Journal of the Korean Astronomical Society
49: 19 ∼ 23, 2016 February

http://dx.doi.org/10.5303/JKAS.2016.49.1.19
pISSN: 1225-4614 · eISSN: 2288-890X
http://jkas.kas.org

Structure of a Magnetic Decrease Observed in a Corotating Interaction Region

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Received October 1, 2015; accepted January 3, 2016

Abstract: Magnetic decreases are often observed in various regions of interplanetary space. Many studies are devoted to reveal the physical nature and generation mechanism of the magnetic decreases, but still we do not fully understand magnetic decreases. In this study, we investigate the structure of a magnetic decrease observed in a corotating interaction region using multi-spacecraft measurements. We use three spacecraft, ACE, Cluster, and Wind, which were widely separated in the x- and y-directions in the geocentric solar ecliptic (GSE) coordinates. The boundaries of the magnetic decrease are the same at the three locations and can be identified as tangential discontinuities. A notable feature is that the magnetic decrease has very large dimension, $\gtrsim$268 $\mathrm{R_E}$, along the boundary, which is much larger than the size, ∼6 $\mathrm{R_E}$, along the normal direction. This suggests that the magnetic decrease has a shape of a long, thin rod or a wide slab.

Key words: Solar wind plasma — Interplanetary magnetic fields — Discontinuities — Corotating streams

1. Introduction

Magnetic holes or magnetic decreases are structures with depression in the magnetic field intensity observed in various regions of interplanetary space (Turner et al. 1977; Winterhalter et al. 1994; Tsurutani & Ho 1999). These structures are filled with hotter and denser plasmas than the surrounding solar wind. Magnetic holes have been referred to as small-scale structures, while magnetic decreases as large-scale structures bounded by directional discontinuities such as rotational discontinuities or tangential discontinuities. Tsurutani et al. (2002a) suggested magnetic holes and decreases are different evolution stages of nonlinearly steepened Alfvén waves. Magnetic holes or decreases are more often observed near the ecliptic plane, but also observed at high heliographic latitudes (Winterhalter et al. 2000). They are also often observed in corotating interaction regions (CIRs) (Tsurutani et al. 2010).

The formation mechanism for magnetic holes or decreases has been investigated in many studies. Burlaga & Lemaire (1978) explained the structures as pressure-balanced equilibrium structures. Mirror mode instabilities have been proposed to generate magnetic holes or decreases (Winterhalter et al. 1994, 2000). However, Tsurutani et al. (2009) argued the structures observed in CIRs would not be generated by mirror mode instabilities. Soliton approaches were used to explain the magnetic holes or decreases (Baumgärtel 1999). Buti et al. (2001) proposed large-amplitude Alfvén wave packets can evolve into the magnetic holes or decreases. Phase-steepened nonlinear Alfvén waves have also been suggested as the origin of the magnetic holes or decreases (Tsurutani et al. 2002a,b, 2005a; Tsubouchi 2009). However, the formation mechanism is not fully understood yet.

In this paper, we investigated the structure of a magnetic hole or decrease (hereafter we will use magnetic decrease for simplicity) observed in a corotating interaction region (CIR). Especially we focus on the large-scale structures and variations of the magnetic decrease using multi-spacecraft observations near 1 AU. Previously Tsurutani et al. (2005b) showed that magnetic decreases can vary significantly between the ACE and Cluster spacecraft, which were separated by ∼0.01 AU along the Sun-Earth direction. They interpreted the variation as due to steepening of the Alfvén wave front. In this paper, we used three spacecraft separated very widely both in the Sun-Earth direction and the direction perpendicular to the Sun-Earth direction. Thus, we could examine the large-scale structure of a magnetic decrease in both the normal and tangential directions to the structure.

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2. Results

A magnetic decrease was observed on 2 February 2002 when a CIR was passing the interplanetary space around Earth's magnetosphere. Figure 1 shows magnetic field and plasma measurements from the Magnetic Field Experiment (MAG) (Smith et al. 1998) and Solar Wind Electron Proton Alpha Monitor (SWEPAM) (McComas et al. 1998) instruments onboard the ACE spacecraft, which was located at ∼(236, −32.9, 22.5) $\mathrm{R_E}$ in the geocentric solar ecliptic (GSE) coordinates. An interplanetary shock attached in front of the CIR passed ACE at ∼20:40 UT on 31 January 2002 and ACE entered into the faster solar wind region although

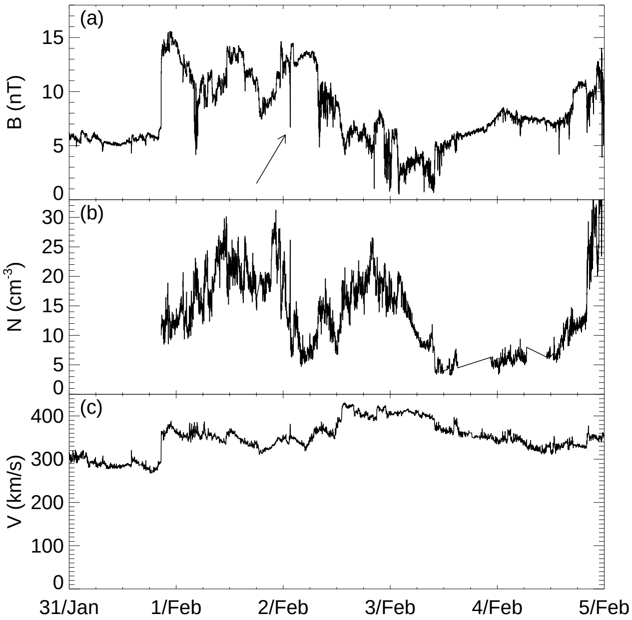

Figure 1. Magnetic field and plasma measurements from ACE on 2002. (a) The magnitude of magnetic field, (b) solar wind ion density, and (c) the speed of solar wind ions. The arrow in (a) indicates a magnetic decrease.

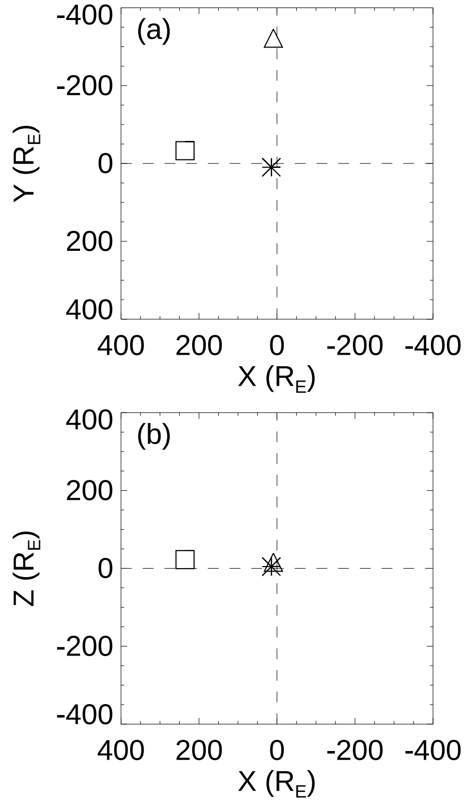

Figure 2. The locations of ACE (square), Cluster (asterisk), and Wind (triangle) projected onto the (a) xy- and (b) xz-planes in the GSE coordinates when the magnetic decrease was observed.

the speed of the solar wind, $V_{sw} \sim 370$ km/s, was not as fast as the usual high speed streams with the speed higher than ∼500 km/s. Within the faster solar wind region ACE observed a sharp dip in the magnetic field as marked by the arrow in Figure 1(a), which is identified as a magnetic decrease or magnetic hole.

The Cluster and Wind spacecraft were also in the solar wind and observed the magnetic decrease with some time delays. Figure 2 shows the locations of the spacecraft projected onto the xy- and xz-planes when they observed the magnetic decrease. Cluster was at ∼(14.4, 9.75, 4.56) R_E and Wind at ∼(9.22, −322, 15.9) R_E in the GSE coordinates. Thus, the three spacecraft were widely separated in the x- and y-directions. Using the observations from the three spacecraft we could examine the structure of the magnetic decrease in large scales in the x- and y-directions. However, because the separations in the z-direction were small the large-scale structure of the magnetic decrease in the z-direction could not be examined.

Figure 3 shows the magnitude of the magnetic fields observed by ACE, Cluster 1, and Wind. For Cluster we used the data from the Fluxgate Magnetometer (FGM) experiment (Balogh et al. 2001) and for Wind from the Magnetic Field Investigation (MFI) experiment (Lepping et al. 1995). Although there are some variations, the magnetic decrease was stable for ∼2.5 hours travelling ∼370 R_E from ACE to Wind, which is much longer than the ion gyro-period $T_g \sim 5$ s of the solar wind. Figure 4 shows the magnetic field measurements from ACE, Cluster 1, and Wind in detail. The magnetic decrease is surrounded by two sharp boundaries with very rapid variation of magnetic fields. At ACE there are large-amplitude Alfvenic fluctuations inside the magnetic decrease, but at Cluster and Wind the fluctuations disappeared and the magnetic fields are more or less constant with a little fluctuation. Also, the boundaries become steeper at Cluster and Wind.

To examine the structure of the magnetic decrease we performed the minimum variance analysis (MVA) (Sonnerup & Cahill 1967) using the magnetic field data for each spacecraft. First, we applied the MVA to each boundary of the magnetic decrease observed at Cluster 1. The results of the MVA are similar for both boundaries. However, two of the eigenvalues corresponding to the intermediate and minimum variance directions are almost same. For example, at the downstream boundary at ∼02:32 UT the three eigenvalues are 0.30, 0.45, and 51.6. Thus, the maximum variance direction is very clearly determined, but the other directions are degenerate and the normal vector, which corresponds to the minimum variance direction, could not be determined exactly. The results of the MVA applied to ACE and Wind were almost same as those of Cluster, and we could not determine the normal vector without uncertainty using the MVA.

On the other hand, because the results for the three spacecraft are very similar, the magnetic decrease has almost the same boundary structure at the locations of ACE, Cluster, and Wind. This implies that the structure is stable and has almost planar boundaries, which enables us to use timing analysis to estimate the normal

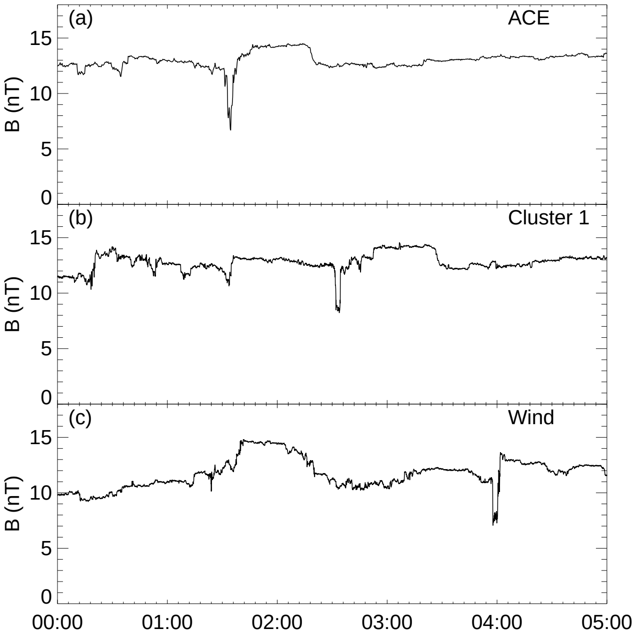

Figure 3. The magnitude of the magnetic fields observed by (a) ACE, (b) Cluster 1, and (c) Wind on 2 February 2002.

vector of the boundaries. Thus, we performed timing analysis using ACE, Wind, and Cluster 1 and 3, and determined that the normal vector, **n**, is ~(-0.745, -0.568, 0.350) and the speed of the structure along the normal vector, V_{bn}, is ~243 km/s. Errors in the timing analysis mainly occur from the estimation of the time difference between the detections of a boundary at different locations. In this case, the estimation errors of the time differences are less than 10 seconds while the time differences are 1 hour or more. Thus, the errors are almost negligible and the estimated normal vector and speed are quite reliable. The distances between ACE and Cluster and between Cluster and Wind along the normal vector are ~135 R_E (~8.58×10^5 km) and ~196 R_E (~1.25×10^6 km), respectively. Dividing the distances by the normal speed V_{bn} results in ~1 hour between ACE and Cluster and ~1.4 hour between Cluster and Wind, which are consistent with the time lags between the observations in Figure 3.

Figure 5 shows the magnetic fields transformed into the normal coordinate system. We used the maximum variance direction from the MVA as a tangential direction ($\mathbf{t}_2$) and the other was estimated by $\mathbf{t}_1 = \mathbf{t}_2 \times \mathbf{n}$. It is seen that the normal component of the magnetic field, B_n, is almost zero across the magnetic decrease. Thus, the boundaries can be interpreted as tangential discontinuities.

To make the interpretation more complete we analyzed ion moments observed by Cluster 1. We used Cluster Ion Spectrometry (CIS) experiment (Rème et al. 2001) for the ion moments. Figure 6 shows the bulk velocity and pressure of ions in the GSE coordinates. We transformed the bulk velocity in the spacecraft frame (Figure 6a) into the normal coordinate system (Figure 6b). This shows that the normal velocity

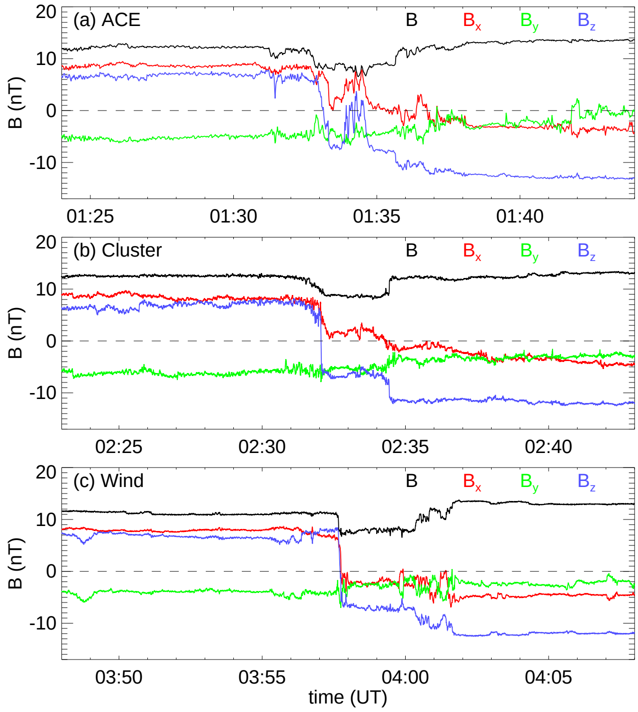

Figure 4. The magnitude and components of the magnetic fields observed by (a) ACE, (b) Cluster 1, and (c) Wind. Black line represents the magnitude, red the B_x component, green the B_y component, and blue the B_z component in the GSE coordinates. Note that the observation times (the x-axis) are all different.

is almost constant across the structure and finite with V_{in} ~ 252 km/s in the spacecraft frame. Because the structure is moving with V_{bn} ~ 243 km/s, the normal velocity of the ions is almost zero in the moving frame of the magnetic decrease. Thus, the bulk velocity of ions satisfies the condition for the tangential discontinuity. Note that there exists a significant increase of the velocity in the maximum variance direction $\mathbf{t}_2$ while the other components remain almost constant. Figure 6c shows the thermal, magnetic, and total pressures. Within the magnetic decrease, the thermal pressure of ions is significantly enhanced, which makes the total pressure more or less constant across the structure although there are some fluctuations. Thus, the condition that the total pressure is conserved across the tangential discontinuity is also satisfied.

The additional information we can obtain from the timing analysis is the speed of the boundary normal to the boundary. In this case the magnetic decrease is moving with V_{bn} ~ 243 km/s. Using this we estimated the size of the structure perpendicular to the boundaries. At Cluster the time difference between the boundaries is ~165 s. Thus, the perpendicular size of the magnetic decrease is ~40 000 km (~6.29 R_E). This is much larger than the gyro-radius, r_g ~ 45 km, of ions in the magnetic decrease. The perpendicular size estimated at ACE and Wind is almost same as the size at Cluster. Thus, the magnetic decrease does not expand or contract. The dimension of the magnetic decrease

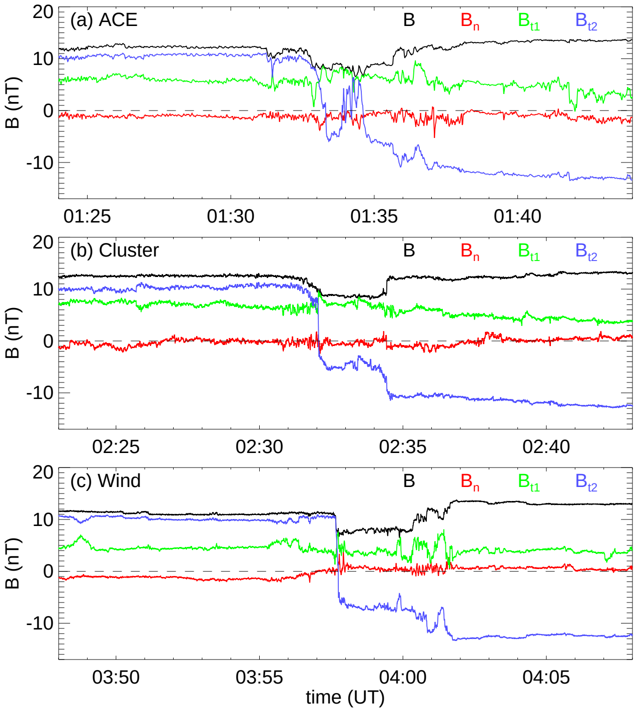

Figure 5. The magnitude and components of the magnetic fields observed by (a) ACE, (b) Cluster 1, and (c) Wind in the boundary normal coordinates. Black line represents the magnitude, and red the normal component, B_n. Green and blue lines represent the tangential components, B_{t1} and B_{t2}, respectively.

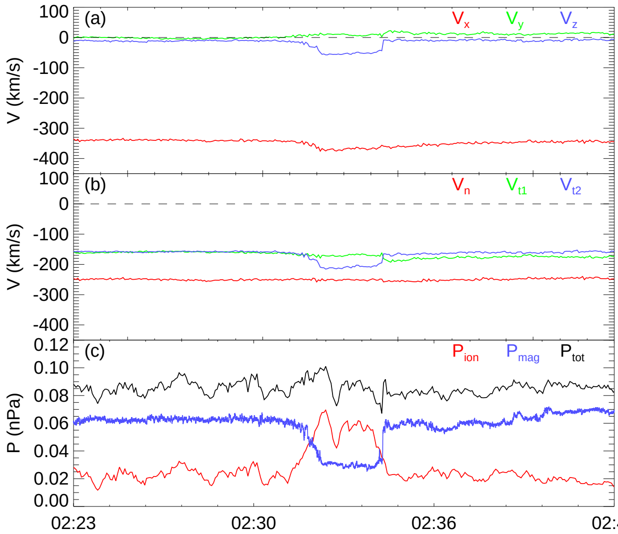

Figure 6. The bulk velocity and pressure of ions observed by Cluster 1 on 2 February 2002. (a) The components of the bulk velocity in the GSE coordinates. Red line represents V_x, green V_y, and blue V_z. (b) The components of the bulk velocity transformed into the boundary normal coordinates. Red line represents V_n, green V_{t1}, and blue V_{t2}. (c) The ion pressure (red), magnetic pressure (blue), and total pressure (black).

along the boundary is also estimated using the normal vector and spacecraft locations. Because the magnetic decrease was observed by all the spacecraft, the dimension along the boundary is larger than the separation of the spacecraft along the boundary, which is estimated to be ~268 R_E. This is much larger than the perpendicular size.

Note that because Cluster consists of four identical spacecraft we could perform the timing analysis using the four Cluster measurements. However, the largest separation between the spacecraft was ~640 km in the x-direction, and the time differences between the detections of the boundaries at the spacecraft were less than only a few seconds, which was too short to accurately estimate the time differences and normal vector. Thus, we could not apply the timing analysis for the four Cluster measurements.

3. Discussion and Conclusions

In this study, we investigated the structures of a magnetic decrease observed in a CIR using multi-spacecraft measurements. ACE, Cluster, and Wind were widely separated in the x- and y-directions in the GSE coordinates, which could be utilized to examine the large-scale structures and variations of the magnetic decrease. It is found that the boundary structures of the magnetic decrease remained stable as it traveled from ACE to Wind, which were separated by ~370 R_E. The boundaries were identified as tangential discontinuities. The dimension of the magnetic decrease along the tangential direction to the boundaries was greater than ~268 R_E, which was much larger than the size, ~6 R_E, along the normal direction to the boundaries.

Tsurutani et al. (2005b) reported that the magnetic decreases can rapidly evolve from ACE to Cluster, which were separated by ~220 R_E in the x-direction. The size of the magnetic decreases substantially reduced from ACE to Cluster. However, in this study the magnetic decrease did not evolve, but remained stable and the size along the normal direction was almost same. This could be because the magnetic decrease in this study was already quite well developed at the location of ACE. At ACE the magnetic decrease had quite sharp boundaries and they became steepened slightly more at Cluster and Wind. On the other hand, the magnetic decreases in Tsurutani et al. (2005b) have more gradual boundaries and fluctuations even at Cluster. Thus, they could be in less-evolved state than the magnetic decrease in this study. This suggests that the magnetic decreases can rapidly evolve in their growing phase, but after they evolve sufficiently they remain stable for quite a long time.

In previous studies it was not possible to investigate how large the magnetic decreases form along the boundary due to the limitation of observations. In this study we found that the size of the magnetic decreases along the boundary can be much larger than the size normal to the boundary using the observations obtained from the spacecraft widely separated in the x- and y-directions. Thus, the structure could have a shape like a long, thin rod or a thin slab. However, because the separations in the z-direction were much shorter than those in the x- and y-directions, we could estimate the size in only a direction along the boundary. As a result, we cannot clearly determine whether the structure is a long rod or a wide slab. Also, the magnetic field in the magnetic decrease had both y and z components. Thus, the dimension we estimated along the boundary is not parallel or perpendicular to the magnetic field. More complete information about the shape of the magnetic decrease could have been obtained had there been another spacecraft widely separated in the z-direction from the others, which unfortunately was not available.

Acknowledgments

The work by E. Lee was in part supported by the BK21 Plus Program and Basic Science Research Program (NRF-2013R1A1A2010711) through the National Research Foundation funded by the Ministry of Education of Korea. The work by G. K. Parks was in part supported by a NASA grant to the University of California Berkeley, NNX11AD49G-2/15. The authors appreciate the ACE, Cluster, and Wind instrument teams and the Cluster Science Archive and CDAWEB for the use of the data.

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