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Multiple-spacecraft study of an extended magnetic structure in the solar wind

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[1] An extended magnetic structure was observed consecutively by five spacecraft (ACE, WIND, STEREO A and B, and CLUSTER) in the solar wind on 15 January 2007. The similar bipolar magnetic field variations from five spacecraft suggest that the magnetic structure is two-dimensional. The abrupt disappearance of the beam electrons in the core of the structure suggests that the core of the structure is magnetically isolated from the surrounding environment. Our analysis shows that this magnetic structure is a magnetic flux rope, which extends over at least 180 R_E in space. The length and orientation of the flux rope were determined by a local minimum variance analysis (MVA) from individual spacecraft observations of the magnetic field and a timing analysis based on the joint observations by all five spacecraft. The results show that the orientation of the flux rope stays constant in space and time. The flux rope is embedded in a corotating interaction region (CIR), which followed a magnetic cloud.

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1. Introduction

[2] Recently, multiple-spacecraft observations have been often used to study magnetic structures in the solar wind. Their advantage, compared to single-spacecraft observations, is that they enable us to differentiate space and time variations of magnetic structures. *Phan et al.* [2006] and *Gosling et al.* [2007] applied multiple-spacecraft observations to analyze magnetic reconnection X lines in the solar wind. They reached the conclusion that the reconnection X lines can extend widely in space. *Eastwood et al.* [2002] studied the heliospheric current sheet (HCS) and a flux rope with observations from ACE and CLUSTER. One of their results is that the flux rope orientation can change in space. These results from multiple-spacecraft observations cannot be obtained from single-spacecraft observations.

[3] Flux ropes have been observed in the solar wind by *Moldwin et al.* [1995, 2000], and they suggested that these flux ropes might be generated locally in the solar wind. Basic characteristics, such as the length, diameter, and possible generation mechanism of the flux rope in the solar wind are still not well known. Individual-spacecraft observations suggested that a flux rope in the Earth magnetotail could be a two-dimensional structure, elongated in its nearly invariant third dimension [*Slavin et al.*, 2003]. Multiple-spacecraft observations are still needed to confirm this conclusion. In situ observations in the solar wind by the two STEREO A and B spacecraft now provide an opportunity to study the scale of flux ropes.

[4] A similar type of magnetic structure in the solar wind is magnetic clouds, which are generated in the solar corona and convected into interplanetary space by the solar wind. (To avoid confusion, the flux ropes mentioned in this paper do not include magnetic clouds, which are large flux-rope-type structures.) Both flux ropes and magnetic clouds show signatures of a helical magnetic structure in the observations. *Moldwin et al.* [1995] studied a small-scale flux rope in the solar wind, which is in close proximity to a heat flux dropout at the heliospheric current sheet (HCS). *Moldwin et al.* [2000] identified several differences between these small-scale flux ropes and magnetic clouds. The average estimated diameter of magnetic clouds is around 6350 R_E (Earth Radii), but the size of the flux ropes is about 20 times smaller. The plasma temperature inside flux ropes shows little change compared to the surrounding environment, while the temperature in magnetic clouds is usually lower than in the ambient solar wind. There is no expansion for these flux ropes, but magnetic clouds usually show expansion at 1 AU (Astronomical Unit). On the basis of these differences, *Moldwin et al.* [2000] suggested that the flux ropes might be generated by local magnetic reconnection in the solar wind, instead of being convected from the solar corona like magnetic clouds. *Feng et al.* [2007] carried out a statistical study about flux ropes and magnetic clouds. In contrast to the findings of *Moldwin et al.* [2000], *Feng et al.* [2007] found that the crossing time of the flux ropes varies continuously from tens

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of minutes to tens of hours. Though the results of *Feng et al.* [2007] are not totally conclusive, they suggested that, like magnetic clouds, these interplanetary magnetic flux ropes are manifestations of small coronal mass ejection (CME) events, which are too weak to appear in coronagraph observations. However, the statistical study of *Cartwright and Moldwin* [2008] on the flux ropes in the solar wind found that the size of the flux ropes appears to be bimodal, with the most events having less than four hours duration. This result suggests different source mechanisms for small-scale flux ropes and magnetic cloud.

[5] In this paper, we will describe observations of a coherent structure in the solar wind from five spacecraft. The analysis shows that this magnetic structure is a flux rope, which is embedded in a corotating interaction region (CIR). The magnetic field data from five spacecraft provide clear evidence that the flux rope is a quasi two-dimensional structure and extends in space. The diameter of the flux rope is about 90 times smaller than that of the magnetic cloud, which passes the spacecraft immediately before the flux rope.

2. Observations

[6] In this section we show and discuss the in situ observations from five different spacecraft. The GSE coordinates (in units of R_E) of the spacecraft are (218, −12, 22) for ACE, (249, −55, 18) for WIND, (259, −112, −39) for STEREO A, (103, −6, −17) for STEREO B, and (12, 14, −4) for CLUSTER 4 (C4) on 15 January 2007. Compared to the size of the flux rope we will study, the distances between four CLUSTER spacecraft are very close together, so we are treating them as a single point measurement. All the spacecraft were in the solar wind upstream of Earth's bow shock.

[7] First we present the magnetic field observations from STEREO A [*Luhmann et al.*, 2008]. Figure 1 (top) shows the observation of the B_X component of the magnetic field in GSE coordinates by STEREO A from 9 to 23 January 2007. STEREO A caught the heliospheric current sheet (HCS) with the reversal of B_X on 15 January 2007. The other panels show observations from 05:00 UT to 13:00 UT on this day. The blue highlighted region shows the crossing of the HCS around 08:20 UT. From the B_X component and the azimuth angle Φ_B, we can see that the magnetic field changed its direction from toward the Sun to away from the Sun during this crossing. Before the crossing of the HCS, the B_Y and B_Z components around 07:35 UT exhibited a bipolar signature indicating a special magnetic structure, which we will identify as a flux rope. The yellow highlighted region shows the crossing of this flux rope. From Figure 1 (bottom), we can see that the angle Φ_B changed from ~350° to ~120° during the crossing of the HCS. However, during the crossing of the flux rope, the Φ_B shows only a little variation around 350°, which means that the flux rope is a different magnetic structure from the HCS. These observations also indicate that the flux rope is not embedded in the center of the HCS.

[8] The orientation of the flux rope was determined by a local minimum variance analysis (MVA) from individual spacecraft observations and a timing analysis based on the joint observations of all five spacecraft, because by MVA alone one cannot determine the flux rope orientation [*Xiao et al.*, 2004]. (We did not apply a current MVA (CMVA) based on CLUSTER four-point data, to analyze the flux rope orientation, because the distances between the four CLUSTER spacecraft were too small compared to the flux rope size.) The magnetic field vector inferred from the five spacecraft is decomposed into the three directions, $\mathbf{L}_{FR}$ (0.17, −0.34, 0.92), $\mathbf{M}_{FR}$ (0.76, −0.54, −0.34), and $\mathbf{N}_{FR}$ (0.61, 0.76, 0.16) based on the MVA of the ACE observations, and shown in Figure 2. For the MVA of the flux rope, we found that the eigenvalues obey $\lambda_L/\lambda_M \approx 10 \gg 1$ and $\lambda_M/\lambda_N \approx 10 \gg 1$ for all five spacecraft. This means that the MVA gives the maximum ($\mathbf{L}_{FR}$), intermediate ($\mathbf{M}_{FR}$) and minimum ($\mathbf{N}_{FR}$) variance directions of the magnetic field with high accuracy [*Sonnerup and Scheible*, 1998]. For all spacecraft the corresponding **LMN** coordinate axes are almost parallel. The $\mathbf{M}_{FR}$ direction, which we will identify as the flux rope orientation, is in GSE (0.76, −0.54, −0.34) for ACE, (0.73, −0.58, −0.35) for WIND, (0.88, −0.25, −0.39) for STEREO A and (0.74, −0.53, −0.41) for STEREO B, and finally (0.85, −0.43, −0.29) for CLUSTER. There is a little difference in the flux rope orientation from the STEREO A observation. The angular separations of the $\mathbf{M}_{FR}$ directions from ACE, WIND, STEREO B and CLUSTER are about only 10 degrees.

[9] In Figure 2, the similarity of the magnetic field component variations observed by the five spacecraft with a time delay suggests an extended, quasi two-dimensional structure.

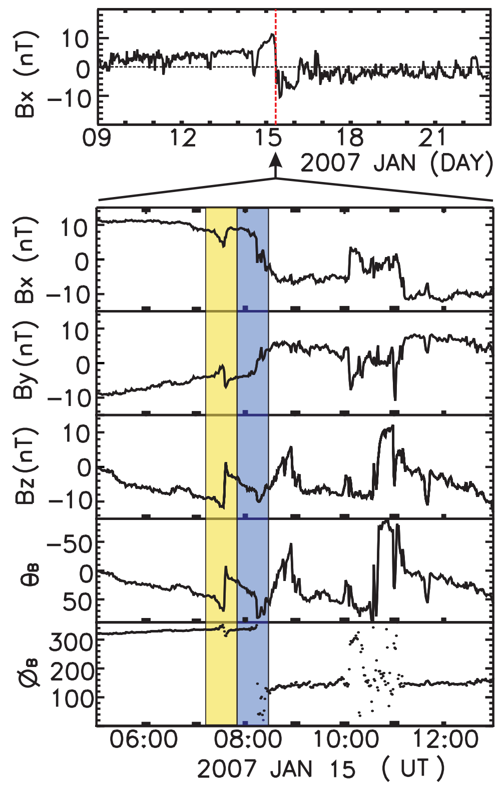

Figure 1. Magnetic field parameters during the crossing of the flux rope and the HCS in the solar wind by STEREO A. The red dashed line in the top shows the reversal of the B_X component, which indicates the HCS. The yellow strip in the bottom highlights the flux rope. The blue strip highlights the crossing of the HCS.

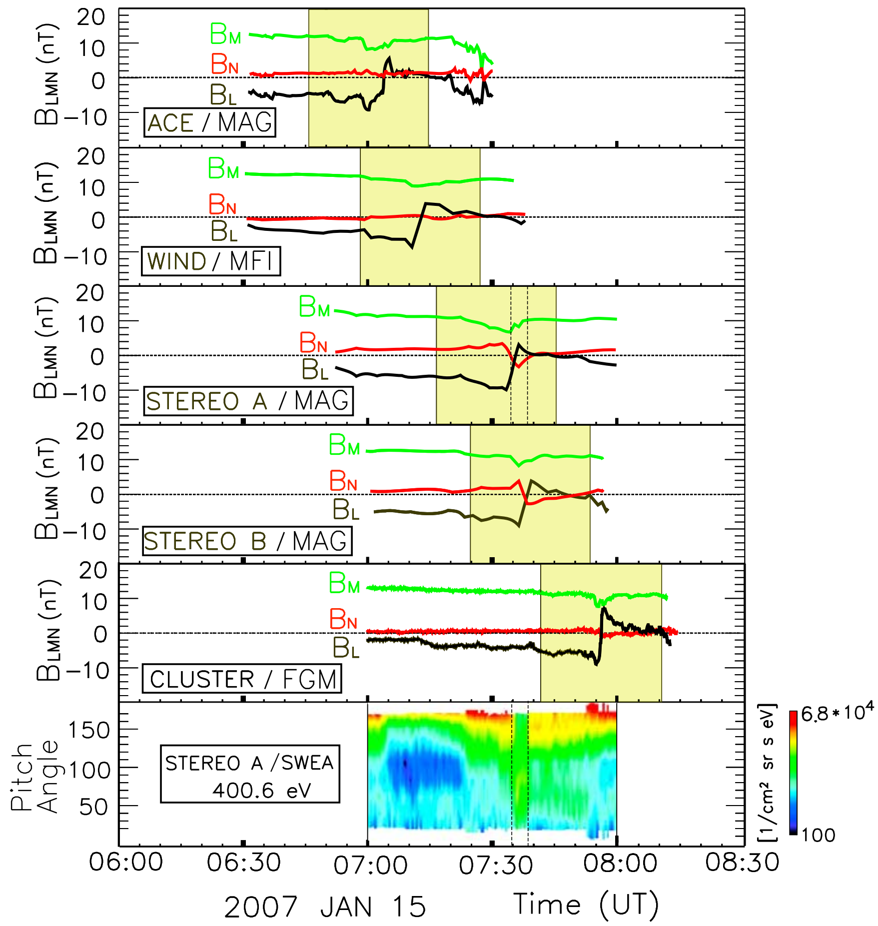

Figure 2. Magnetic field signatures of the same flux rope observed by five spacecraft consecutively. (top) Three magnetic field components measured by the five spacecraft in the **LMN** coordinate system of the ACE spacecraft. The time resolution of the magnetic field observations is 4 seconds from CLUSTER, 16 seconds from ACE, and 1 minute from other spacecrafts. (bottom) Pitch angle distribution (PAD) of electrons at 400.6 eV in the spacecraft frame from STEREO A.

The bipolar signatures of the magnetic field variations in $\mathbf{L}_{FR}$ direction are typical for a helical flux rope. (There is a small residual variation of B_N across the rope in the diagram of STEREO A and B, and CLUSTER. This is due to a decomposition of the magnetic field in the MVA system of the spacecraft ACE, which is slightly rotated with respect to the corresponding system of the other spacecraft.) The flux rope touched ACE, WIND, STEREO A, STEREO B and CLUSTER, consecutively. This timing of the multiple-spacecraft observations confirmed that the $\mathbf{M}_{FR}$ direction derived from the MVA defines the flux-rope orientation. If we selected the $\mathbf{L}_{FR}$ or $\mathbf{N}_{FR}$ direction as principal orientation, this would not be consistent with the timing of these observations and the magnetic field signature inside the flux rope. With this main orientation of the flux rope, we obtain a length of the flux rope of 180 R_E based on the distance between STEREO A and B.

[10] Figure 2 (bottom) displays the pitch angle distribution (PAD) of electrons at 400.6 eV from STEREO A [*Luhmann et al.*, 2008]. The dashed black lines in the third and sixth panels are based only on the electron data, and mark the inferred boundaries of the flux rope core. Outside of the flux rope core, we can see strahl electrons antiparallel to the magnetic field, which indicate that one end of these field lines is still connected to the Sun. In the core, there is a clear drop in the flux of the strahl electrons.

[11] Figure 3 displays the detailed observations from CLUSTER 4 (C4). The sequence of the panels from top to bottom in Figure 3 shows several relevant plasma parameters: Figures 3a and 3b show the magnitude of the magnetic field and three components of the magnetic field in the **LMN** coordinate system based on the MVA of the CLUSTER observations, versus time from 07:00 UT to 08:30 UT. (So Figure 3b is a little different from the fifth panel of Figure 2.) Figures 3c and 3d give the proton density and temperature versus from 07:53 UT to 07:58 UT, respectively. Panel **e** shows the sum of the toroidal magnetic and thermal pressure from 07:53 UT to 07:58 UT. (Since here the flux rope is a quasi two-dimensional structure, we use only the toroidal magnetic field B_M instead of $|B|$ to calculate the magnetic pressure [*Low*, 1990]. The thermal pressure includes the ion and electron pressure.) At the rope center marked by the B_L reversal versus time from 07:55 to 07:56, the spacecraft instruments measured an increase in density and temperature. From Figure 3e, we can see that the total pressure is around 0.065 nPa before and after the flux rope core. However, there is an increase by more than 20% to 0.08 nPa in the core.

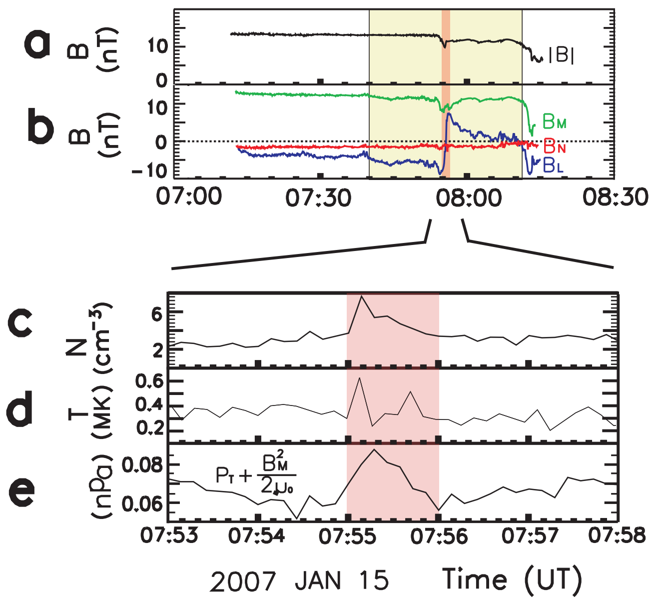

Figure 3. Detailed field and plasma observations from CLUSTER 4 (C4). The yellow highlighted region is the flux rope, and the red highlighted region signals the flux rope core that reveals itself by the B_L reversal.

[12] Figure 4 shows the global environment of this flux rope from ACE observations. From top to bottom, the parameters in these six panels are the magnitude of the solar wind velocity, the proton temperature, the proton number density, the magnitude of the magnetic field, the polar angle Θ_B and the azimuth angle Φ_B of the magnetic field in GSE coordinates. The time period for these observations is two and a half days from 00:00UT 14 on January 2007 to 12:00UT on 16 January 2007. The spacecraft caught signatures of a magnetic cloud, which is shown in the red highlighted region in Figure 4. Inside the magnetic cloud, there is an enhancement of the magnetic field magnitude, and the angle Θ_B rotates from $\sim$80° to $\sim$0°, and the angle Φ_B changes from $\sim$150° to $\sim$330°. Following the magnetic cloud, a corotating interaction region (CIR) is observed and indicated by the blue highlighted region in Figure 4. The solar wind velocity is $\sim$370 km s^{-1} before the CIR and reaches $\sim$600 km s^{-1} after the CIR. The plasma temperature and density increased in the CIR. The HCS, indicated by the reversal of the angle Φ_B, is embedded in the CIR. The red arrow and the red solid line through all the panels mark the flux rope, which is observed immediately before the HCS. Since Figure 4 shows observations of more than two days, we cannot see the detailed signature of the flux rope, whose time period is only about half an hour. Though it is very difficult to determine the exact boundary between the magnetic cloud and the CIR, the flux rope appears to be embedded in the CIR.

[13] On the basis of these observations, we estimate the magnetic cloud size to be about 3600 R_E. A rough estimate of the flux rope diameter is 40 R_E. The diameter of the flux rope core is $\sim$4 R_E. The magnetic cloud is therefore 90 times larger than the flux rope, and 900 times larger than the flux rope core. The flux rope diameter is much smaller than its axial extent of 180 R_E or more. The coherence of the magnetic signature observed by five different spacecraft strongly suggest that we are dealing with a quasi two-dimensional structure.

3. Discussion

[14] The five separated spacecraft observed a similar bipolar signature of the magnetic field, indicating a special magnetic structure in the solar wind. To the best of our knowledge, there are several possible interpretations for the bipolar signature. One is a random fluctuation of the magnetic field. Since five spacecraft caught a similar bipolar signature, and the three directions $\mathbf{L}_{FR}$, $\mathbf{M}_{FR}$, and $\mathbf{N}_{FR}$ derived by a local MVA from individual spacecraft observation did not change in space and time, a random fluctuation of the

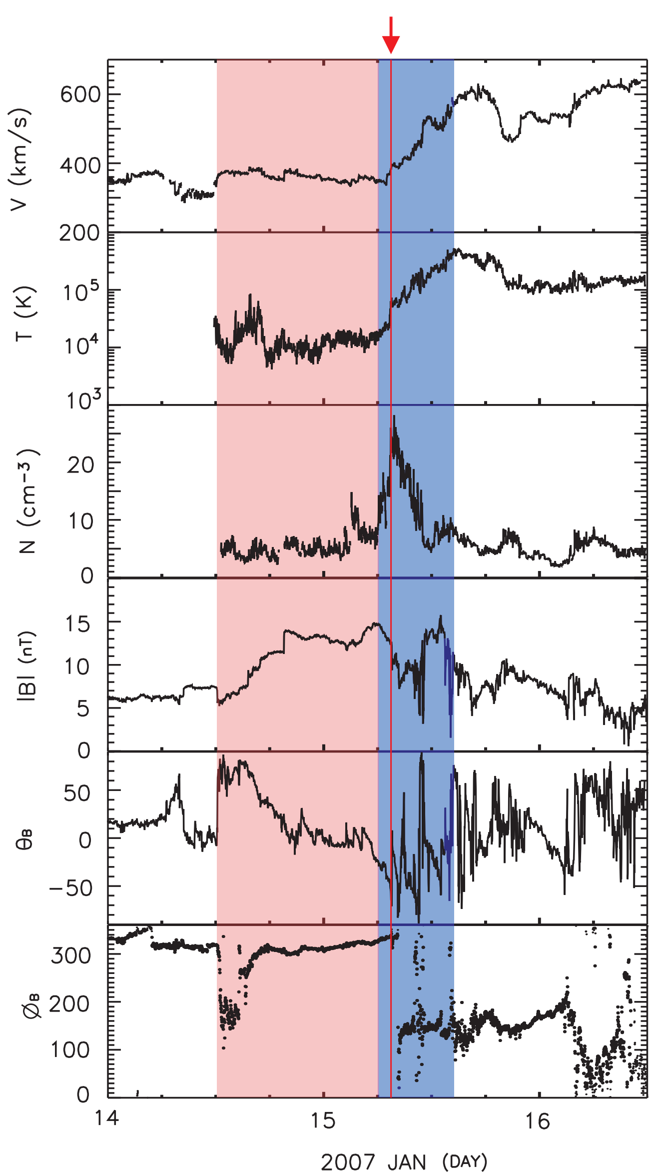

Figure 4. Global environment of the flux rope in the solar wind based on the observations from ACE. The red highlighted region indicates the magnetic cloud observed before the flux rope. The blue highlighted region shows the CIR. The red arrow and the red line running through all the panels mark the flux rope.

magnetic field is very unlikely to be the reason for this observation. Another interpretation of the bipolar signature could be the crossing of a local current sheet or rotational discontinuity [*Lepping and Wu*, 2005]. Figure 3e shows that there is an enhancement by more than 20% of the total pressure in the core of this magnetic structure. This excess pressure should be balanced by the inward curvature force of the magnetic field. The observed pressure enhancement is not expected at the crossing of a solar wind current sheet or rotational discontinuity, because the magnetic field of the current sheet or rotational discontinuity is not supposed to provide a significant curvature force. The remaining third interpretation of the bipolar signature is the crossing of a flux rope, which could well provide the necessary inward curvature force [*Tu et al.*, 1997]. Since the observed magnetic-field signature and the pressure enhancement are consistent with the crossing of a flux rope, we conclude that this interpretation is the most likely one. The electron signature from STEREO, which will be discussed below, gives further evidence confirming the flux rope. As the orientation of the flux rope did not change in space and time within the range of our observation, this evidence leads us to conclude that the flux rope is a coherent structure [*Hughes and Sibeck*, 1987; *Moldwin and Hughes*, 1991].

[15] Strahl electron observations helped us in specifying the magnetic field topology. The loss of the strahl electrons in the solar wind can be due either to magnetic disconnection from the Sun [*Gosling et al.*, 2005] or to scattering [*Crooker et al.*, 2003; *Crooker and Pagel*, 2008; *Pagel et al.*, 2005]. If the core of the structure is disconnected from the Sun, the core should be isolated from the ambient solar wind with observed sharp boundaries to the surrounding magnetic field lines, which are connected to the Sun. An alternative explanation for this electron drop out is local Coulomb scattering. However, the ratio of the mean free path to the size of the structure is around 10^4, so local scattering due to Coulomb collisions within the core of the structure cannot be responsible for the electron signature of this event. Another possible scattering mechanism is wave-particle interaction. In this case, the wave should be trapped inside the core of the structure and highly guided along the magnetic field, because there is no loss of strahl electrons outside of the core. This means again that the core of the structure should be magnetically isolated from the surrounding environment. From the list of above possibilities, magnetic isolation of the core appears to be the most plausible cause. The abrupt disappearance of the strahl electrons rules out the possibility of a local current sheet and rotational discontinuity.

[16] *Slavin et al.* [2003] studied flux ropes in the Earth magnetotail. They compared the observations with the result of a force-free model, and the comparison shows these flux ropes are in the force-free state in the magnetotail. Because of the limitation of the maximum scale of the Earth magnetotail, both length and the diameter of the flux ropes in the magnetotail are much smaller than the flux rope observed in the solar wind. However, magnetic field signature inside these two types of flux ropes can be still compared. In the work of *Slavin et al.* [2003], the B_Z component (corresponding to our B_L component) shows a bipolar signature in Figures 2a and 2b of their paper. Figure 3b also shows that the B_L component also reveals a clear bipolar signature. In the work of *Slavin et al.* [2003], the B_X component (corresponding to our B_N component) shows an increase in the rope center (Figure 2b of their paper) or remains small and almost constant (Figure 3 of their paper). The B_N component of our observations also remains small and almost constant. The main difference between our observations and their work is in the B_M component. Figures 3a and 3b show that the B_M component decreases a little in the rope core, but the B_Y component (corresponding to our B_M component) of *Slavin et al.* [2003] always increases in the rope core (Figure 3 of their paper). A possible reason might be that the flux rope has not been compressed enough to generate the core field. However, though the B_M component decreases a little in the rope core, the total pressure increases by more than 20% in the rope core (Figure 3e). The decrease of the magnetic pressure is totally compensated by an increased thermal pressure in the core. This enhancement of the total pressure should be balanced by the inward curvature force of the magnetic field in the flux rope.

[17] Another notion is that the increase of the B_M component and the magnitude of magnetic field might not be general. *Zong et al.* [2007] found an earthward flowing plasmoid in the magnetotail. Figure 1 of their work shows no obvious increase of the axial B_Y component in their plasmoid compared to the surrounding environment. The existence of the decreasing field strength at the flux rope core could be suggestive of an O-type neutral configuration opposed to one that has a pre-existing guide field [*Karimabadi et al.*, 1999]. Further work is still needed to clarify this issue.

[18] Figure 5 shows an artist's drawing of the flux rope as it is crossed consecutively by ACE, WIND, STEREO A, STEREO B and CLUSTER, which is the interpretation of Figure 2. ACE and WIND are above the ecliptic plane (the yellow plane in the Figure 5), but STEREO A and B are below the ecliptic plane. The distances between the spacecraft are drawn to scale in Figure 5. Models suggest that the flux rope should extend in space (see Figure 12a of *Slavin et al.* [2003]). On the basis of the data from five spacecraft, our observations demonstrate that the flux rope is a quasi two-dimensional magnetic structure, extending over at least 180 R_E in space. The variation of the flux rope orientation in space is another important issue. With the observations from ACE and CLUSTER, *Eastwood et al.* [2002] found that the orientation of a flux rope changes in space, which may be caused by the nearby bow shock. For our event, all the data are taken in the solar wind. According to the MVA for this flux rope, we did not find a systematic bending of the flux rope axis ($\mathbf{M}_{FR}$ direction) along the 180-R_E extension in space. This means that the flux rope orientation can stay constant in the solar wind, a conclusion that cannot be obtained with single-spacecraft observations.

[19] Two possible mechanisms have been proposed to explain the presence of a flux rope in the solar wind. One is that local magnetic reconnection in the solar wind can generate these small-scale flux ropes [*Moldwin et al.*, 2000]. The other one is that the flux ropes are convected from the Sun and related to coronal mass ejections (CMEs), which are similar to magnetic clouds [*Feng et al.*, 2007]. From Figure 4 we can see that this flux rope and the magnetic cloud are two types of structures with different scales. The diameter of the flux rope is around 40 R_E. If we map this structure to the solar corona, the size of this flux rope will become $\sim$1000 km, which is twenty times smaller than a typical supergranule.

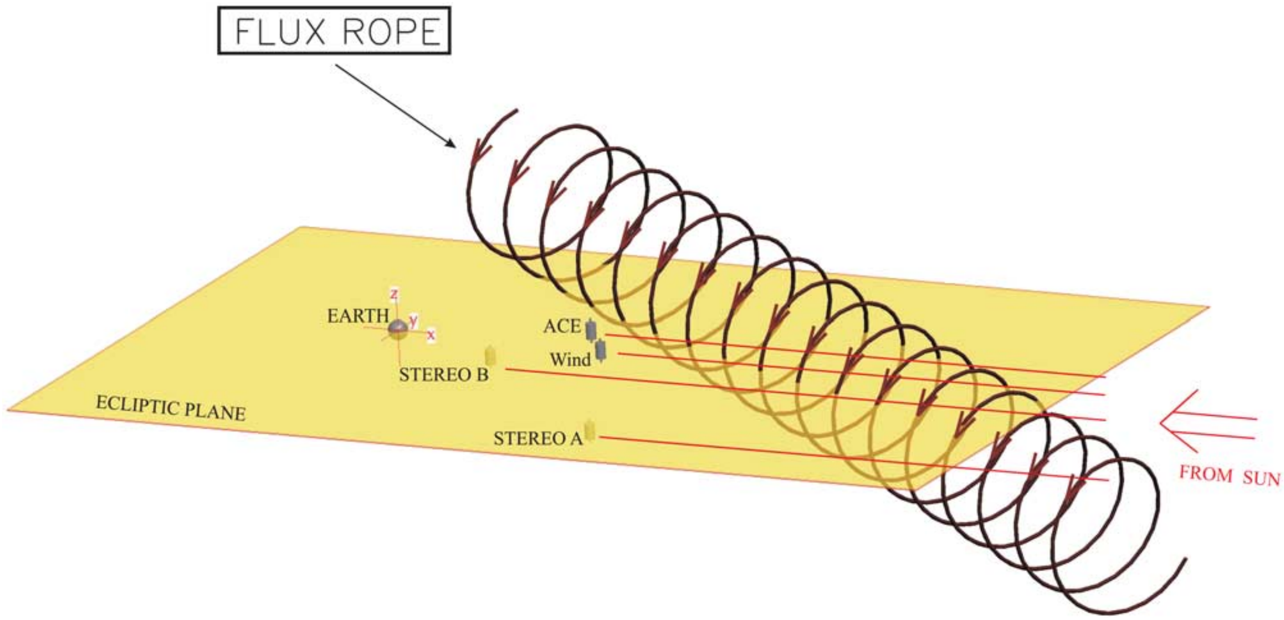

Figure 5. Artist's sketch of the flux rope being crossed by the five spacecraft. ACE and WIND are above the ecliptic plane (the yellow plane), but STEREO A and B are located below. CLUSTER 4 (C4) is not drawn because it is too close to the Earth.

It seems to us very unlikely that such a small-scale structure was generated in the solar corona. If the flux rope was really generated in the corona, it might not be easy for this flux rope to survive from the corona to 1 AU in the CIR, which is a highly compressive and dynamic region. Though we cannot totally eliminate the possibility that this small-scale flux rope originated in the solar corona, we suggest it is more likely that the flux rope was generated locally by magnetic reconnection in the solar wind.

4. Conclusion

[20] An extended flux rope in the solar wind was observed and studied on the basis of observations from five spacecraft. The analysis shows this flux rope is a quasi two-dimensional magnetic structure, and the orientation of its invariant axis does not change in space and time. These results can be obtained only with multiple-spacecraft observations. The size of the flux rope is about 90 times smaller than that of the magnetic cloud, which passed the spacecraft immediately before the rope. This indicates that the flux rope and the magnetic cloud are two types of structures with different scales.

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