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OBSERVATIONS OF A SMALL INTERPLANETARY MAGNETIC FLUX ROPE ASSOCIATED WITH A MAGNETIC RECONNECTION EXHAUST

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ABSTRACT

A small interplanetary magnetic flux rope prior to an X-line magnetic reconnection exhaust was observed on 1998 March 25 at 1 AU. The X-line magnetic reconnection exhaust has been identified and reported by Gosling et al. The duration of this small magnetic flux rope is about 2 hr. We fitted the constant alpha force-free model to the observed magnetic fields. The model fitting results show that the spacecraft crosses the magnetic flux rope well away from the axis, with d_0/R_0 being 0.76. The fitting results also show that its magnetic configuration is a right-handed helical flux rope, that the estimated field intensity at the axis is 16.3 nT, and that its diameter is 0.0190 AU. In addition, the axial direction of this rope is ($\theta = 6°$, $\phi = 214°$), namely, this magnetic flux rope is lying nearly in the ecliptic plane. According to the geometric relation of the small flux rope and the reconnection exhaust, it is very possible that the small magnetic flux rope has a larger scale initially and comes from the corona; its magnetic fields are peeled off when moving from the Sun to the Earth and at last it reaches a small scale. Though magnetic reconnection can produce a flux-rope topology, in this case the X-line magnetic reconnection is destroying rather than generating the small magnetic flux rope.

Key words: solar–terrestrial relations – solar wind – Sun: magnetic fields

1. INTRODUCTION

Magnetic flux ropes (MFRs), which are often observed by spacecraft and have a wide timescale distribution are an important kind of magnetic structure in the interplanetary space. Their durations vary from tens of minutes to tens of hours (Moldwin et al. 1995, 2000; Feng et al. 2007). Among the interplanetary magnetic flux ropes (IMFRs), magnetic clouds (MCs) have large-scale structures, and their diameters are about $0.20 \sim 0.40$ AU near the Earth (e.g., Goldstein 1983; Burlaga 1988; Lepping et al. 1990; Farrugia et al. 1995). Some scientists searched for the solar origin of MCs (e.g., Smith & Phillips 1997; Bothmer & Schwenn 1998; Leamon et al. 2004) and offered evidence that MCs are the interplanetary manifestations of coronal mass ejections (CMEs). In contrast, the source of small IMFRs is still a matter of debate. First Moldwin et al. (1995, 2000) reported several small IMFRs by the *Ulysses*, IMP 8 and *Wind* spacecraft. They suggested that these small IMFRs did not originate as such in the corona; instead, the small IMFRs could have resulted from magnetic reconnection locally in the solar wind. Their evidence for this argument includes the following: (1) no intermediate-sized events (durations of several hours) have been reported; (2) there is no expansion within these flux ropes; and (3) there is a difference in plasma characteristics such as the proton temperature compared to MCs. Then Wei et al. (2003) argued that small IMFRs had a larger scale initially and came from the corona, and its magnetic fields were peeled off by magnetic reconnection near their boundaries when moving from the Sun to the Earth, where at last they reached a small scale. Recently, Feng et al. (2007) provided the size and energy spectrums of IMFRs, which included many small- and intermediate-sized IMFRs. Their analysis for the IMFRs with different scales showed that the physical properties of the IMFRs changed slowly with the increase of their scale sizes. Therefore, Feng et al. (2007) suggested that as MCs are interplanetary manifestations of CMEs, the small IMFRs are the interplanetary manifestations of small CMEs produced in small solar eruptions, which are too weak to appear as clearly as ordinary CMEs do in coronagraph observations.

As mentioned above, there are two possibilities that have been proposed if small IMFRs were indeed generated from the sun. One is that the small IMFRs are the interplanetary manifestations of small CMEs. The other one is that small IMFRs have a larger scale initially, but when the magnetic reconnection process occurs near the boundaries, their magnetic fields are peeled off when moving from the Sun to the Earth and at last they reach a small scale (Wei et al. 2003). However, to the best of our knowledge, there is no direct evidence for these suggestions so far. Recently, many observed solar wind reconnection events were reported by Gosling et al. (2005a, 2005b, 2006a, 2006b, 2006c, 2007) and Phan et al. (2006). These observations clearly indicate that the magnetic reconnection is common in the interplanetary space. In addition, small IMFRs are encountered frequently by spacecraft (e.g., Moldwin et al. 1995, 2000; Slavin et al. 2003; Eastwood et al. 2002; Feng et al. 2007, 2008; Cartwright & Moldwin 2008; Ruan et al. 2009). Thus it is possible to find a small IMFR associated with an X-line reconnection exhaust. In this paper, we report a small IMFR associated with a reconnection exhaust, which was observed by *Wind* and *ACE* on 1998 March 25. Its trailing boundary is just the leading boundary of the X-line reconnection exhaust reported by Gosling et al. (2005a). The geometric relation of the IMFR and the reconnection exhaust indicate that the magnetic flux in the flux rope is decreasing. There are no available solar wind data of *ACE* for the small IMFR due to the data gap, so we will analyze this event using only the *Wind* data.

2. OBSERVATIONS

Figure 1 shows the magnetic field and plasma data of the IMFR as well as the following magnetic reconnection exhaust, which is marked by the gray rectangle. From the top to the bottom, the panels show the magnitude of the total magnetic

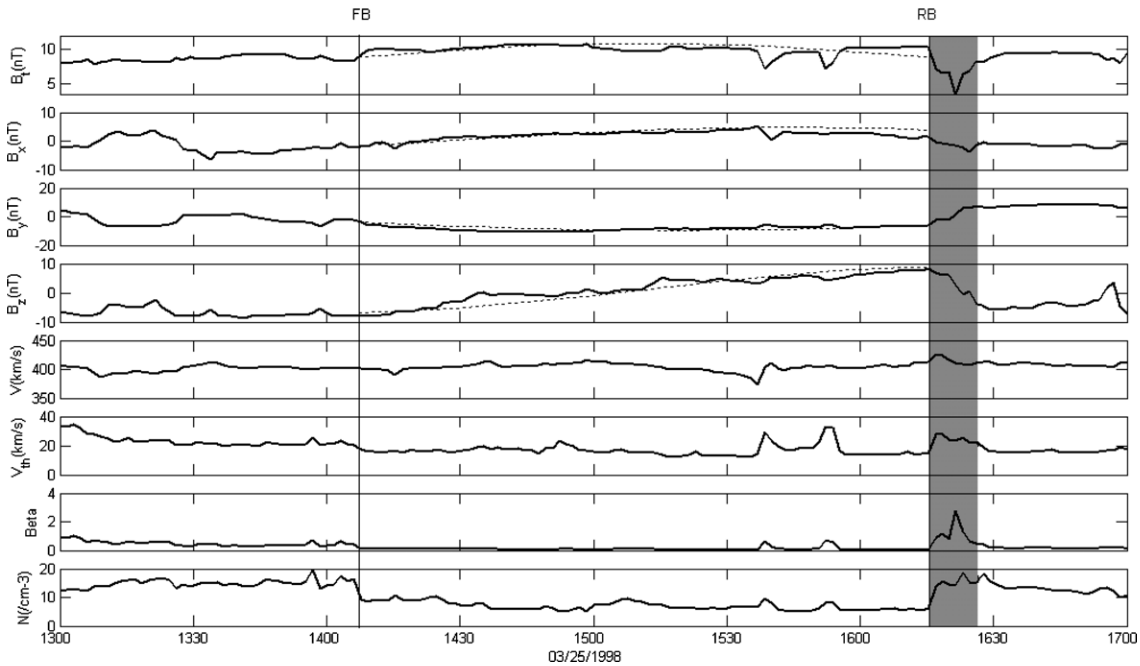

Figure 1. Interplanetary magnetic field and plasma data measured by the *Wind* spacecraft on 1998 March 25. The gray-colored region indicates the X-line magnetic reconnection exhaust. The dot curves are flux rope fitting values. FB and RB are the estimated front and rear boundaries of the interplanetary magnetic flux rope, respectively.

field (B_t); the x, y, and z components of the magnetic field (B_x, B_y, B_z); the proton speed (V); the proton thermal speed (V_{th}); the plasma beta (β); and proton density (N). The magnetic field data were obtained from the magnetic field investigation (MFI) magnetometer, and the proton data were obtained from the three-dimensional plasma (3DP) analyzer. The description of the instruments onboard *Wind* can be found in Lepping et al. (1995) and Lin et al. (1995). Here, the coordinate system is the geocentric solar ecliptic (GSE) Cartesian system, where x is along the Earth–Sun line and points to the Sun, y points to the dusk in the ecliptic plane (opposing planetary motion) and z points to the ecliptic north pole.

From Figure 1, it is easy to see that the IMFR has the classic flux rope signature and that the bipolar field appears in the B_z component. One can also find that the core field is observed in the B_x and B_y components. In addition, this event also displays a smooth rotation of the magnetic field direction, low plasma beta, low proton density, and enhanced magnetic field magnitude. As shown in Figure 1, the total magnetic field magnitude begins to enhance at about 1408 UT on March 25 (denoted by the vertical solid line FB), at which time the plasma beta, proton density, and temperature (the proton thermal speed) all decrease abruptly. In contrast, the total magnetic strength decreases at about 1616 UT, and the plasma beta, proton density, and temperature all increase there. Therefore, the boundaries of this IMFR are easy to identify, and we take FB and RB as the front and rear boundaries to analyze this IMFR.

IMFRs of all sizes have an approximate constant alpha force-free field configuration (e.g., Goldstein 1983; Lepping et al. 1990; Moldwin et al. 2000; Feng et al. 2007), i.e., IMFRs can be described with the Lundquist (1950) solution:

$$\begin{cases} B_R = 0 & \text{radial component} \\ B_T = B_0 H J_1(\alpha R) & \text{tangential component} \\ B_A = B_0 J_0(\alpha R) & \text{axial component,} \end{cases} \tag{1}$$

where J_n is the nth-order Bessel function, $H = \pm 1$ denotes the right and left handedness of the field twist, respectively, B_0 is the field intensity at the axis of the rope, and R is the radial distance from the axis. In order to obtain detailed information of this IMFR, we fit the constant alpha model to the observed magnetic fields. A detailed description of the fitting method can be found in Feng et al. (2007, 2008). Figure 1 also displays the best-fit magnetic field curves (dot lines). It can be seen that the two sets of curves are approximately consistent, which means that the model fits the observed data well. The model fitting results reveal that the spacecraft traverses the IMFR above its magnetic axis, and the spacecraft trajectory depart considerably from the axis of the IMFR, with d_0/R_0 being 0.76, where d_0 is the closest approach distance to the axis, and R_0 (in the event $2R_0 = 0.0190$ AU) is the flux rope's radius. The fitting results also show that this is a right-handed helical flux rope, that the estimated field intensity at the axis is 16.3 nT, and that the axial direction is ($\theta = 6^\circ$, $\phi = 214^\circ$), where θ and ϕ are the latitude and longitude with respect to the ecliptic plane. So, the IMFR is almost lying in the ecliptic plane.

As mentioned previously, Figure 1 also indicates the X-line reconnection exhaust, which is marked by the gray rectangle. This exhaust was first reported by Gosling et al. (2005a) using *ACE* data. As Gosling et al. pointed out, reconnection exhausts typically occur at relatively large shears in the magnetic field separating solar wind regions; in addition, they are considerably different in the plasma densities, plasma beta, temperatures, and Alfvén speeds on opposite sides of the exhaust layer. The reconnection exhaust on 1998 March 25 has all the above characteristics. As can be seen, (1) within the exhaust the plasma β, the proton temperature and density are all higher than outside; (2) the change of the observed field orientation in this event is 164°; (3) the magnetic field strength is weaker than that of the surrounding solar wind; (4) the surrounding solar wind has a low proton beta (<0.2); (5) the changes in the velocity and magnetic field components are correlated at the leading boundary and anti-correlated at the dialing boundary (not shown). These features satisfy the criteria of most of the reconnection exhausts (e.g., Gosling et al. 2005a, 2005b, 2006a, 2006b).

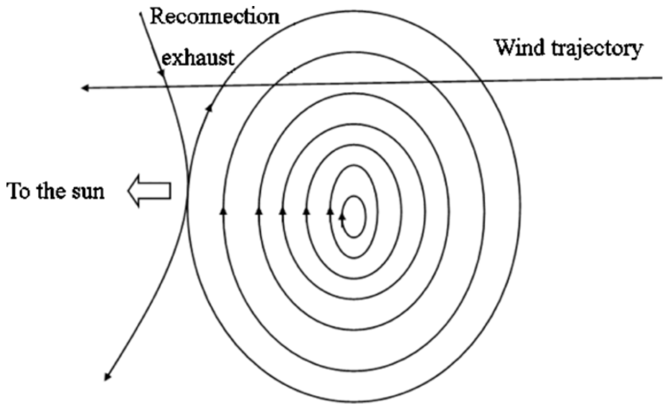

Figure 2. Sectional sketch of the flux rope and the reconnection exhaust.

According to the fitting results, Figure 2 gives the sectional sketch of the flux rope and the reconnection exhaust. From Figure 2, one can see that the magnetic flux in the flux rope is decreasing by the magnetic reconnection, which means that the magnetic fields are peeling off from the magnetic flux rope. Therefore, the spatial scale of the flux rope would diminish gradually.

3. SUMMARY AND DISCUSSION

Recently, many small IMFRs were reported (e.g., Moldwin et al. 1995, 2000; Slavin et al. 2003; Eastwood et al. 2002; Feng et al. 2007, 2008; Cartwright & Moldwin, 2008; Ruan et al. 2009), but the origin of small IMFRs is still disputed. Two possible mechanisms have been proposed to explain the generation of small IMFRs. One is that these IMFRs result from magnetic reconnection in the solar wind well away from the Sun (Moldwin et al. 2000; Cartwright & Moldwin, 2008). The other one is that the IMFRs are produced by solar eruptions (Feng et al. 2007, 2008; Wei et al. 2003). In this paper, we report a small IMFR associated with an X-line magnetic reconnection event. It is interesting that the rear boundary of the IMFR is just the leading boundary of the magnetic reconnection exhaust reported by Gosling et al. (2005a). According to the geometric relation of this rope and the magnetic reconnection exhaust, we can conclude that the magnetic fields of the IMFR are merging with those of the background solar wind. Therefore, it is very possible that all the SMFRs have larger scales initially and come from the corona; their magnetic fields are peeled off when moving from the Sun to the Earth, where they reach small scales. On the other hand, though the simulation result showed that multiple X-line magnetic reconnections may produce the rope topology (Lee et al. 1993), the X-line magnetic reconnection is unrelated to the generation of the IMFR. If the IMFR were generated by the magnetic reconnection, the direction of reconnection exhaust should be toward the IMFR.

Finally, it is necessary to point out that the present work cannot absolutely exclude the possibility of the interplanetary origin of small IMFRs. Perhaps small IMFRs have two formation mechanisms: some are small-scale CMEs and others have an interplanetary origin. However, it is currently difficult to distinguish between the two mechanisms and further observations are needed.

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