources for computing the height-integrated ionospheric Hall and Pedersen conductivities.

The code has been parallelized to allow us to use a large number of grid points ($\approx 1.5 10^6$). The dimensions of the system are 23 R_E in the sunward direction (x), 100 R_E along the tail and ± 45 R_E in the y and z directions. The computational mesh is a stretched Cartesian system and has the highest resolution near the Earth. The grid size varies from 0.4 R_E in a 15 R_E box centered at the Earth to about 7 R_E along the tail axis at x = -100 R_E and 2 R_E in the transverse directions at y and z = ± 45 R_E. The simulation box is initially filled with a tenuous (0.1 cm^{-3}) and cold (5000°K) plasma. The solar wind magnetic field ($B_z = \pm 5.4$ nT), density (7.3 cm^{-3}), temperature (65000°K), and velocity (420 km/s) are imposed on the sunward face of the simulation box; open boundaries ($\partial/\partial n = 0$) are assumed for all of the other sides.

Magnetic Flux Ropes

Using the set of parameters described above we start the simulation with a southward magnetic field. We let the system evolve for 40 min to allow the unphysical initial state to be convected out of the simulation system and then flip the IMF from southward to northward at the inflow boundary. The three panels shown in Figure 1 are snapshots of the magnetic field configurations viewed from dusk and taken every 10 min after the IMF has been flipped. The first snapshot (Figure 1a) shows that reconnection takes place tailward of the polar cusp. Since the IMF is imposed at the sunward boundary, the reconnection process started at most 5 min before this snapshot was taken. In the figure, open field lines of the northern lobe have started to reconnect with magnetosheath field lines. Those portions of the

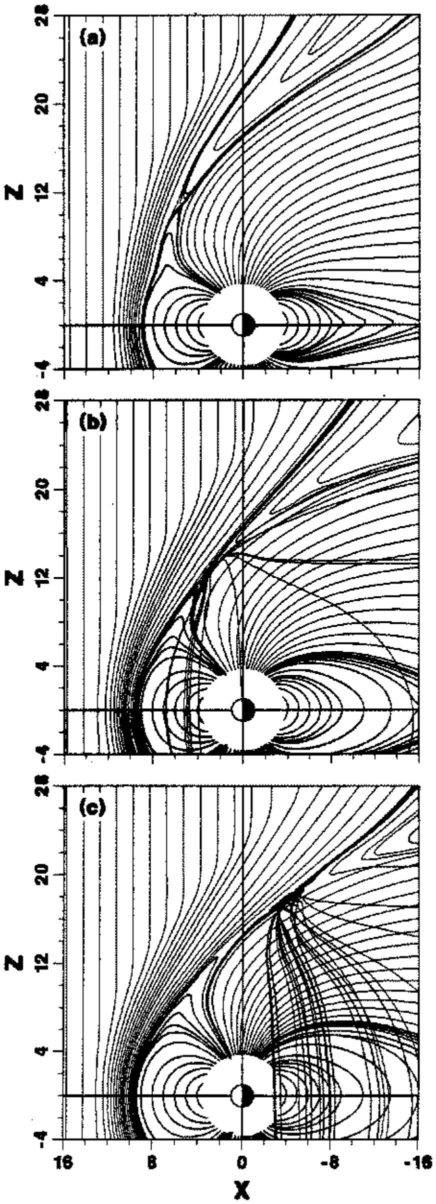

Fig. 1. Dusk views of the meridian plane showing magnetic field lines traced at different times of the simulation. Panels (a), (b), and (c) show the magnetic field configurations obtained at 10, 20 and 30 min, respectively, after the northward turning of the IMF at the upstream boundary located at x = 23 R_E.

open field lines tailward of the reconnection site have lost their connection to the Earth, resulting in the erosion of the plasma mantle.

While some northern lobe field lines sunward of the reconnection site remain open, with new ends located somewhere in the southern hemisphere, a symmetrical reconnection process occurs simultaneously in the southern hemisphere and results in the formation of closed field lines appended to the dayside magnetopause. As a result, the magnetopause moves sunward, and the flaring of the near-Earth tail decreases. This process is readily seen in the second snapshot (Figure 1b) taken 20 min after the northward turning. The subsolar magnetopause has moved sunward by 0.5 R_E, while the reconnection site has moved by about 1 R_E northward and 3 R_E tailward, increasing the amount of the dayside magnetic flux on closed field lines. The small "horn," a region of strong field line curvature concave towards the subsolar point and formed by the newly closed field lines below the reconnection site, is now well developed. A few open field lines drape across the flanks of the dayside magnetosphere: they are magnetosheath field lines that have reconnected in the southern hemisphere but not in the northern one. Looking closely at the reconnection site, we observe the formation of a small "island" structure to which open and closed field lines are connected; the open field lines are convecting around the magnetosphere and slipping on the magnetospheric boundary, whereas the closed field lines are part of the flank boundary itself.

In the next snapshot (Figure 1c) taken 30 min after the northward turning, we notice that the subsolar location of the last closed field line has remained unchanged. However, the reconnection site has moved significantly tailward and is now located on the nightside. As a result, closed dayside field lines stretch towards the nightside, covering the cusp region and forming an elongated current sheet above most of the polar region. A very similar magnetic field topology was reported by Wu [1985]. The "island" structure at the reconnection site has grown and the field lines out of the meridian plane have moved to the nightside. These field lines bend tailward because they convect along the magnetospheric flanks faster than the reconnection site does. By this time, the reconnection site has reached a stationary location, as plots for the next time steps (not shown here) indicate.

A three-dimensional rendering of the northern magnetosphere viewed from the duskside is displayed in Figure 2. It shows that the ropes in the high latitude nightside region drape over the magnetospheric flanks. The other detached field lines seen on the front side drape over the dayside, and slip over the dawn magnetospheric boundary but are not connected to the northern reconnection site. A complete mapping of these field lines (not shown here) indicates that they are the southern counterpart of those seen on the nightside. Close-up views of the tip of the current sheet seen in Figure 1c are displayed in Figure 3. A view from dusk (Figure 3a) shows that the overall island structure is wedge shaped. It lies between closed field lines and a mixture of magnetosheath field lines and southern open field lines. The structure extends over at least five cells of the computational mesh, and is about 2 R_E long and almost 1 R_E thick. A view from the sun (Figure 3b) reveals that the "island" structure is an artifact of the orthogonal projection. The field lines extending out of the meridian plane are helical which is characteristic of twisted magnetic field tubes or magnetic flux ropes.

It is interesting to note that the ropes are formed of intertwined open and closed field lines that are stretched over the polar

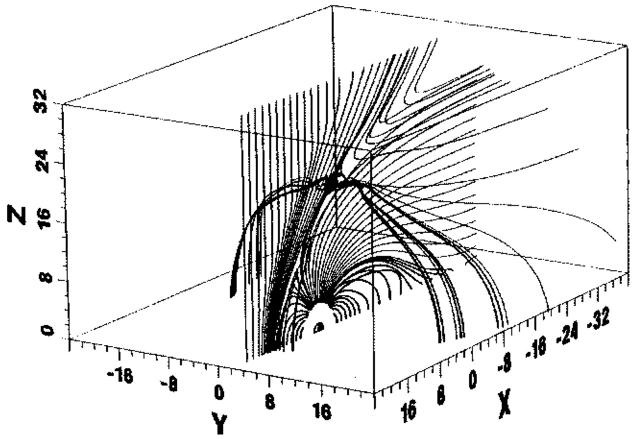

Fig. 2. Three-dimensional plot of the magnetic field lines shown in Figure 1c. The northern magnetosphere is viewed from the afternoon sector; only field lines originating from the dusk side of the meridian plane are plotted.

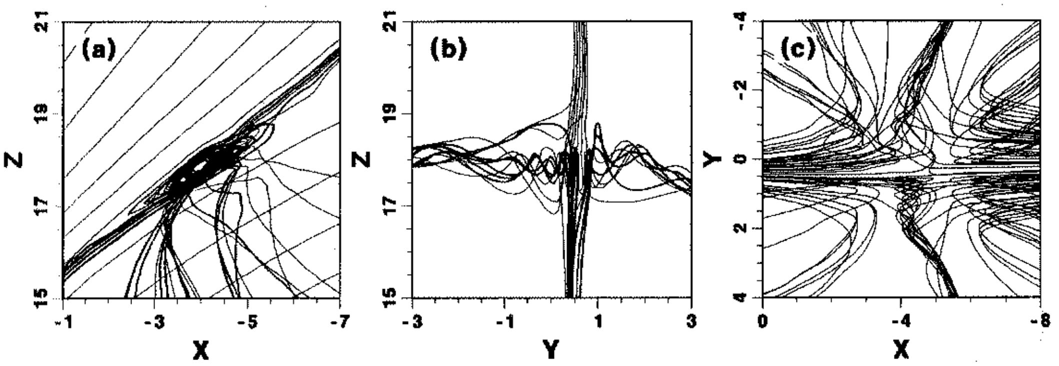

Fig. 3. Close-up views of the reconnection site and the magnetic flux ropes. Two-dimensional projections of the magnetic field lines in the x-z (a) and y-z (b) planes are viewed from dusk and noon respectively. Panel (c) is a view from above the reconnection site, the sunward direction being on the left.

region. This combination of open and closed field lines is important since it suggests that the plasma composition found in these flux tubes is a mixture of magnetosheath and magnetospheric plasma. Each rope has at least one end attached to the Earth, and does cross the meridian region. Two distinct systems of ropes are thus formed dawnward and duskward of the meridian plane, depending on the side of the magnetospheric boundary on which the equatorial portion of the ropes are convecting. The plane of symmetry of the two systems lies along the direction of the IMF and is thus the meridian plane for the purely northward IMF case shown here.

Most of the properties mentioned above are reminiscent of the FTEs observed at the dayside magnetopause. In looking down at the reconnection region along the z axis (Figure 3c), we observe a magnetic field topology very similar to that proposed by *Lee and Fu* [1985] to explain the formation of FTEs. They suggested that the presence of a B_y component in the magnetosheath field leads to multiple interconnections with the geomagnetic field lines and hence to the formation of twisted field lines between merging lines. The only difference between *Lee and Fu*'s reconnection geometry and that seen in Figure 3c is that in the figure multiple reconnections occur independently on each side of the meridian plane, leading to the formation of two sets of ropes as seen in Figure 3b. A significant new feature is that the component transverse to the geomagnetic field, which is needed to produce magnetic flux ropes, is not imposed by the east-west component of the IMF, but results from the convection and draping of the magnetic field lines along the magnetospheric boundary. As a consequence, the east-west component of the IMF does not control the process, which explains why the ropes occur even for purely northward IMF. This result was confirmed by running a simulation (not shown here) where the IMF was rotated by a 30° clock angle. In that simulation, magnetic flux ropes are also observed, but they are formed away from the meridian plane and closer to the plane lying along the IMF direction.

Observations

In order to test the validity of the ropes found in our simulations, we examined measurements from the Hawkeye-1 magnetometer [*Van Allen et al.*, 1974]. With an initial apogee of about 21 R_E and an inclination of approximately 90°, Hawkeye-1's orbit provides broad coverage of the high-latitude magnetopause [e.g. *Van Allen and Adnan*, 1992]. Since we expect that the ropes are well developed predominantly in the nightside region, we limited our search to observations near midnight magnetic local time (MLT). In addition we surveyed only the first year of Hawkeye-1's operation, and used IMP-8 solar wind data to select magnetopause crossings for which the IMF was predominantly northward during at least 1 hour prior to the crossings. This selection procedure left us with a very small data set, about 25 passes, from which 5 exhibited the spiky signatures to be expected when such rope structures are crossed. Figure 4 shows one of these crossings. In that figure, Hawkeye-1 magnetic field measurements from 12:00 to 13:00 UT on November 25, 1974, are plotted using 5.76 second resolution data that we averaged over 3 samples and then overlapped by 2/3 to restrict the bandwidth. The data are rotated into normal boundary coordinates (**l**, **m**, **n**) as defined by Russell and Elphic [1978], the l direction pointing roughly northward and tailward. The direction normal to the magnetopause (**n** = 0.329, 0.321, 0.867 in GSM coordinates) was calculated using the cross product of the average magnetospheric and magnetosheath field vectors. This direction is reasonable given the location of the spacecraft near 80° dipole magnetic latitude and 22.2 hours MLT. Three regions can be discerned on this inbound pass: the magnetosheath, identified by weak moderately variable magnetic field strengths and an orientation antisunward dawnward, the magnetosphere marked by the crossing of the magnetopause at 12:40 UT and identified by a strong constant magnetic field which points sunward and dawnward, and

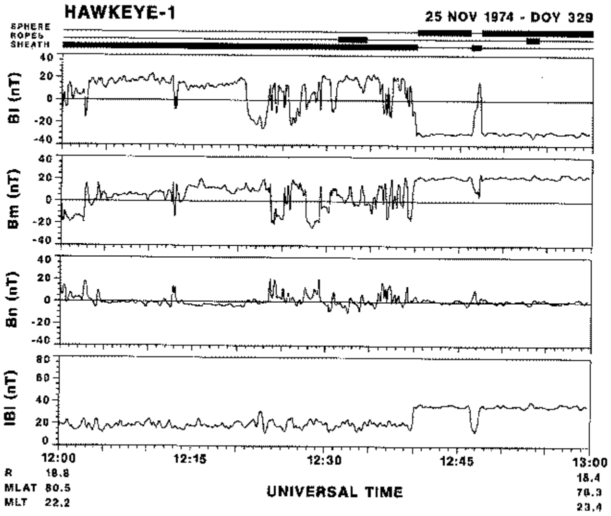

Fig. 4. Magnetopause crossings observed by the Hawkeye-1 spacecraft on November 25, 1974. The data are plotted in boundary normal coordinates; R indicates the radial geocentric distance of the spacecraft in units of the Earth's equatorial radius, MLAT is the dipole magnetic latitude and MLT is the magnetic local time in hours.

between those regions, from 12:20 to 12:40 UT, a transition region in which the magnetosheath field is highly variable both in strength and direction. This transition region is marked by the occurrence of several transient events that exhibit bipolar signatures in the normal component and field directions that are neither of the orientations previously identified. In addition a small bipolar signature accompanied by a small increase in the total field is observed in the magnetospheric field around 12:53 UT, just after a brief incursion into the magnetosheath around 12:47 UT. These features are fairly consistent with the signatures that one would expect [e.g. *Sonnerup*, 1988] when crossing the ropes seen in the simulations.

The somewhat weak increase in the field magnitude observed during these events might indicate that the spacecraft is relatively far from the core field region of the flux tubes. More obtrusive and better defined events may be found when a more systematic search of the Hawkeye-1 data is undertaken. Additional clues for the occurrence of the ropes could be found in the earlier Heos-2 data sets. Since the ropes observed in the simulations start forming in the dayside cusp (Figure 1b), it is possible that some impulsive events reported by *Haerendel et al.* [1978] might have been caused by such structures passing over the spacecraft.

Conclusion

We have examined the consequences of magnetic reconnection at the high-latitude magnetopause using a global MHD simulation of the solar wind interaction with Earth's magnetosphere for periods with northward IMF. In doing so we have identified the formation of magnetic flux ropes and showed that they result from multiple reconnection processes between the lobe field lines and draped magnetosheath field lines that are convected around the flank of the magnetosphere. Plasma features associated with these magnetic flux ropes are at the limit of what we can effectively resolve using our present computational mesh. However, intertwined open and closed magnetic field lines suggest that the ropes contain a mixture of magnetosheath and magnetospheric plasmas. Using a limited data set of magnetic field measurements from Hawkeye-1 during a period in which lobe and magnetosheath magnetic field orientations were nearly antiparallel, we tentatively identified transient event signatures that are consistent with those predicted by the simulation. However, further work including a search for a mixture of magnetosheath and magnetospheric plasmas must be undertaken to confirm the generation of such magnetic flux ropes at the high latitude magnetopause.

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