Journal of the Korean Astronomical Society
49: 59 ∼ 64, 2016 April

http://dx.doi.org/10.5303/JKAS.2016.49.2.59
pISSN: 1225-4614 · eISSN: 2288-890X
http://jkas.kas.org

KINETIC PROPERTIES OF MAGNETIC DECREASES OBSERVED IN THE SOLAR WIND AT ∼1 AU

Ensang Lee[1] and George K. Parks[2]

[1]School of Space Research and Institute of Natural Sciences, Kyung Hee University, Giheung-gu, Yongin, Gyeonggi 17104, Korea; eslee@khu.ac.kr
[2]Space Sciences Laboratory, University of California, Berkeley, CA 94612, USA; parks@ssl.berkeley.edu

Received February 26, 2016; accepted March 24, 2016

Abstract: In this study, we investigate the kinetic properties of magnetic decreases observed in the solar wind at ∼1 AU using the Cluster observations. We study two different magnetic decreases: one with a short observation duration of ∼2.5 minutes and stable structure and the other with a longer observation duration of ∼40 minutes and some fluctuations and substructures. Despite the contrast in durations and magnetic structures, the velocity space distributions of ions are similar in both events. The velocity space distribution becomes more anisotropic along the direction parallel to the magnetic field, which differs from observations obtained at high heliographic latitudes. On the other hand, electrons show different features from the ions. The core component of the electrons shows similar anisotropy to the ions, though the anisotropy is much weaker. However, while ions are heated in the magnetic decreases, the core electrons are slightly cooled, especially in the perpendicular direction. The halo component does not change much in the magnetic decreases from the ambient solar wind. The strahl component is observed only in one of the magnetic decreases. The results imply that the ions and electrons in the magnetic decreases can behave differently, which should be considered for the formation mechanism of the magnetic decreases.

Key words: solar wind plasma: interplanetary magnetic fields: discontinuities

1. INTRODUCTION

Magnetic decreases, also known as magnetic holes, are localized depressions in the magnetic field intensity observed in interplanetary space (Turner et al. 1977; Winterhalter et al. 1994; Tsurutani & Ho 1999). Magnetic decreases are observed at all heliographic latitudes, but more frequently observed near the ecliptic plane than at high heliographic latitudes (Winterhalter et al. 2000). The highest occurrence rate was reported in the region near the reverse shock of corotating interaction regions (Tsurutani et al. 2005). Magnetic decreases are often bounded by directional discontinuities such as rotational discontinuities or tangential discontinuities. Some magnetic decreases have durations of tens of seconds as observed by spacecraft, but there are also large-scale magnetic decreases with durations of tens of minutes (Chisham et al. 2000).

One of the unsolved problems about magnetic decreases is their formation mechanism. Because the plasma pressure is enhanced within magnetic decreases, Burlaga & Lemaire (1978) explained that they are pressure-balanced equilibrium structures. Winterhalter et al. (1994, 2000) have proposed that mirror mode instabilities can generate linear magnetic decreases, which have less than 10% rotation in the direction of the magnetic field. They showed that within magnetic decreases the temperature anisotropy was increased and the surrounding plasmas were also close to the criterion for the mirror mode instabilities. Baumgärtel (1999) used soliton approaches to explain the formation of the magnetic decreases, and Buti et al. (2001) proposed that large-amplitude Alfvén wave packets propagating at large angles to the magnetic field can evolve into magnetic decreases. It has also been suggested that magnetic decreases are formed by diamagnetic effect due to perpendicular proton energization produced by phase-steepened nonlinear Alfvén waves (Tsurutani et al. 2002a,b, 2005; Tsubouchi 2009). However, the formation mechanism is still under debate.

In most of the previous studies, macroscopic quantities, e.g., temperature, pressure, plasma beta, have been used to study the magnetic decreases. However, we can better understand their nature and formation mechanism by directly analyzing the phase space distribution functions. Previously, Neugebauer et al. (2001) investigated the phase space distribution functions of ions in large magnetic holes observed by the Ulysses spacecraft in the fast solar wind at high heliographic latitudes at ∼3 AU. They showed that differential streaming between H^+ and He^{++} and between H^+ and H^+ beams in the high-latitude solar wind significantly decreased and the temperature perpendicular to the magnetic field ($T_\perp$) increased in the magnetic holes. This caused $T_\perp/T_\parallel$ increase, where $T_\parallel$ is the temperature parallel to the magnetic field, and the plasma in the magnetic holes be marginally stable against mirror

---

Corresponding author: E. Lee

mode instabilities.

In this paper, we report on our investigation of the kinetic properties of magnetic decreases observed by the Cluster spacecraft (Escoubet et al. 2001) in the solar wind at ~1 AU. We focused on the differences in the phase space distribution functions of ions and electrons observed in magnetic decreases and ambient solar wind. During the observations Cluster was located near the ecliptic plane at ~1 AU. Thus, the solar wind observed by Cluster has different properties with the fast solar wind observed by Ulysses at high heliographic latitudes at ~3 AU (Neugebauer et al. 2001), and the magnetic decreases may have different kinetic properties.

2. RESULTS

We analyzed two magnetic decreases with large density enhancements. One of them was observed on 2 February 2002 and had duration of ~2.5 minutes. The other was observed on 13 February 2001 and had much longer duration of ~40 minutes. We used magnetic field measurements with 4 s resolution from the Fluxgate Magnetometer (FGM) experiment (Balogh et al. 2001) to identify the magnetic decreases. The Cluster Ion Spectrometry (CIS) (Rème et al. 2001) and Plasma Electron And Current Experiment (PEACE) (Johnstone et al. 1997) instruments were used to obtain three-dimensional distribution functions for thermal ions with energies from 4 eV to 32 keV and thermal electrons with energies less than 26 keV, respectively.

2.1. 2 February 2002 Event

Figure 1 shows an overview of the event. A magnetic decrease was observed at ~02:33 UT with a decrease in intensity of a few nT. When the magnetic decrease was observed, Cluster was at ~(14.4, 9.8, 4.6) R_E in the geocentric solar ecliptic (GSE) coordinates. Lee & Parks (2016) investigated the same event and showed that the magnetic decrease was stable and bounded by tangential discontinuities. It is seen that within the magnetic decrease the energy of the solar wind ion beam significantly increases, bulk flow changes its direction, and the density increases about 50% from the ambient solar wind.

Figure 2 shows the velocity space distribution functions of ions observed using the solar wind mode (low geometric factor mode) of the Hot Ion Analyzer (HIA) instrument included in the CIS instrument onboard Cluster 1 (C1). The left panels represent two-dimensional cuts of the three-dimensional distribution functions in the plane parallel and perpendicular to the magnetic field. The right panels are one-dimensional cuts of the two-dimensional distribution functions in the left panels along $V_{\parallel} = 0$ and $V_{\perp} = 0$. In the ambient solar wind (Figure 2a and g) the distribution functions are almost isotropic and well fitted by a Maxwellian (blue and red lines in the right panels). The temperatures estimated by the fitting are ~6.5 and ~6.0 eV in the parallel and perpendicular directions, respectively, at 02:26:00 UT (Figure 2b). At 02:39:55 UT (Figure 2h) the temperatures are ~9.1 and ~10.0 eV in the parallel and perpendicular directions, respectively. On the other hand, in the magnetic decrease (Figure 2c and e) the distribution functions are broader in the parallel direction than in the perpendicular direction, but well fitted by a Maxwellian in both directions. The temperatures at 02:32:25 UT (Figure 2d) are ~17.2 and ~7.4 eV in the parallel and perpendicular directions, respectively, and at 02:33:29 UT (Figure 2f) they are ~16.1 and ~6.8 eV in the parallel and perpendicular directions, respectively. Thus, the parallel temperature ($T_{\parallel}$) is more than two times higher than the perpendicular temperature ($T_{\perp}$) in the magnetic decrease ($T_{\parallel}/T_{\perp} \sim 2.3$). Note that the weak enhancements in the lower half region in the two-dimensional distributions are He^{++}.

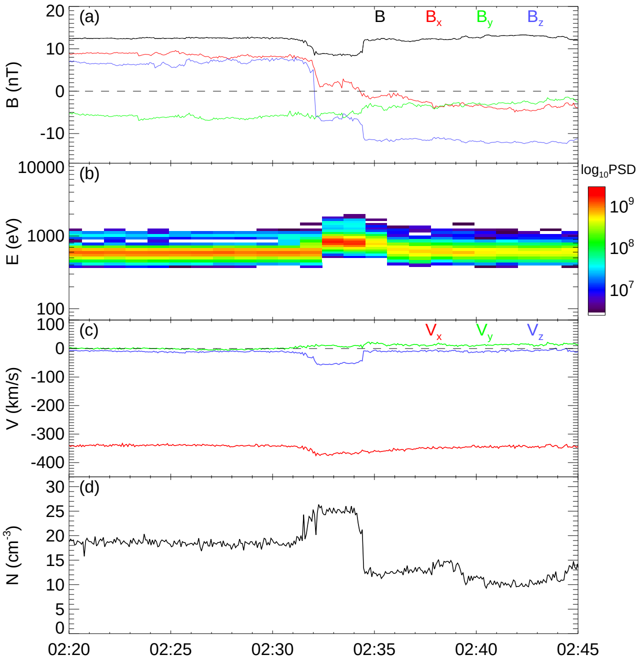

Figure 1. Overview of the event observed by C1 on 2 February 2002. (a) Magnetic field, (b) spectrogram of omnidirectional energy fluxes of ions, (c) ion bulk velocity, and (d) ion density.

Figure 3 shows the velocity distribution functions of electrons observed by Cluster 2 (C2) at the times corresponding to the ion distributions in Figure 2. In the ambient solar wind (Figure 3a and d) the velocity distributions consist of the core and halo components and both components are almost isotropic. The core component is well fitted by a Maxwellian and the estimated temperatures are ~9.4 and ~8.9 eV at 02:26:00 (Figure 3a) and 02:39:55 UT (Figure 3d), respectively. Within the magnetic decrease the velocity distributions become anisotropic. Compared to the ambient solar wind (dashed line) the core distributions become a little broader in the parallel direction, but a little narrower in the perpendicular direction. The estimated temperatures of the core component are ~10.1 and ~8.8 eV in the parallel and perpendicular directions, respectively, at 02:32:24 UT (Figure 3b) and ~10.2 and ~8.5 eV in

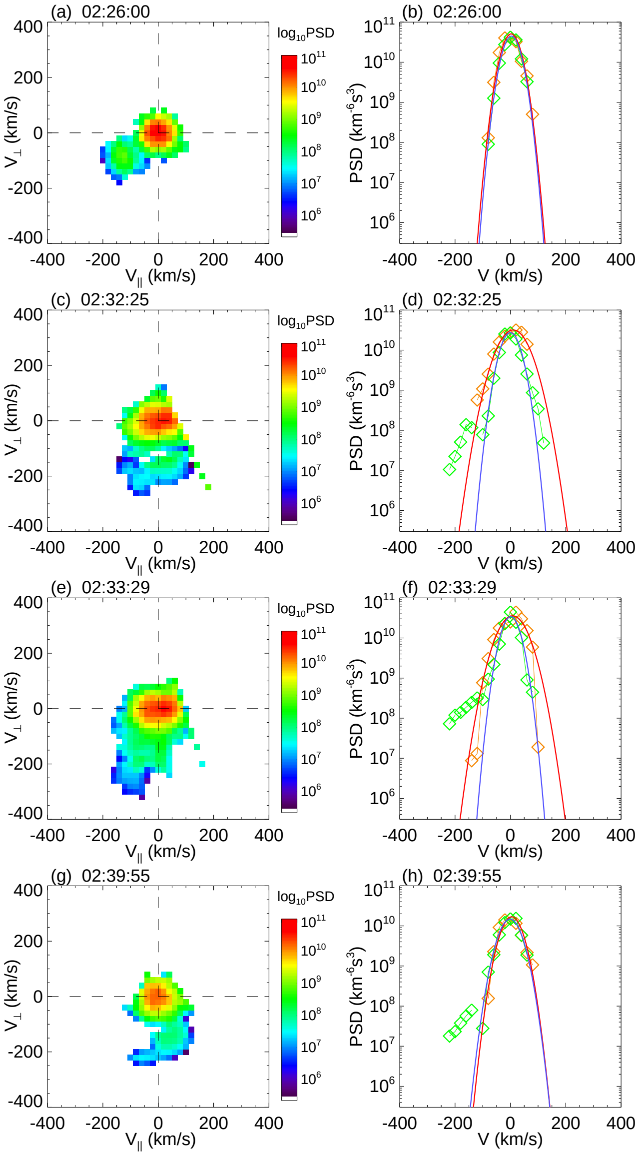

Figure 2. Velocity space distribution functions of ions observed using the solar wind mode of the HIA instrument onboard the Cluster C1 spacecraft on 2 February 2002. The left panels show two-dimensional cuts of the three-dimensional velocity space distribution functions on the plane parallel and perpendicular to the magnetic field. The right panels show one-dimensional cuts of the two-dimensional distributions along $V_\parallel = 0$ (orange) and $V_\perp = 0$ (green). The red and blue solid lines represent the Maxwellian fittings of the one-dimensional distributions along $V_\parallel = 0$ and $V_\perp = 0$, respectively.

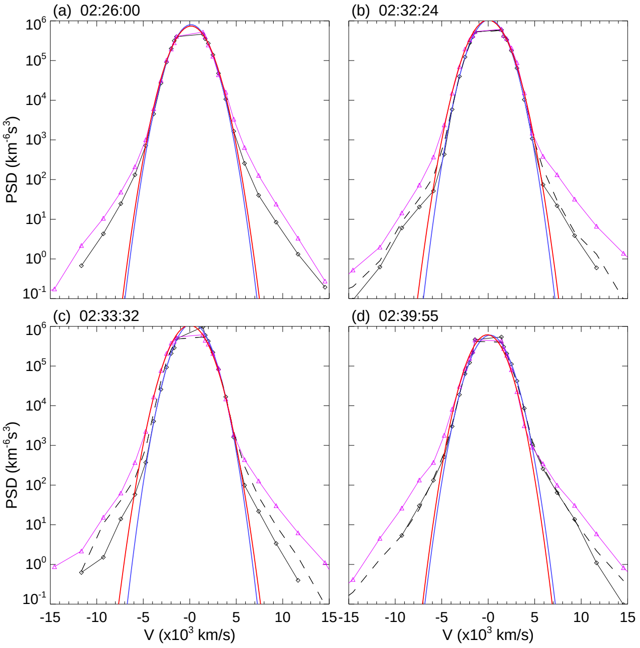

Figure 3. Velocity space distribution functions of electrons observed by the PEACE instrument onboard the Cluster C2 spacecraft on 2 February 2002. The black solid lines with diamonds represent the one-dimensional distributions along the parallel direction to the magnetic field. The magenta solid lines with triangles represent the one-dimensional distributions along the perpendicular direction to the magnetic field. The perpendicular distribution in (a) is added in (b) - (d) for comparison (dashed lines).

the parallel and perpendicular directions, respectively, at 02:33:32 UT (Figure 3c). Thus, the electrons in the magnetic decrease are slightly hotter in the parallel direction, but slightly colder in the perpendicular direction than those in the ambient solar wind. The same change is observed in the halo component except that in the magnetic decrease a strahl component is observed in the parallel direction. This makes the distribution in the parallel direction anisotropic, which can produce current along the magnetic field.

2.2. 13 February 2001 Event

Figure 4 shows an overview of the other magnetic decrease observed at ~00:30 UT on 13 February 2001, which has much longer duration (larger size) compared to the previous event. At this time Cluster was at ~(18.7, 5.6, 0.7) R_E in the GSE coordinates. In this case the magnetic decrease has multiple structures with some fluctuations. Also, it has longer duration at Cluster than at ACE, which was located closer to the Sun, implying that the magnetic decrease has expanded as it traveled from ACE to Cluster. The magnetic field intensity decrease is larger than the previous event and in the center it decreases ~8 nT, which is ~80% from the ambient solar wind (Figure 4). Also, the density increases ~200% from the ambient solar wind.

The velocity distributions of ions show similar features to the previous event, but the anisotropy between the parallel and perpendicular directions in the magnetic decrease is much weaker (Figure 5). The estimated temperatures are ~14.5 and ~9.7 eV in the parallel and perpendicular directions, respectively, at 00:26:03 UT (Figure 5d), and ~12.7 and ~11.0 eV at 00:32:03 UT (Figure 5f). Thus, The temperature ratio, $T_\parallel/T_\perp$, is ~1.5 at 00:26:03 UT and ~1.2 at 00:32:03 UT. In the ambient solar wind the temperatures are ~10.1 and ~8.3 eV at 23:12:48 UT (Figure 5b) and

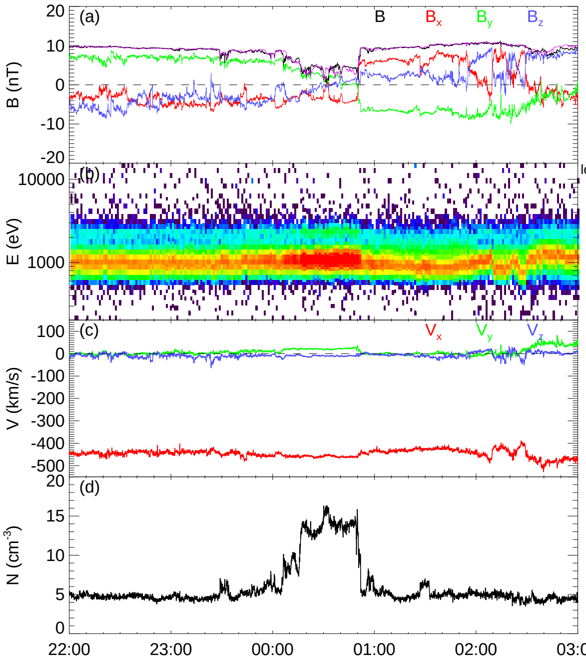

Figure 4. Overview of the event observed by C1 on 12 and 13 February 2001. The format is the same as Figure 1. Magnetic field intensity obtained from ACE, shifted about 46 minutes in time, is added in (a) for comparison (magenta line).

01:20:05 UT (Figure 5h), respectively. Thus, the ions in the magnetic decrease are slightly hotter than those in the ambient solar wind.

For electrons the velocity distributions show different features from the previous event. The core component is almost isotropic both in the magnetic decrease and the ambient solar wind. The estimated temperatures are ∼8.4 eV in the magnetic decrease (Figure 6b and c) and ∼9.2 eV in the ambient solar wind (Figure 6a and d). Thus, the electrons in the magnetic decrease are slightly colder than those in the ambient solar wind. In the magnetic decrease the halo component is almost isotropic. Although the density of the core component increases largely in the magnetic decrease, the halo component in the magnetic decrease is comparable to the ambient solar wind. Contrary to the previous event, a strahl component exists in the solar wind, but not in the magnetic decrease.

3. DISCUSSION AND CONCLUSIONS

In this study, we investigated the kinetic properties of magnetic decreases observed in the solar wind at ∼1 AU using the Cluster observations. We analyzed two examples of magnetic decreases: one with short duration of ∼2.5 minutes and the other with longer duration of ∼40 minutes. The short magnetic decrease was very stable, but the long magnetic decrease had some fluctuations and substructures within it and expanded a little as it traveled from ACE to Cluster.

In the solar wind and magnetic decreases ions consist of H^+ and He^{++}. In this study, we focused only on the properties of H^+ because the population of He^{++} was too small to obtain meaningful results. The ions are well fitted by a Maxwellian distribution both in the magnetic decreases and the ambient solar wind, implying that the ions are in thermal equilibrium in both regions. In the magnetic decreases the ions are anisotropic and hotter in the parallel direction to the magnetic field. This is different from the magnetic decreases observed by the Ulysses spacecraft in the high heliographic latitudes, in which perpendicular temperatures increase and the distributions are more isotropic (Neugebauer et al. 2001). In the high latitudes the solar wind has different properties from the solar wind near the ecliptic plane. In the high latitudes there exist differential streamings between H^+ and He^{++} and between H^+ and H^+ beams. This is because the solar wind more dom-

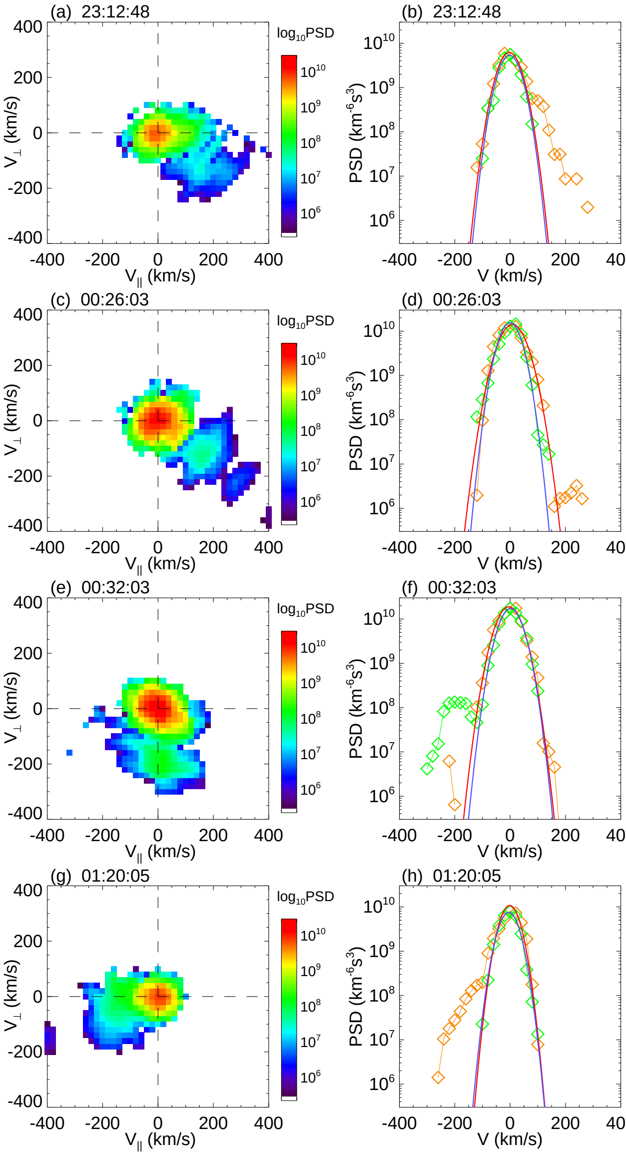

Figure 5. Velocity space distribution functions of ions observed on 12 and 13 February 2001. The format is the same as Figure 2.

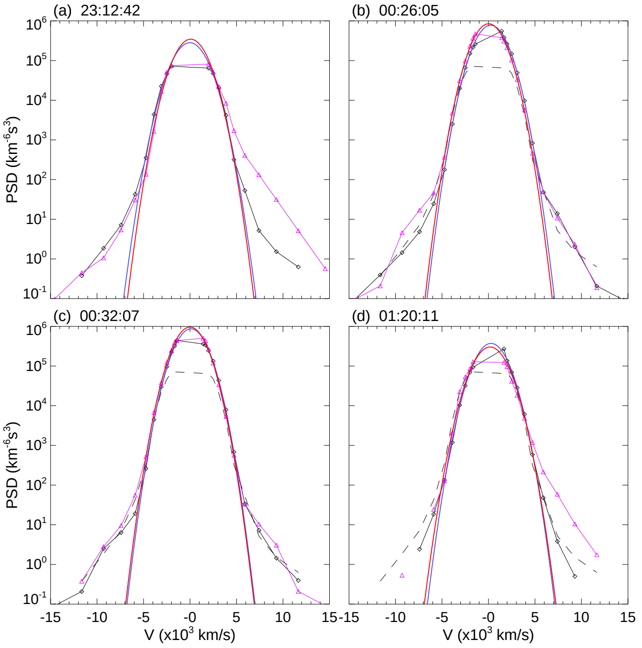

Figure 6. Velocity space distribution functions of electrons observed on 12 and 13 February 2001. The format is the same as Figure 3.

inantly streams along the magnetic field in the high latitudes. On the other hand, near the ecliptic plane, the bulk drift perpendicular to the magnetic field is significant. The difference in the solar wind might have resulted in the differences in the velocity space distributions in the magnetic decreases observed in the high latitudes and near the ecliptic plane.

Electrons consist of the core, halo, and strahl components. The core component shows similar anisotropy to the ions in the magnetic decreases. However, the anisotropy is much weaker and the core component is even almost isotropic for the large magnetic decrease. Moreover, the core component is slightly cooled in the magnetic decreases, especially in the perpendicular direction, while the ions are heated. Although the magnitude of the core component increases a few times in the magnetic decreases, the halo component does not vary much for both magnetic decreases. The formation mechanisms suggested in the previous studies have mostly considered the heating of ions, but the cooling of the core electrons and the invariability of the halo component should also be considered. The strahl component is different for the two magnetic decreases. For the small magnetic decrease the strahl component occurs in the magnetic decrease, but for the large magnetic decrease it occurs in the ambient solar wind. It is not clear whether the difference is owing to the different sizes or fluctuation levels of the magnetic decreases. It is needed to examine more examples to verify what causes the differences in the electron distribution functions in the magnetic decreases.

Previous studies have tried to understand the formation mechanism of the magnetic decreases using the observations from the spacecraft such as ACE, Ulysses, and Cluster. However, the magnetic decreases are already well developed when they are observed by the spacecraft, which suggests that they might have started to grow close to the Sun or even in the solar corona. Thus, it is needed to use the observations obtained close to the Sun to fully understand the formation mechanism. Future missions such as Solar Orbiter and Solar Probe Plus will provide useful observation data for the region in the inner heliosphere where the magnetic decreases are excited.

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 Cluster and ACE instrument teams and the Cluster Science Archive and CDAWEB for the use of the data.

References

Balogh, A., Carr, C. M., Acuña, M. H., et al. 2001, The Cluster Magnetic Field Investigation: Overview of In-Flight Performance and Initial Results, Ann. Geophys., 19, 1207

Baumgärtel, K. 1999, Soliton Approach to Magnetic Holes, J. Geophys. Res., 104, 28295

Burlaga, L. F., & Lemaire, J. F. 1978, Interplanetary Magnetic Holes: Theory, J. Geophys. Res., 83, 5157

Buti, B., Tsurutani, B. T., Neugebauer, M., & Goldstein, B. E. 2001, Generation Mechanism for Magnetic Holes in the Solar Wind, Geophys. Res. Lett., 28, 1355

Chisham, G., Schwartz, S. J., Burgess, D., Bale, S. D., Dunlop, M. W., & Russell, C. T. 2000, Multisatellite Observations of Large Magnetic Depressions in the Solar Wind, J. Geophys. Res., 105, 2325

Escoubet, C. P., Fehringer, M., & Goldstein, M. 2001, The Cluster Mission, Ann. Geophys., 19, 1197

Johnstone, A. D., et al. 1997, PEACE: A Plasma Electron and Current Experiment, Space Sci. Rev., 79, 351

Lee, E., & Parks, G. K. 2016, Structure of a Magnetic Decrease Observed in a Corotating Interaction Region, JKAS, 49, 19

Neugebauer, M., Goldstein, B. E., Winterhalter, D., et al. 2001, Ion Distributions in Large Magnetic Holes in the Fast Solar Wind, J. Geophys. Res., 106, 5635

Rème, H., Aoustin, C., Bosqued, J. M., et al. 2001, First Multispacecraft Ion Measurements in and near the Earth's Magnetosphere with the Identical Cluster Ion Spectrometry (CIS) Experiment, Ann. Geophys., 19, 1303

Tsubouchi, K. 2009, Alfvén Wave Evolution within Corotating Interaction Regions Associated with the Formation of Magnetic Holes/Decreases, J. Geophys. Res., 114, A02101

Tsurutani, B. T., & Ho, C. M. 1999, A Review of Discontinuities and Alfvén Waves in Interplanetary Space: Ulysses Results, Rev. Geophys., 37, 517

Tsurutani, B. T., Dasgupta, B., Galvan, C., et al. 2002a, Phase-Steepened Alfvén Waves, Proton Perpendicular

Energization and Creation of Magnetic Holes and Magnetic Decreases: The Ponderomotive Force, Geophys. Res. Lett., 29, 2233

Tsurutani, B. T., Galvan, C., Arballo, J. K., et al. 2002b, Relationship between Discontinuities, Magnetic Holes, Magnetic Decreases, and Nonlinear Alfvén Waves: Ulysses Observations over the Solar Poles, Geophys. Res. Lett., 29, 1528

Tsurutani, B. T., Lakhina, G. S., Pickett, J. S., et al. 2005, Nonlinear Alfvén Waves, Discontinuities, Proton Perpendicular Acceleration, and Magnetic Holes/Decreases in Interplanetary Space and the Magnetosphere: Intermediate Shocks?, Nonlin. Proc. Geophys., 12, 321

Turner, J. M., Burlaga, L. F., Ness, N. F., & Lemaire, J. F. 1977, Magnetic Holes in the Solar Wind, J. Geophys. Res., 82, 1921

Winterhalter, D., Neugebauer, M., Goldstein, B. E., et al. 1994, Ulysses Field and Plasma Observations of Magnetic Holes in the Solar Wind and Their Relation to Mirror-Mode Structures, J. Geophys. Res., 99, 23371

Winterhalter, D., Smith, E. J., Neugebauer, M., Goldstein, B. E., & Tsurutani, B. T. 2000, The Latitudinal Distribution of Solar Wind Magnetic Holes, Geophys. Res. Lett., 27, 1615