



FLUX ROPES IN THE MAGNETOTAIL: CONSEQUENCES FOR ION POPULATIONS

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ABSTRACT

We have investigated the origin of ions in magnetotail flux ropes by using a large scale trajectory calculation in which we launched solar wind ions into the electric and magnetic fields from a global magnetohydrodynamic simulation of the magnetosphere. We analyzed many ions entering the flux rope and found that three types of reconnection – on the dayside, in the magnetotail, and on the distant magnetotail flanks – as well as single particle drifts were important in forming this population.

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INTRODUCTION

Observations in the magnetotail during substorms have demonstrated the existence of large bundles of magnetic flux and plasma moving tailward that are called plasmoids [Hones *et al.*, 1984]. These were envisioned as magnetic O regions containing magnetic field lines in closed loops. Further observations made it apparent that in many, if not most, of these structures a cross-tail component of the magnetic field results in structures in which the field lines have a helical form [Elphic *et al.*, 1986; Sibeck, 1990; Moldwin and Hughes, 1991, 1992; Kivelson *et al.*, 1991, Frank *et al.*, 1994.] In a “traditional” plasmoid the magnetic field becomes small in the center of the structure and plasma pressure provides force balance while in a flux rope force balance is provided by the component of the magnetic field parallel to the flux rope which reaches a maximum in the center of the structure. This maximum in the cross tail component is in addition to a bipolar signature in the other components of \vec{B} .

Analyses of both spacecraft observations [Moldwin and Hughes, 1992] and magnetohydrodynamic (MHD) simulations [Birn and Hesse, 1990, 1991; Ogino *et al.*, 1990; Hesse and Birn, 1991] have shown that flux ropes form when the interplanetary magnetic field (IMF) has a southward component as well as a nonzero B_y component (in GSM coordinates). The cross-tail (B_y) component of the flux rope field has the same sign as the IMF B_y . A striking distinction between the dynamics of plasmoids and those of flux ropes can be seen in the MHD simulations. The plasmoids, consisting of closed loops of magnetic field, are accelerated rapidly down the tail due to the tension in the magnetotail field draping the plasmoid while the flux ropes, which contain bundles of field lines attached to the Earth, experience a slower tailward motion until all these field lines are disconnected from the Earth [Walker and Ogino, 1996].

The MHD simulations have clarified the nature of flux ropes. An important problem that remains is the distribution of particles in the flux rope and their origin. Richard *et al.* [1994] calculated ion entry trajectories for a northward IMF configuration determined from MHD simulations and found that non-adiabatic acceleration and guiding center drifts that are not included in the MHD approach are important for the entry and energization of ions in the magnetosphere. The same approach showed that non-MHD effects were also critical for a southward IMF case [Walker *et al.*, 1996]. This paper presents results from a large scale particle trajectory calculation in the electromagnetic fields from an MHD simulation in which an IMF B_y component has resulted in the formation of a flux rope.

2. THE MODEL

Our approach is to follow thousands of particles through a fixed magnetic and electric field model [Ashour-Abdalla *et al.*, 1994]. Our electric and magnetic field model is a snapshot of a three dimensional global MHD simulation of the magnetosphere [Walker and Ogino, 1996]. We chose a snapshot 720 min. after the beginning of the run when the IMF was oriented 30° dawnward of pure southward (Case 2 in Walker and Ogino, 1996) and a large flux rope contained a combination of closed, open and solar wind field lines. At this time magnetic reconnection was taking place on the dayside, earthward of the magnetotail flux rope and on the flanks in the distant tail. The flux rope was moving tailward at a slow rate. Because we used a field model that was constant in time we make the implicit assumption that the evolution of the field is slow compared to the motion of the particles.

In this paper we use an Earth-centered coordinate system with x along the Earth-sun line pointing sunward, z positive northward and y completes a right handed system with the positive direction toward dusk. We launched 19757 H^+ ions in the solar wind at $x = 20 R_E$. The particles were initially distributed in y and z on a grid. A denser grid was used near the Sun-Earth line because these particles are more likely to enter the magnetosphere. The particles were distributed in velocity space as a Maxwellian with a temperature of 18 eV, the solar wind temperature in the MHD simulation. The ions were halted when they reach $x = -60.75 R_E$, $y = \pm 33.75 R_E$, $z = \pm 33.75 R_E$. The MHD simulation has an inner boundary at a radial distance of $5.5 R_E$ from the Earth just outside of which ($6 R_E$) we also stopped the particles.

3. CALCULATION RESULTS AND DISCUSSION

Particles on field lines experiencing reconnection on the dayside move onto open field lines. As they interact with the regions of weak magnetic field near the reconnection regions they can be transported across magnetic field lines and energized by the electric field. The most energetic particles move along field lines at high velocities away from the magnetosphere, while the lower energy ones enter and form the plasma mantle, as was observed for purely southward IMF in Walker *et al.*, [1996].

Figure 1 is a scatter plot of the locations of all particle crossings of the $x = 4 R_E$ plane where the points have been shaded according to their energies. Bands of particles with energies greater than 8 keV that have interacted with the reconnection regions can be seen on the dusk side for large values of z and on the dawn side for large negative values of z . However, most of the particles entering the magnetosphere in the mantle have lower energies. Some of these low energy particles interact with the cusp and are energized. These higher energy particles are seen around $z = \pm 10$. Some of the particles reach closed field lines and are temporarily trapped. These can be seen in the vicinity of the Sun-Earth line, particularly on the dusk side.

Some of the particles that reached energies of a few keV in the cusp region (see Figure 1) moved onto closed field lines lost much of this energy again before drifting onto open field lines. These particles, plus many more mantle particles, then propagate tailward on open (lobe like) field lines. In the magnetotail many of the particles encounter and enter the flux rope region. Particles affected by magnetic reconnection in the magnetotail associated with the flux rope can increase their energy by several keV. The flux rope region consists of a mixture of closed, open

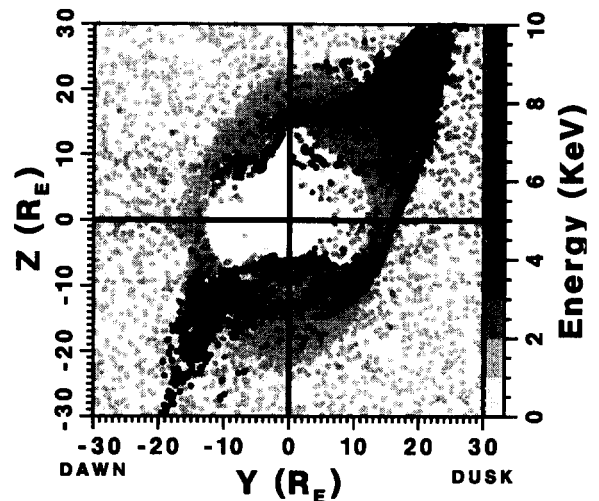


Fig. 1. Scatter plot of all particle crossings of the $x = 4 R_E$ plane. Each time any particle crossed this plane a dot was made that is shaded according to the energy of the particle (see scale). The IMF orientation was 30° dawnward of south. Higher energy particles can be seen exiting the magnetosphere on open field lines while lower energy ones form a plasma mantle closer to the Earth. Higher energy particles in the less dense regions inside the magnetosphere either interact with the cusp or are mirror bouncing on closed field lines.

and solar wind field lines. Some particles leave open field lines in this region and populate the other field line types. The particles that reach solar wind field lines in the flux rope usually drift toward the dusk side (Figure 2) and exit the magnetosphere due to the weak reconnection on the flanks of the distant tail that is gradually eroding the closed flux rope field lines.

Next we will consider two representative single particle trajectories that further illustrate how the distribution of particles in Figures 1 and 2 were formed. One of the most interesting results of our calculation is that the particles that populate the flux rope all seem to encounter similar sequences of field line types. The first particle we will discuss is shown in Figure 3. This particle began on a solar wind field line (1) which reconnected on the dayside transferring it briefly to a kinked open field line (2) and then onto a closed field line (3) at large z . Moving to the nightside it crossed onto an open field line along which it moved tailward (4,5). The open field line that the particle was on then reconnected. The particle reached the flux rope region and it moved onto a looped solar wind field line (6). It then drifted toward the dusk side, increasing in energy from a few hundred eV to about 4 keV. Next it entered a region of closed field lines on the dusk side (7) and convected in an earthward direction, nearly reaching $x = -12 R_E$. Because of the reconnection on the dusk flank it was transferred to an open field line (8) on which it exited the magnetosphere and the simulation box.

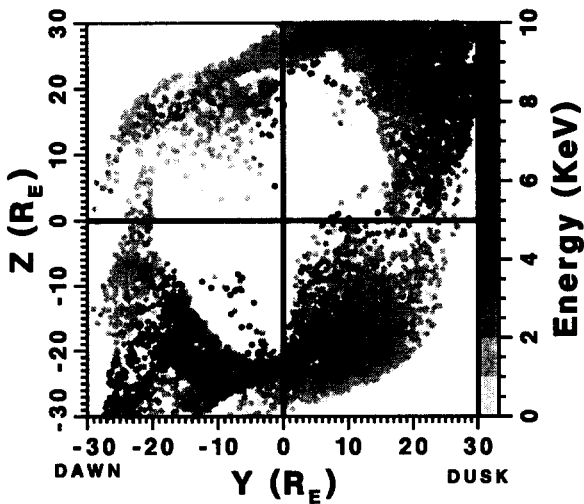


Fig. 2. Scatter plot of all particle crossings of the $x = -40 R_E$ plane. Each time any particle crossed this plane a dot was plotted that is shaded according to the energy of the particle. A dense cluster of particles occupies the region corresponding to the dusk side of the flux rope. Some particles have been energized by drifting duskward across the magnetotail electric field.

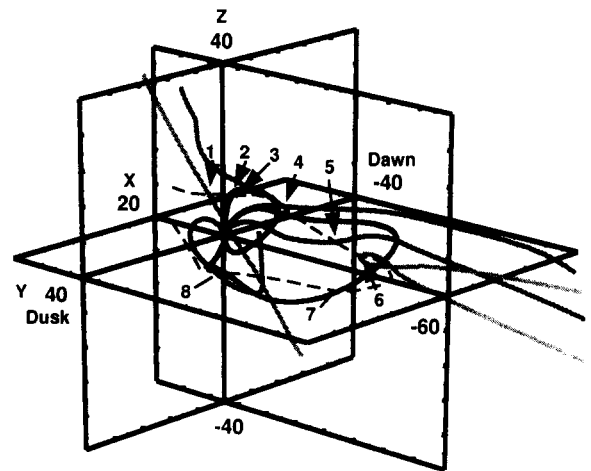


Fig. 3. Trajectory of a particle that entered the flux rope, shown in a three-dimensional perspective. The dashed line is the particle trajectory. Solid curves are field lines intersecting the particle trajectory at various points along its path. The field lines are shaded according to their topology (closed are black, open are dark gray, solar wind are light gray). The numbered arrows distinguish the particle location on some of these field lines (see text). Three reconnections help transport the particle among different regions.

The second particle we will discuss (shown in Figure 4) had a very different trajectory but reached the flux rope through a similar sequence of field line type transitions. Like the other particle it went through a solar wind-open-closed field line sequence (1,2,3) in the vicinity of the cusp because of dayside reconnection. Like the other particle, it then convected tailward along open field lines (4,5) until it encountered the flux rope. There it was transferred to twisted solar wind field lines in the flux rope (6,7). Within the flux rope it experiences a complex series of spiral motions along twisted field lines combined with mirror reflections. It exits the tailward boundary at $y = 5 R_E$, $z = 1 R_E$. While moving duskward in the flux rope, it was energized up to about 6 keV.

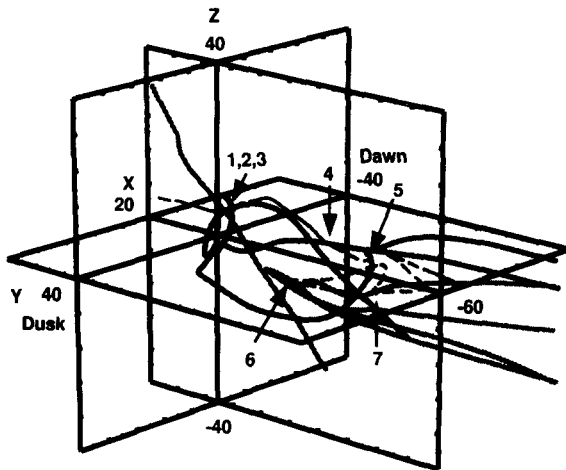


Fig. 4. Trajectory of a particle that interacted with the flux rope, shown in a three dimensional perspective. The dashed line is the particle trajectory. Solid curves are field lines intersecting the particle trajectory at various points along its path. The numbered arrows distinguish these field lines the particle location on some of these field lines (see text). Note the complicated trajectory in the flux rope region.

rope are convecting were typically involved in three reconnections, once on the dayside as they enter the magnetosphere, again in the magnetotail as they enter the flux rope and a third time as they leave the flux rope on the dusk flank.

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In our calculation, solar wind ions were able to easily populate a flux rope in the magnetotail. Several general statements can be made about these particles. The ions that populated the flux rope entered the magnetosphere on field lines reconnecting on the dayside. The ions which gained the most energy in the process were those that entered the magnetosphere in the weak B region associated with the reconnection. These were lost on open field lines. The lowest energy particles were those that missed the weak B region. Some of these particles convected toward the flux rope on open field lines. Others were energized by electric fields near the cusp but decreased in energy later and were transferred onto open field lines. Once particles reached the flux rope, they underwent significant energization and drifted duskward due in part to gradient and curvature drifts. Particles that were energized in the magnetotail moved easily between the closed, open and solar wind field lines in the flux rope. The particles reaching the flux rope experienced complex motion there. Particles could enter the closed field region of the flux rope, where they often moved back toward the Earth before being lost from the magnetosphere by reconnection on the dusk flank. A surprising result of this calculation is that the field lines on which particles populating the flux

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