NOZOMI observation of transient, non-spiral magnetic field in interplanetary space associated with limb CMEs

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Abstract. The magnetic fields of interplanetary objects that were ejected as coronal mass ejections (CMEs) from the limb of the Sun were observed by the NOZOMI spacecraft at 1.38 AU above the east limb of the Sun. The solar wind magnetic field whose launch time coincided with ejection of the limb CME was different from that estimated from ACE observations near the Earth, suggesting that NOZOMI encountered transient magnetic structures, or that the heliospheric magnetic field re-structured after ejection of the CMEs. The corresponding interplanetary magnetic field showed non-spiral magnetic field, enhancements of magnetic field, or magnetic discontinuities, but no common structure was yet found.

INTRODUCTION

Acceleration of the solar wind is the most important problem in the study of the solar wind. Evolution of the speed of the solar wind as a function of the distance from the Sun remains uncertain. We do not have enough information on the velocity, density, and temperature of solar wind streams at various distances from the Sun observed simultaneously.

A comparison of the solar wind speed in interplanetary space with its initial speed at the departure from the Sun would give basic information to the solar wind profile. To do this, we have to find some signatures to distinguish solar wind streams. Although there is no established method to mark a stream, we can start with coronal mass ejections (CMEs) and some unusual, perhaps non-spiral, interplanetary magnetic field.

The initial speed of a CME is measured most accurately on the limb of the Sun as it is launched into interplanetary space in a direction perpendicular to the line of sight of the imagers in the vicinity of the Earth. In order to detect interplanetary counterparts of the limb ejections, a spacecraft must be located in planetary orbit above the limb of the Sun.

Schwenn [1] used plasma measurements from Helios 1 and 2 together with white-light-coronagraphs. They showed that flare-related ejecta with shocks and disturbed plasma had no post acceleration in interplanetary space, while slowly rising transients had post acceleration beyond several solar radii. Sheeley *et al.* [2] compared interplanetary shocks detected by Helios 1 with CMEs. Burlaga *et al.* [3] studied an association of a magnetic cloud observed by Helios 1 with a low-latitude CME. Richardson *et al.* [4] used ICE energetic ion data combined with IMP 8 magnetic field to compare with SMM coronagraphs. Lindsay *et al.*[5] investigated plasma and magnetic field data from Pioneer Venus Orbiter and Helios 1. Gopalswamy *et al.* [6] [7] presented a model to predict CME arrival time at 1AU, but they had to struggle against effect of projection of CMEs onto the line of sight of the imager.

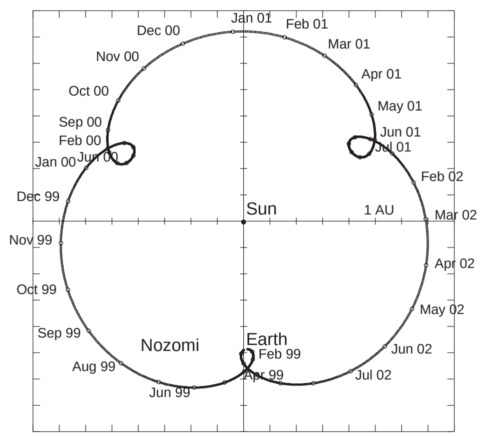

FIGURE 1. Orbit of Nozomi in ecliptic plane with Sun-Earth line fixed.

The Japanese Mars explorer Nozomi has brought us another opportunity to detect interplanetary counterparts of limb CMEs. Figure 1 shows the separation of Nozomi from the Sun-Earth line. Nozomi went as far as 83^o – 97^o east from the Sun-Earth line at a radial distance of 1.38 AU from the Sun during the period from November 1, 1999, to November 30, 1999. The magne-

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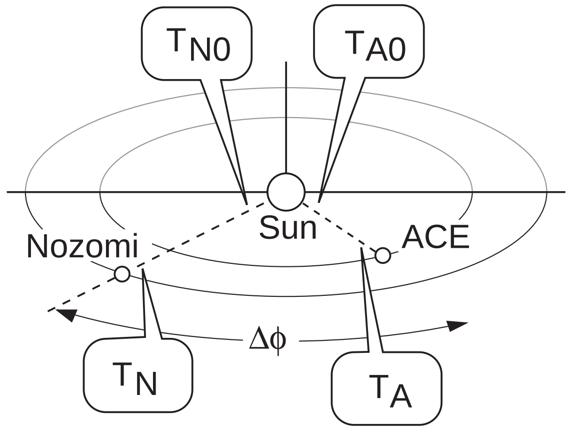

FIGURE 2. The time T_N of solar wind observation by NOZOMI, related with the time T_{N0} of launch toward NOZOMI, the time T_{A0} of launch of the plasma toward ACE, and the time T_A of solar wind observation by ACE.

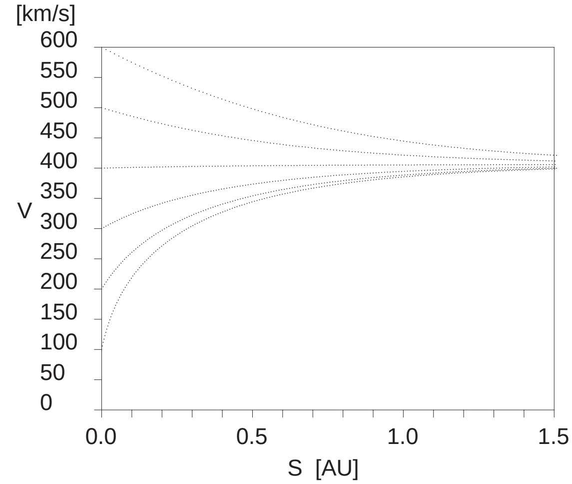

FIGURE 3. Model calculation of solar wind velocity V as a function of distance S from the Sun.

tometer [8] [9] was operating during the period. Imaging spacecraft such as Yohkoh and SOHO were also operating simultaneously with Nozomi. We can compare the interplanetary magnetic field observed by Nozomi with limb CMEs in the SOHO/LASCO CME Catalog (http://cdaw.gsfc.nasa.gov/CME_list/) presented by Gopalswamy *et al.* [10].

ESTIMATION OF LAUNCH TIME AND ARRIVAL TIME

In order to examine the magnetic field of the solar wind whose launch time coincided with a time of ejection of a limb CME, we need to relate the time of launch with the time of arrival at NOZOMI. The relationship was estimated in 2 ways: i) estimation of launch time from arrival time, and ii) estimation of arrival time from launch time.

Launch time of the solar wind

Figure 2 illustrates the method of estimation of the time T_{N0} of launch of the solar wind encountered by NOZOMI at T_N. As NOZOMI had only limited opportunities to measure solar wind speed, the launch time was estimated with an aid of ACE/SWEPAM observation.

The solar wind observed by ACE at time T_A must have left the Sun at around $T_{A0} = T_A - \frac{R_A}{V_A}$, where R_A is the distance between ACE and the Sun, and V_A is the average of the wind speed measured at ACE. Here we use 1-hour averages of the solar wind speed. The launch time T_{N0} of a wind stream toward NOZOMI from the same source is calculated as $T_{N0} = T_{A0} - \frac{\Delta\phi}{\omega_{SUN}}$ where ω_{SUN} and $\Delta\phi$ are the angular velocity of the spin of the Sun, and the separation between the two spacecraft in heliospheric latitude, respectively. The solar wind launched toward Nozomi at T_{N0} was to be observed at $T_N = T_{N0} + \frac{R_N}{V_N}$, where R_N is the heliospheric distance of NOZOMI. Assuming that the solar wind speed from the source remained the same, $V_N \sim V_A$, we can relate T_N and T_{N0} as $T_N = T_{N0} + \frac{R_N}{V_A}$.

Arrival time of CMEs

The arrival time of limb CMEs at NOZOMI at 1.38 AU from the Sun was estimated in a separate way. Gopalswamy *et al.* [6] [7] showed statistically that there is a linear relationship between initial speed V_0 of ejection and its initial acceleration a_0 as

$$a_0 = c_0 - c_1 V_0, \tag{1}$$

where $c_0 = 2.193[\mathrm{m/s^2}]$ and $c_1 = 0.54 \times 10^{-5}[/\mathrm{s}]$ for limb CMEs [7]. This relationship suggests some dragging force acting on CMEs, and it is likely that the dragging force is acting beyond a significant distance from the Sun. If we extend the relationship as

$$\frac{dV(t)}{dt} = c_0 - c_1 V(t), \tag{2}$$

we can solve the differential equation to get the velocity as a function of time t

$$V(t) = w + (V_0 - w)\exp(-c_1 t) \tag{3}$$

and the distance

$$S(t) = wt + \frac{1}{c_1}(V_0 - w)(1 - \exp(-c_1 t)) + 1R_{\mathrm{SUN}}, \tag{4}$$

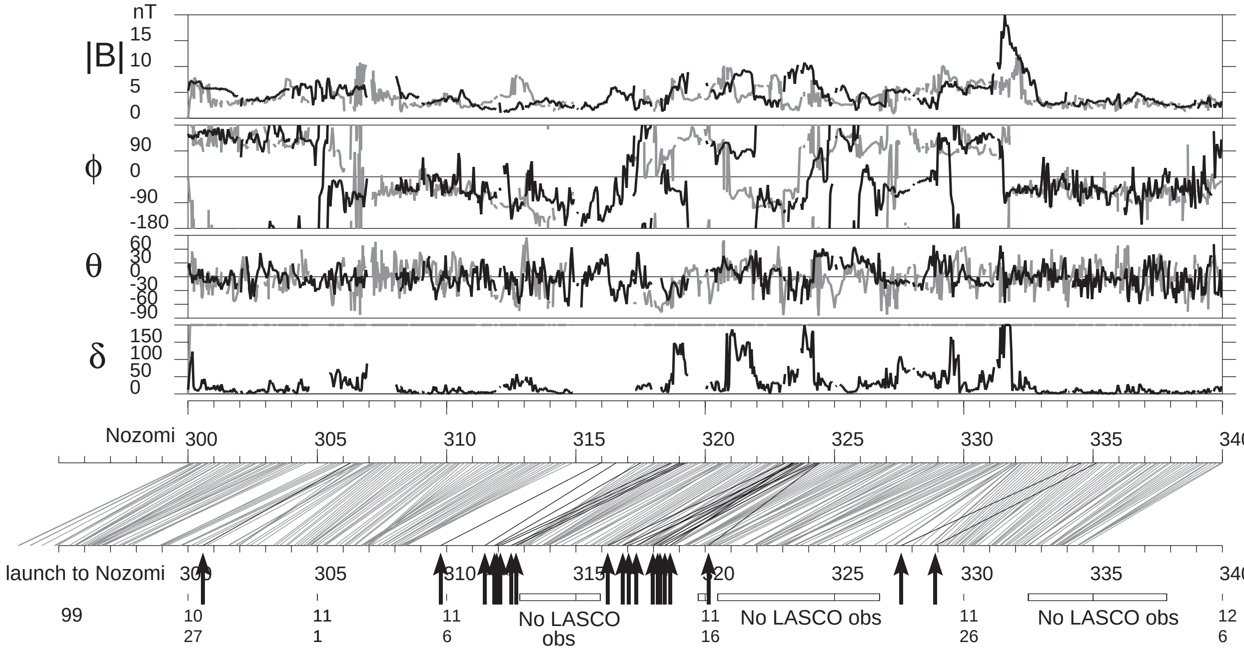

FIGURE 4. Hourly averaged magnetic fields obtained by NOZOMI (dark) and ACE (light), covering the period from November 1, 1999 to November 30, 1999. ACE data are shifted to the dates on which the solar wind of the same source was observed by NOZOMI. From top to bottom, the magnitude $|\mathbf{B}|$ of the magnetic field, azimuthal angle ϕ and inclination θ of the field vector from the ecliptic plane, and deviation $\delta \equiv |\mathbf{B}_{\mathrm{NOZOMI}} - \mathbf{B}_{\mathrm{ACE}}|^2$ of the NOZOMI magnetic field vector $\mathbf{B}_{\mathrm{NOZOMI}}$ from the ACE observation $\mathbf{B}_{\mathrm{ACE}}$. The bottom diagram shows the time T_N of NOZOMI observation related with the estimated launch time T_{N0}. Light lines indicate estimation based on ACE observation, while dark lines indicate results from model calculation. Arrows indicate time of CMEs that appeared on east limb at low latitude and looked likely to be ejected toward NOZOMI. The limb CMEs are adapted from the SOHO/LASCO CME catalog (http://cdaw.gsfc.nasa.gov/CME_list/).

where $w = \frac{c_0}{c_1}$ is the speed to which $V(t)$ converges. Figure 3 illustrates the evolution of solar wind velocity $V(t)$ as a function of the distance $S(t)$ from the Sun. The speeds of CMEs converge to a value $w = 406$[km/s] as they propagate in interplanetary space after their launch at various initial speeds. Substituting the initial speed V_0 of each CME into equation (4) we can calculate the time of arrival and the speed at $S = 1.38$ AU.

INTERPLANETARY MAGNETIC FIELD EJECTED AS CMES

Figure 4 shows hourly averaged magnetic fields obtained by NOZOMI (dark) and ACE (light), covering the period from November 1, 1999 to November 30, 1999. ACE data are shifted to the time T_N and corrected for the heliocentric distance. The bottom diagram shows the relationship between the time T_{N0} of launch of solar wind or CMEs and the time T_N of encounter by NOZOMI estimated from ACE observation (light lines) and model calculation (thick lines). Arrows in the bottom diagram indicate CMEs that would hit NOZOMI.

The magnetic field observed by NOZOMI agreed with the result from ACE shifted to NOZOMI position until November 10, 1999, indicating that the heliospheric magnetic field structure was stable and the solar wind speed was unchanged. A disagreement started on November 13, 1999 at NOZOMI position, and lasted for 2 weeks. The period of disagreement between NOZOMI and ACE magnetic field corresponds to the successive release of CMEs on the east limb which started on November 7, 1999.

The limb CMEs launched on November 7 - 8, 1999, were related to the directional disagreement between NOZOMI and ACE weak magnetic fields on November 13 - 14 according to the assumption of unchanged solar wind speed (light lines), while they were related to the disagreement of intense fields observed on November 15, 1999 (at NOZOMI position) according to equation (4) (thick lines). The propagation speed of CMEs estimated from equation (4) was slower than the solar wind speed estimated from ACE observation. It seems likely that the magnetic field on the solar surface changed its structure after the release of the CMEs and the wind speed also varied. On November 13, 1999, there were 2-hour periods of non-spiral field at 0:40-2:40. On November

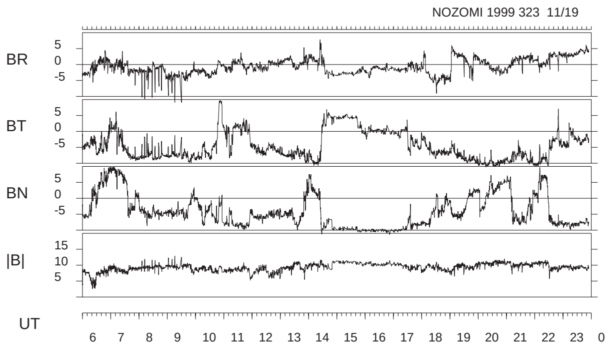

FIGURE 5. Interplanetary magnetic field observed by NOZOMI on November 19, 1999 in RTN coordinates. Non-spiral field and number of tangential discontinuities are recognized.

15, 1999, an intense, non-spiral magnetic field structure bounded by discontinuities was observed by NOZOMI. At present, it is difficult to say which non-spiral field corresponds to the limb CMEs.

The CMEs which left the Sun during the period from November 12 - 16, 1999, were related to the NOZOMI observation on November 19, 1999, according to equation (4) (thick lines), while some of the arrival times were estimated to be 2 days earlier on the assumption of the unchanged solar wind speed (light lines). On both days, i.e., November 17 and November 19, 1999, NOZOMI observed enhancements of magnitude $|\mathbf{B}|$ of the magnetic field and deviation δ from ACE magnetic field. Figure 5 shows the interplanetary magnetic field observed by NOZOMI on November 19, 1999, in RTN coordinate system. The magnetic field showed non-spiral directions, with number of discontinuities. Many of them had characteristic of tangential discontinuities.

The two CMEs observed on November 23 and November 24, 1999, coincided with the sector boundary observed by NOZOMI on November 27, 1999, according to the assumption of unchanged wind speed (light lines). The arrival dates calculated from equation (4) was 3 days behind, where no special signature was found but average spiral field was observed. Around this sector boundary crossing, slower wind was followed by faster wind, and ejecta from wide range were compressed to be observed in a short time in interplanetary space. There is another possibility that these CMEs were just missed by the point observation by NOZOMI.

SUMMARY

The period of disagreement between NOZOMI and ACE magnetic field observations, which indicates loss of stability of the heliospheric structure of magnetic field and solar wind speed, coincided with successive release of CMEs on the east limb of the Sun. The interplanetary magnetic field whose launch time coincide with limb CMEs often showed non-spiral magnetic field, enhanced magnetic field, or discontinuities, but no common structure is yet found.

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