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Tracing the connectivity of magnetic flux ropes to solar surface with ≥100 keV electrons associated with CME on July 14, 2000

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Abstract. It is known that about $1/3$ of all coronal mass ejections (CMEs) at 1 AU exhibit the large and coherent internal field rotations characteristic to magnetic flux ropes (magnetic clouds). But there are still unsolved questions; do CMEs eventually disconnect completely from the Sun?; how long does it take for such complete disconnection to occur? We contribute to solve these questions from the analysis of CMEs observed by the Nozomi spacecraft. On July 12, 2000, a magnetic flux rope was ejected from solar surface associated with a CME and an X1.9 class flare which occurred in solar active region AR 9077. Two days after, on July 14, another large solar flare of X5.7 class (named the Bastille event) occurred in the same region AR 9077 where the former flare had occurred. On the same day, Electron and Ion Spectrometer (EIS) onboard the Nozomi spacecraft observed unidirectional field-aligned ≥100 keV electrons whose flux level is more than 10 particles/[keV sec cm^{2}sr] at the peak and the Magnetic Field Measurement (MGF) instrument on the same spacecraft observed a magnetic flux rope, when the spacecraft was about 1 AU distant from the Sun but 1.8 AU far from the Earth. From its high level of flux it is considered that the second flare accelerated these electrons near the solar surface. From a pitch-angle distribution of the electrons and the position of the active region where these flares occurred, it seems that the electrons propagated along the magnetic flux rope that was ejected on July 12, and reached the Nozomi spacecraft. These considerations suggest that at least one of the footpoints of the magnetic flux rope had been connected to solar surface for two days at least.

1 Introduction

There are still many unsolved problems about CMEs not only near the solar surface but also in interplanetary space (Gosling

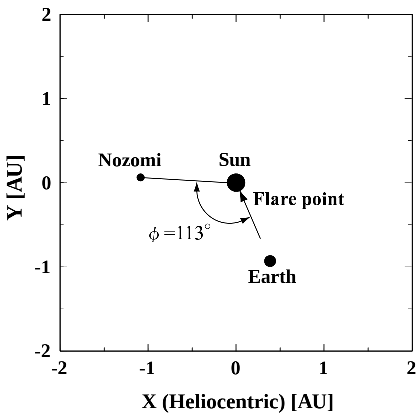

Fig. 1. The locations of Nozomi, the Earth and the flare point on solar surface, on July 14, 2000 in heliocentric ecliptic coordinate system.

, 1997). For example, there are bidirectional electron flows related to the magnetic flux rope (MFR) structure associated with CME events (Gosling et al., 1987), however, its magnetic connection to solar surface is not obvious. If the connection exists, how long does it take for the MFR to be disconnected from solar surface completely? It was once shown with ∼0.1 - 10^2 keV electron observation that one leg of the magnetic cloud was connected to the active region on solar surface (Larson et al., 1997). However the details of the connectivity of MFR to solar surface is still unknown. In this paper, we report that the connectivity of the MFR to solar surface was traced with ≥100 keV electrons associated with CMEs observed on July 14, 2000.

Table 1. List of the significant flare events, 7/12 ∼7/14, 2000

Date	Day of Year	Time	Class	Region No.	Position	ϕ(deg)	Flare	CME
7/12	194.4	10:18	X1.9	9077	N18E26	82	F1	CME1
	194.8	18:41	M5.7	9077	N17E20	89		
7/14	196.4	10:03	X5.7	9077	N17W02	113	F2	CME2
	196.6	13:44	M3.7	9077	N17W04	115	F3	

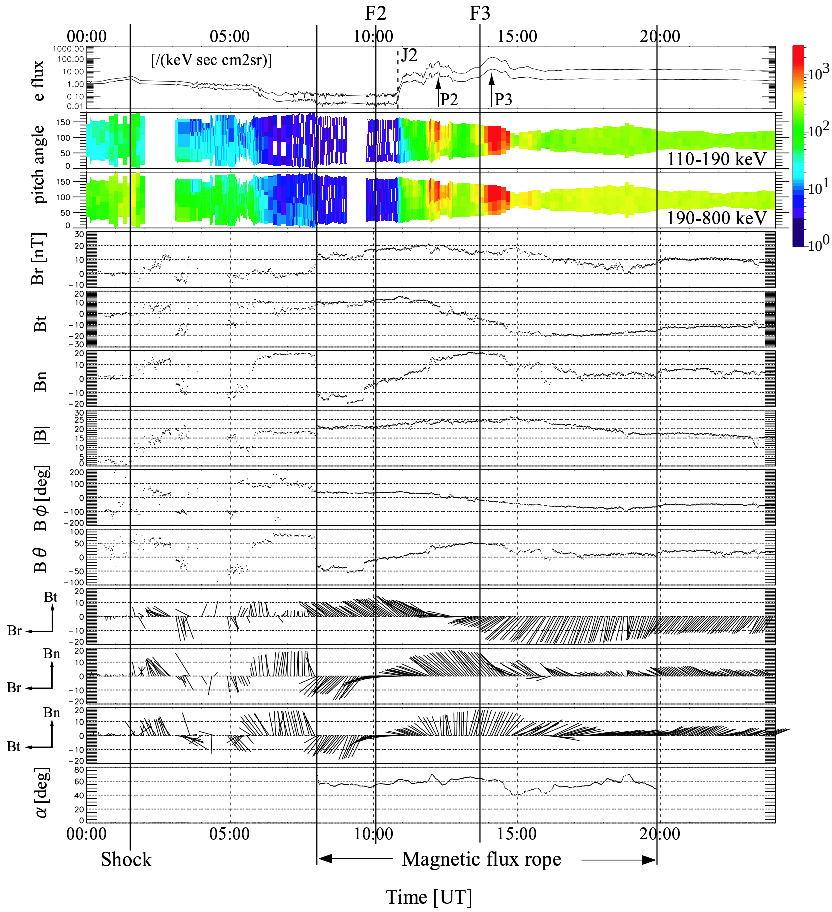

Fig. 2. From top to bottom: the temporal variation of electron fluxes, pitch angle distributions of electrons, components, Br, Bt and Bn, magnitude, azimuthal and elevation angles of the magnetic field in RTN coordinate system, projection of magnetic field vectors on three coordinate planes, and the angle α (see text).

2 Observations and Results

An X1.9 flare (denoted hereafter by F1) accompanied by a CME (denoted by CME1) occurred at 10:18 UT on July 12, 2000 (day of year: 194). This flare occurred at N18E26° in the active region AR 9077 (courtesy of Hiraiso Solar Terrestrial Research Center). Two days after, at 10:03 on July 14, a larger solar flare (class X5.7) occurred in the same region AR 9077. This extremely large flare (F2) was named Bastille event according to the date it occurred. After 3.7 hours, at 13:44, another flare (F3) occurred in the same region. According to the SOHO observation, two of the flares (F1 on July 14 and F2 on July 14) were accompanied by CMEs (CME1 and CME2, respectively). On July 14, Nozomi was at the position 1.0 AU from the sun and 1.8 AU from the Earth, when the MGF (Magnetic Field Measurement) instrument onboard Nozomi observed the MFR structure associated with CME1. During the passage of this MFR, the EIS (Electron and Ion Spectrometer) instrument recorded enhancements in energetic electron flux that may be associated with the flares that occurred on the same day (F2 and F3). Fig. 1 shows the locations of Nozomi and the Earth, on July 14, 2000 in heliocentric ecliptic coordinate system. The angle between Nozomi–Sun line and the region where each flare occurred is denoted by ϕ (the case of F2 is shown in Fig. 1). The list of significant flares (greater than M2.0) that occurred from July 12 to 14, 2000 is given in Table 1 with other information. We can see that all of the four significant flares occurred in the same AR 9077.

The particle and magnetic field observations with EIS and MGF instruments onboard Nozomi on July 14, 2000 are summarized in Fig. 2. Top panel shows the temporal variation of electron fluxes for the two energy bins, 110–190 keV and 190–800 keV. The next two panels show temporal variations

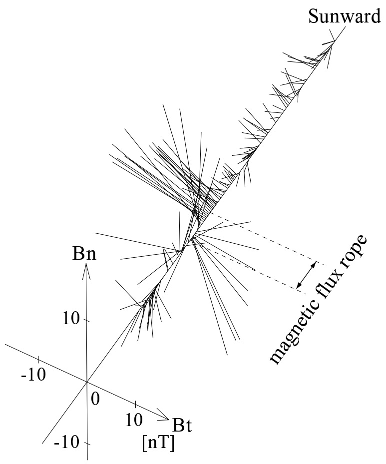

Fig. 3. The magnetic field vectors observed with NOZOMI/MGF indicating the spatial structure along the spacecraft path across the magnetic flux rope.

in the pitch angle distribution of electrons in these energy ranges and the color scale shows the count rates of electrons. Because the field of view (FOV) of EIS is not large, the covered pitch angle range is limited and depends on the magnetic field direction relative to the FOV of EIS (Ihara *et al.*, 2001). Therefore, there are some uncovered areas distributed symmetrically to the 90° line. Other completely blank areas are due to the lack of data. The next six panels show temporal variations in magnetic field components (Br, Bt, Bn), magnitude ($|B|$), azimuthal angle (B_ϕ), and elevation angle (B_θ) in RTN coordinate system. The next three panels show the projection of magnetic vectors to the three coordinate planes, respectively. The last panel is explained in the next section.

Following features can be noted in Fig. 2. At 1:30 (UT), electron fluxes had the maximum and $|B|$ began to increase. We consider it as the arrival time of the interplanetary shock CME1 made. After 6.5 hours, at 8:00, $|B|$, B_θ component made a discontinuous jump, and the magnetic field began to rotate. We consider it as the arrival time of the magnetic flux rope (magnetic cloud) that was ejected with CME1. The panels of projected magnetic vectors show that the rotation ended at 19:50. This type of magnetic field rotation is typically seen when CMEs arrived at the spacecraft. In the top panel, we can see that from 1:30 the electron fluxes decreased gradually until the MFR arrived. This is because electrons produced by previous solar activity decreased before the arrival of CME1. The flux jumped at 10:45 (J2), made a peak (P2) around 12:10, and made another peak (P3) around 14:10. The two vertical lines with letters 'F2' or 'F3' in Fig. 2 shows the times that the flares occurred at the sun. We consider that these two peaks F2 and F3 are caused by the two flares because the time period between J2 and F2 is similar to that between P3 and F3. Besides, around P2, the field-aligned anisotropy of electrons is seen in the pitch angle distribution showing that the electrons propagated promptly from the sun along the magnetic field.

The rotation of the magnetic field is visualized in Fig. 3. The vectors whose components are Bt and Bn are drawn along a time axis. The structure of MFRs is thought to be generally stable because the magnetic field structure is force-free. Therefore, Fig. 3 also represents the spatial structure of the MFR. We can see that the magnetic field gradually rotated from ∼0° to 180° in Fig. 3. This feature is often observed when an MFR passed the spacecraft (Goldstein , 1983).

3 Discussion

We estimated the direction of the axis of the observed MFR from the variance-matrix analysis of the magnetic field data. Its azimuthal angle is found to be -20° and elevation angle -15° in the RTN coordinate system centered on the Nozomi spacecraft. This means that the axis was not quasi-perpendicular as might be expected but quasi-parallel to the Sun–Nozomi line at the Nozomi position (shown in Fig. 4(a)). We also calculated the angle α between the directions of the axis and the magnetic field (shown in Fig. 4 (b)) and plotted the temporal variation of α on the last panel of Fig. 2. It was found that Nozomi did not go deeply into the MFR, because the minimum value of the angle α that occurred around the center of the MFR that lasted from 8:00 to 19:50 was as much as 40°. Moreover, the rotation of the magnetic field from 0° to 180° in Fig. 3 shows that Nozomi passed the MFR from the northern (southern) side to southern (northern) side of the MFR while the axis of the MFR kept its direction. If the spacecraft had passed an MFR parallel to the ecliptic plane, the magnetic field should have rotated from 90° to -90° (or from -90° to 90°) due to its structure (Goldstein , 1983). From above discussion, and from the location of the flares, we infer that Nozomi passed the eastern edge of the large-scale MFR from northern (southern) side to southern (northern) side in the direction almost quasi-parallel to

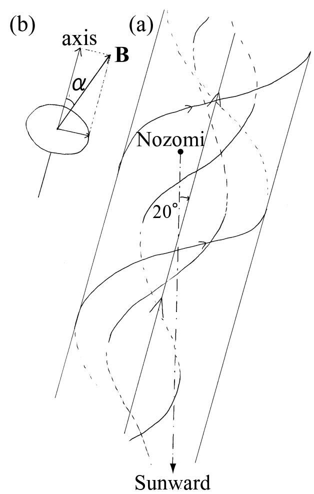

Fig. 4. Schematic drawing of (a) the calculated direction of the flux rope axis relative to Sun–Nozomi line (viewed from north), (b) definition of the angle α between the calculated direction of the axis of the MFR and the direction of the magnetic field.

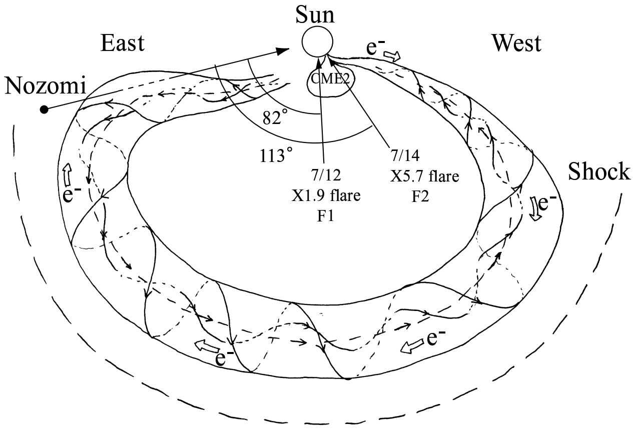

Fig. 5. The large-scale structure of the magnetic flux rope expanding in interplanetary space, and the path of Nozomi relative to the flux rope structure are drawn schematically. Also shown are energetic electrons ($\geq$100 keV) streaming through the magnetic flux rope from the footpoint of the flux rope connected to solar surface on July 14, 2000.

its axis (Fig. 5). When the X1.9 class flare responsible for CME1 occurred on July 12, the angle ϕ defined earlier was 82° (see Fig. 5). Such a large angle supports the view that this MFR had a huge spatial structure.

The anisotropy of electrons in Fig. 2 shows the unidirectional electron flow which is anti-parallel to the magnetic field (pitch angle being around 180°). We consider that these electrons propagated along the field lines of MFR from the sun, not along the east leg (to the left in Fig. 5), but along the west leg (to the right) of the MFR. We have two reasons to believe this. First, the electron anisotropy around P2, which was anti-parallel to the field, shows that the electrons came from the anti-sunward direction, consistent with the west leg interpretation. (The directions of the magnetic field and the propagating electrons are indicated with solid and open arrows, respectively, in Fig. 5.) Second, the flight time of electrons with energies from 110 to 800 keV through the west side leg of the MFR is consistent with the time difference, 40 minutes, between F2 and J2. The west side path can be estimated as 4 AU if the large-scale structure of the MFR is approximated by a semicircle whose radius is 1 AU. Considering the spiral magnetic field of the MFR and the gyromotion of electrons, the real path of electrons was probably longer than 4 AU. On the other hand, the electrons with energies from 110 to 800 keV can propagate 3.1$\sim$8.5 AU (mean value is 5.8 AU) for 40 minutes, which is consistent with the estimated real path length of electrons.

We consider that one of the two ends of the MFR was connected to solar surface (footpoint) based on the following scenario. Taking the large jump (J2) of the electron fluxes beyond two orders of magnitude into account, it is probable that the electrons are accelerated near solar surface by the X5.7 class flare (F2) of July 14 or by the shock associated with F2 which is supposed to have been still near the sun. The magnetic footpoint of the MFR on solar surface, if the field line is connected, must have been close to the point where F2 occurred, because both F1 of July 12 associated with the MFR and F2 of July 14 occurred at the same active region AR 9077. The accelerated electrons was probably injected into the MFR at the footpoint on the solar surface, and arrived at Nozomi. We can say that one end of the MFR was kept connected to solar surface from its creation time on July 12 till July 14 when F2 occurred.

4 Conclusion

From above discussions, we can conclude that at least one of the footpoints of the MFR has been connected to solar surface for two days (from July 12 to 14) at least. And we can also guess that the large-scale structure of MFR associated with the CME event expands in interplanetary space, and high energetic electrons ($\geq$100 keV) accelerated near solar surface propagate in the MFR. Details of the west side structure of MFR (right side of Fig. 5) are still unclear because MFRs may not evolve symmetrically with respect to the occurrence point on solar surface. We may need more analysis of plasma and magnetic field data obtained by another spacecraft located at another position.

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