A Global Structure of the Magnetic Flux Rope Observed in Interplanetary Space Fitted by A Torus-type Force-free Model

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Abstract

A large percentage of coronal mass ejections (CMEs) at 1 AU exhibit large and coherent internal field rotations characteristic to magnetic flux ropes (magnetic clouds). But the global structure of flux ropes, i.e., the length and the curvature of flux ropes along their axis, has not been clarified yet. In order to obtain a clue to this problem, we here examine a case where data from two spacecraft are available. In our previous paper ([4]), the magnetic field from the NOZOMI spacecraft was analyzed with a cylindrical flux rope model ([3]). In this paper, we applied a torus-type force-free field model ([7]) to the magnetic field data obtained by both NOZOMI and ACE on July 14, 2000. The results from our model fits show that a single large-scale magnetic flux rope with local curvature extended globally with the angular extent of $\sim 120^\circ$ (seen from the sun) in interplanetary space. This picture is consistent with that in our previous work ([4]).

1. Introduction

Interplanetary magnetic clouds associated with coronal mass ejections (CMEs) are characterized by (1) an enhanced magnetic field strength, (2) a smooth and large rotation of the magnetic field, and (3) a low ion temperature ([1]). Burlaga ([2]) suggested that magnetic clouds at 1 AU can be described reasonably well by a cylindrically symmetric force-free field (a magnetic flux rope structure) with a

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constant α solution for $\nabla \times \mathbf{B} = \alpha(\mathbf{r})\mathbf{B}$ ([6]). Farrugia et al. explicitly considered the expansion of magnetic flux ropes in interplanetary space and formalized the expansion ([3]). On the other hand, a toroidal configuration of magnetic flux ropes was suggested by Ivanov et al. ([5]) on the basis of an analytical solution to a torus-type force-free field obtained by Miller and Turner ([7]). We applied this torus-type field model to the interplanetary magnetic cloud observed by NOZOMI and ACE.

2. A torus-type force-free field model

The analytical solution ([7]) of a torus-type, constant α force-free field is given by

$$\begin{aligned} B_r &= \frac{B_0}{R_0\alpha}\left(-J_0(\alpha r) + \frac{r_0 F}{r}\right)\sin\theta, &(1)\\ B_\theta &= B_0\left[J_1(\alpha r) - \frac{1}{\alpha R_0}\left(J_0(\alpha r) - r_0\frac{dF}{dr}\right)\cos\theta\right], &(2)\\ B_\zeta &= B_0\left(J_0(\alpha r) - \frac{r_0}{R_0}F\cos\theta\right) &(3)\end{aligned}$$

where

$$\begin{aligned} F &= \frac{r}{2r_0}J_0(\alpha r) + \frac{1}{2}\frac{J_0(\alpha r_0)}{J_1(\alpha r_0)}J_1(\alpha r), &(4)\\ B_\zeta &= 0 \text{ at } r = r_0 \quad \text{requires} \quad J_0(\alpha r_0) = 0 \quad \text{(Boundary Conditions)} &(5)\end{aligned}$$

and J_0 and J_1 are the Bessel functions, B_0 is the magnetic field magnitude at the flux rope axis, s (=+1 or -1) determines the twist type (right-handed or left-handed), r, θ, ζ are the torus coordinates, which are linked with the usual cylindrical coordinates R, ϕ, z, and Cartesian coordinates x, y, z (z; the major axis of the torus) in the following way:

$$\begin{aligned} R &= R_0 + r\cos\theta,\ z = r\sin\theta,\ \phi = -\zeta/R, &(6)\\ x &= (R_0 + r\cos\theta)\cos\phi,\ y = (R_0 + r\cos\theta)\sin\phi,\ z = r\sin\theta. &(7)\end{aligned}$$

The aspect ratio q is defined by the ratio of major radius R_0 to minor radius r_0 (flux rope radius). Hence a smaller q means a more curved magnetic flux rope. Note that if $q = \infty$, the solution becomes a cylindrical model ([2]).

3. Observations and Results

NOZOMI and ACE observed a magnetic flux rope on July 14, 2000 at largely separated positions in interplanetary space. In our previous work, the magnetic field data observed by NOZOMI were analyzed in detail ([4]), and we concluded that at least one of the footpoints of the magnetic flux rope has been connected to the solar surface for two days (from July 12 to 14) at least, based on the pitch angle anisotropy of the observed $\geq$ 100 keV electrons and model fits of a constant α force-free cylindrical flux rope. Here a torus-type force-free field model is applied to the magnetic field data observed by ACE and NOZOMI on July 14, 2000.

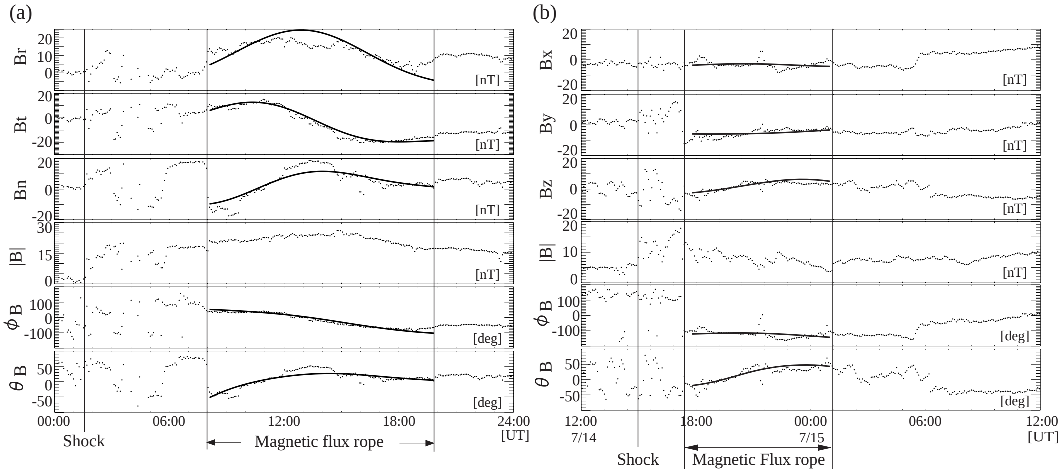

Fig. 1. From top to bottom, the temporal variation of magnetic field three components, magnetic field magnitude, azimuthal and elevation angles in (a) RTN and (b) GSE coordinates observed by (a) NOZOMI and (b) ACE on July 14, 2000. The curved solid lines are the model fits (see text).

In our previous paper, we have discussed that this magnetic flux rope is associated with an X1.9 flare that occurred at 10:18 UT on July 12, 2000. The flare occurred at N17E27° in the active region 9077 (National Geophysical Data Center). According to the observation by the SOHO spacecraft at the L1 point, the flare was accompanied by a CME. Two days later on July 14, NOZOMI and ACE observed magnetic clouds in interplanetary space. Both spacecraft were almost on the ecliptic plane about 1 AU distant from the sun but 1.8 AU distant from each other ($\sim$120° angular separation seen from the sun). Fig. 1. shows the magnetic field obtained by (a) NOZOMI and (b) ACE on July 14, 2000. The NOZOMI data on the left panel were discussed in detail in our previous paper [4]. The curved solid lines represent the results of the least squares fit with the torus-type model. The obtained parameters of the torus-type flux rope at the NOZOMI location are q=2.1, B_0=30 nT, r_0=0.06 AU. The impact parameter p, the ratio of the minimum distance between the flux rope axis and the spacecraft to the flux rope radius, is 0.41. At the ACE location, the intensity of the magnetic field ($|B|$) jumped at 15:00, and the magnetic field began to rotate at 17:16 (ϕ_B) shown on the right panel of Fig. 1.. We consider that the flux rope produced as the CME passed by ACE. We selected the time 1:12 on July 15 as the arrival time of the trailing edge, judging from the temporal variations of $|B|$ and θ_B. The model fit at the ACE location (L1 point) shows that the flux rope is characterized by the parameters: q=3.4, B_0=13 nT, r_0=0.07 AU, p=0.79. The twist was right-handed which is consistent with the twist type determined from NOZOMI data.

Fig. 2. is the geometrical relations between the NOZOMI, ACE locations and the curved flux rope. We can clearly visualize a large-scale structure of the flux rope which has locally determined curvatures. Multi-spacecraft observation in combination with the torus-type field model enabled us to clarify a curved magnetic flux rope expanding globally in interplanetary space with the angular extent of $\sim 120°$ seen from the sun. The obtained picture is consistent with that in our previous work ([4]), and clarifies its local curvature in detail.

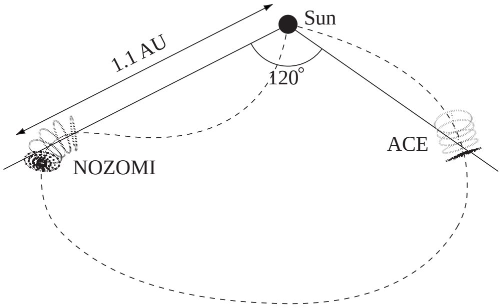

Fig. 2. The result of torus model fits to the magnetic flux rope observed by NOZOMI and ACE on July 14, 2000. The curved broken line is the axis of the large scale magnetic flux rope inferred from the torus model fits at the spacecraft positions.

4. Conclusion

The results from model fits of the curved flux rope for two largely separated spacecraft positions are consistent with each other, and show that a single large-scale magnetic flux rope with significant local curvature is extended into interplanetary space at 1 AU with the angular extent of $\sim 120°$ (as seen from the sun).

1. Burlaga L. F. et al. 1981, JGR 86, 6673
2. Burlaga L. F. 1988, JGR 93, 7217
3. Farrugia C. et al. 1993, JGR 98, 7621
4. Ihara A. et al. 2001, ICRC 2001, 3429–3432
5. Ivanov K. G. et al. 1989, Sol. Phys. 120, 407
6. Lundquist S. 1950, Ark. Fys. 2, 361
7. Miller G., Turner L. 1981, Phys. Fluids 24, 363