On the origin of cold-dense plasmas in the dusk magnetotail plasma sheet: MMS Observations

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Key Points:

- MMS observed the cold-dense plasma sheet in the dusk magnetotail under the strongly northward IMF.
- Energy dispersions of the low-energy ions in the field-aligned direction were identified.
- Magnetic reconnection in the Kelvin-Helmholtz vortices near the magnetopause is a possible mechanism of generating the energy dispersions.

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Abstract

The near-Earth plasma sheet becomes cold and dense under the northward interplanetary magnetic field (IMF) condition, which suggests entry of solar wind plasma into the magnetosphere across the magnetopause. The cold and dense characteristics of the plasma sheet are more evident in the magnetotail flank regions that are interface between cold solar wind plasma and hot magnetospheric plasma. Several physical mechanisms have been proposed to explain the entry of solar wind plasma across the magnetopause and resultant formation of the cold-dense plasma sheet (CDPS) in the tail flank regions. However, transport path of the cold-dense plasma inside the magnetotail has not been understood yet. Here we present a case study of the CDPS in the dusk magnetotail by Magnetospheric Multiscale (MMS) spacecraft under the conditions of the strongly northward IMF and the high-density solar wind. The ion distribution function consists of high- and low-energy components, and the low-energy one intermittently shows energy dispersion in the directions parallel and anti-parallel to the local magnetic field. Considering the time-of-flight effect of the energy-dispersed low-energy ions, we infer that these ions originate in the region down the tail, and move along the magnetic field toward the ionosphere and then come back to the magnetotail by the mirror reflection. The pitch-angle dispersion analysis gives consistent results on the travelling time and path length of the energy-dispersed ions. Based on these observations, we discuss possible generation mechanisms of the energy-dispersed structure of the low-energy ions during the northward IMF.

1 Introduction

The plasma sheet in the Earth's magnetosphere is an important target of magnetospheric physics, since it is strongly related to geomagnetic activities through its role as the plasma reservoir. Previous research has revealed that the near-Earth plasma sheet becomes cold and dense under the northward interplanetary magnetic field (IMF) (e.g., Zwolakowska et al., 1992; Zwolakowska & Popielawska, 1992; Terasawa et al., 1997; Borovsky et al., 1998; Nishino et al., 2002; Wing et al., 2005; Nagata et al., 2008). The formation of the cold-dense plasma sheet (CDPS) has been thought as a result of solar wind entry across the magnetopause and subsequent plasma transport inside the magnetotail.

Several mechanisms have been proposed to explain the solar wind plasma entry across the magnetopause under the northward IMF, and some of them have been verified. In particular, under the strongly northward IMF condition, double-lobe reconnection (also known as magnetic reconnection poleward of the cusp) (e.g., Song & Russell, 1992; Li et al., 2005; Sorathia et al., 2019) and Kelvin-Helmholtz instability (e.g., Fairfield et al., 2000; Hasegawa et al., 2004) play an important role in solar wind plasma entry across the magnetopause. The solar wind entry across the magnetopause results in the formation of the low-latitude boundary layer (LLBL) filled with cold and dense plasma, and it possibly forms the CDPS in a wide region of the near-Earth magnetotail.

On the other hand, the plasma transport mechanism inside the magnetosphere under the northward IMF has not been well understood. Since the plasma flow in the near-Earth magnetotail under the northward IMF should reflect the transport mechanism of the cold-dense plasma, it is important to investigate the plasma flow velocity in the plasma sheet. Statistically, ion flows in the near-Earth plasma sheet during the geomagnetically quiet periods are quite stagnant with a slight earthward component (e.g., Angelopoulos et al., 1993). For most of the time, the ions in the CDPS adjacent to the LLBL slowly flow towards the Earth (Fujimoto et al., 1998).

The response time of the near-Earth plasma sheet to the solar wind during the northward IMF is confirmed to be longer than that during the southward IMF (e.g., Nagata et al., 2008). Based on the longer duration ($\sim$several hours) of the CDPS formation and the low bulk velocity in the near-Earth plasma sheet under the northward IMF, diffusive trans-

port in the plasma sheet has been proposed as a dominant mechanism in the magnetotail (Terasawa et al., 1997; Nagata et al., 2008; Wang et al., 2010). However, the CDPS occasionally appears in the midnight region only a few hours after the start of the strongly northward IMF period (Nishino, Fujimoto, Terasawa, et al., 2007), which suggests that non-diffusive plasma transport may work in the plasma sheet under the northward IMF.

In this paper we report on energy-dispersed low-energy ions in the field-aligned directions observed by the Magnetospheric Multiscale (MMS) mission spacecraft in the near-Earth magnetotail on the duskside under the strongly northward IMF. We will discuss possible mechanisms for generating energy dispersion in relation to the formation and temporal development of the CDPS in the flank of the magnetotail.

2 Instrumentation

We use ion and electron data from Fast Plasma Investigation (FPI) (Pollock et al., 2016) and magnetic field data from Fluxgate Magnetometer (FGM) (Russell et al., 2016) onboard MMS1, which is one of the four spacecraft in the MMS mission (Burch et al., 2016). The ion energy range of FPI for the event studied in this paper is from a few eV to 30 keV, which fully covered the typical energy of low-energy (cold) ions in the plasma sheet. Since burst-mode data were unavailable for the period of the current study, we use the fast survey-mode plasma data with a resolution of 4.5 s, which has no impact on the results presented in this paper. The four spacecraft were positioned at a distance of less than 20 km from each other, which is less than the ion kinetic scale. (The gyroradius of a 0.1-keV proton is ∼70 km in a 20-nT magnetic field.) During the events, all four spacecraft observed almost identical ion signatures at the resolution of 4.5 s, and thus we use only MMS1 data in this study. The solar wind data from the Advanced Composition Explorer (ACE) and Wind spacecraft are referred to. The geocentric solar magnetospheric (GSM) coordinate system is used throughout.

3 Observations

Figure 1 presents an overview of MMS1 observations in the duskside magnetotail from 00:00 to 08:00 UT on August 4, 2017. For the first two hours, MMS1 remained in the lobe/mantle region in the northern hemisphere, which is characterised by a large B_X (Fig. 1a) and tailward plasma flows (Fig. 1f). CDPS observations continued for several hours between ∼02:00 and ∼07:00 UT. The omnidirectional ion energy-time (E-t) spectrogram illustrates the coexistence of high- and low-energy components (Fig. 1b), which is characteristic of the CDPS on the duskside under the northward IMF (Hasegawa et al., 2003; Wing et al., 2005; Nishino, Fujimoto, Ueno, Maezawa, et al., 2007). The electron E-t spectrogram (Fig. 1c) reveals that low-energy electrons (<1 keV) were the main component of the CDPS. The solar wind conditions and the characteristics of the CDPS from 02:00 to 07:00 UT will be examined in the following.

The ion density and temperature in the CDPS were ∼4–6 cm^{-3} and 0.4–0.7 keV, respectively (Fig. 1d and e). The parallel ion temperature is higher than the perpendicular ion temperature, which is consistent with previous statistical results (Nishino, Fujimoto, Ueno, Maezawa, et al., 2007). The plasma beta (β, the ratio of thermal pressure to magnetic pressure) in the CDPS was mainly between 1 and 10, which is characteristic of the central plasma sheet. The bulk speed of the ion flows in the CDPS was very low (typically, below 50 km/s), which is consistent with the previous statistical results for geomagnetically quiet periods (e.g., Angelopoulos et al., 1993).

Solar wind data from ACE (Fig. 2a–e) and Wind (Fig. 2f–j) illustrate that the CDPS in the dusk magnetotail formed during a prolonged northward IMF. After 21:00 UT on 3 August, the IMF pointed weakly northward, and then it turned strongly northward at around 01:00 UT on 4 August as both B_X and B_Y decreased. The IMF strength for the

northward IMF period was higher than 10 nT. As the solar wind density data from ACE are available only for limited periods, we also use the data from Wind. The ACE and Wind spacecraft locations at 01:00 UT (which roughly corresponds to 02:00 UT at the Earth's magnetosphere when the solar wind convection is considered) were (226, −21, −3) R_E and (234, 98, −14) R_E in the GSM coordinate system, respectively, where the Earth's radius (R_E) is defined as 6,378 km. The trends of the prolonged northward IMF and high-density solar wind plasma were observed at both the ACE and Wind locations. When MMS1 observed the CDPS in the magnetotail, the solar wind speed and density at ACE were ∼400 km/s and 20–40 cm^{-3}, respectively. The solar wind dynamic pressure was as high as 6–12 nPa, and the large temporal variation was attributed to the density fluctuations. The solar wind flow had relatively large azimuthal and latitudinal velocity components; a negative V_Y until ∼05:00 UT and a positive V_Z after ∼04:00 UT were detected. These solar wind characteristics indicate the passage of the corotational interaction region around the Earth's magnetosphere.

At around 01:58 UT when MMS1 was located at (−22.6, 9.6, 4.3) R_E in the GSM coordinate system, the spacecraft moved from the northern lobe/mantle region to the stagnant CDPS region. Now we examine the ion E-t spectrograms in the directions parallel (0°–30°), perpendicular (75°–105°), and anti-parallel (150°–180°) to the magnetic field (Fig. 3b–d). Throughout the period of the CDPS, both the parallel and anti-parallel fluxes in the low-energy range (< 3 keV) were higher than the perpendicular flux. This observation is consistent with Nishino et al.'s (2007a) report of parallel anisotropy of low-energy ions in the duskside CDPS under the strongly northward IMF.

In addition, we have found energy dispersions of low-energy ions in both the parallel and anti-parallel directions (indicated by black arrows in Fig. 3b and d) that typically started at 1–2 keV and ended at 0.1–0.3 keV. These energy-dispersed ions were detected on the closed field lines, which is evidenced by bi-directional distributions of the low-energy electrons (Fig. 3i and j). The path length of these energy-dispersed ions from the acceleration source to the observing location can be estimated by assuming the time-of-flight (TOF) effect (e.g., Kazama & Mukai, 2003). From the start of the CDPS observation (at 01:57 UT) until 02:30 UT, the typical duration of the energy dispersion in the parallel direction was ∼3 min (at 01:58, 02:18, 02:22, 02:23, and 02:27 UT). In the anti-parallel direction, faint energy dispersions with longer durations (∼15 min) were observed at around 02:17 UT and 02:27 UT. This signature may demonstrate that these ions were injected from the magnetotail plasma sheet toward the lower altitude region and came back toward the spacecraft by the mirror reflection. However, because the magnetic field direction changed within on a shorter timescale than the dispersion, we refrain from performing further analysis for this event.

We focus on the energy-dispersion event in the parallel direction between 02:23 and 02:26 UT (indicated by the thick arrow in Fig. 3b), when the dispersion signature was most obvious. As in previous studies (see Fig. 3 in Kazama and Mukai (2003) and Fig. 6 in Varsani et al. (2017)), we plot spectrograms of the reciprocal speed (V^{-1}) of the ions with respect to time (Fig. 4e and f). The reciprocal speed linearly increased from 02:23 to 02:26 UT, which is attributed to the TOF effect of the injected ions. By extrapolating the upper cutoff of the V^{-1}-t slope backward in time, the time of the injection is estimated to be around 02:22:30 UT. The path length (L) from the injection point to the spacecraft location is estimated as follows:

$$L = \frac{\Delta t}{(\Delta V)^{-1}} = \frac{120\,[\mathrm{s}]}{0.055\,[\mathrm{km^{-1}s}]} = 3.4\,R_E\ , \tag{1}$$

where 0.055 km^{-1}s was used as the upper cutoff of V^{-1} at 02:24:30 UT and 120 s was used as the traveling time, although the estimation errors are relatively large.

We further investigate the ion distribution function during the energy-dispersion event by making a two-dimensional slice in the plane including the local magnetic field

direction. When drawing the slice, the bulk velocity perpendicular to the local magnetic field was subtracted in the velocity space. A slice in the middle of the event between 02:24:29 and 02:24:34 UT reveals a cold ion beam parallel to the magnetic field (Fig. 5). The beam had a peak around 270 km/s with a lower energy cutoff at around 180 km/s at which the energy flux was roughly $1/e$ of the peak flux. The pitch angles of the beam ions were concentrated within 30°, with a broadened distribution up to 45°. The traveling time and path length from the injection point to the spacecraft location were estimated by a method described in Burch et al. (1982) that uses observed pitch-angle distributions and a geomagnetic field model. We compare the observed lower cutoff velocity of the energy flux with the theoretically calculated velocity, by modifying several injection points and traveling times, and adopting the T96 model (Tsyganenko & Stern, 1996) as the geomagnetic field. The black rectangles in Fig. 5 denote the lower cutoff estimated from the Burch's method under assumptions of a traveling time of 110 s and a path length of $3.3\,R_E$, for the pitch angles every 5° between 0° and 45°. Although this method was unable to generate exact traveling times and path lengths for this event, the estimated values correspond with the observed lower cutoff velocity and thus are consistent with those obtained from the V^{-1}-t spectrograms.

We use the T96 model to trace the magnetic field line to both the northern and southern polar regions. At 02:30 UT when MMS1 remained in the northern plasma sheet with a dominant positive B_X, the magnetic field line traced from the spacecraft's location toward the southern ionosphere crossed the neutral sheet $\sim 10\,R_E$ tailward of the spacecraft (Fig. 6). It is plausible that the ion beams in the parallel (earthward) direction emanated directly from the source, while the anti-parallel ion beams were reflected at lower altitudes in the northern hemisphere and returned to the magnetotail. The interval of the dispersive signatures in the parallel direction was roughly several minutes, and short dispersions in the parallel direction were more frequently detected than longer faint dispersions in the anti-parallel direction. This difference in detection frequencies could indicate a dependence on distance from the acceleration source.

We next examine the CDPS that was continuously observed a few hours after the strongly northward IMF came to the Earth's magnetosphere. Between 04:00–06:00 UT, MMS1 remained in the CDPS where longer energy dispersions were observed in both the parallel and anti-parallel directions (Fig. 7). The ions signatures were similar to those in the preceding period, while B_Z dominated the magnetic field. The magnetic field strength and ion density in the CDPS were about 20 nT and $5\,\mathrm{cm}^{-3}$, respectively, which gave a local Alfvén speed of $\sim$180 km/s.

We then focus on the energy dispersion event in the anti-parallel direction between 04:30 and 04:44 UT (Fig. 8). As in the previous event, a linear increase was revealed in the reciprocal speed of the energy-dispersed ions. By extrapolating the slope of the linear increase, we estimated that an ion injection event occurred at around 04:20 UT. Using the inclination of the slope, and the path length (L) was estimated to be $54\,R_E$ as follows:

$$L = \frac{\Delta t}{(\Delta V)^{-1}} = \frac{1200\,[\mathrm{s}]}{0.035\,[\mathrm{km}^{-1}\mathrm{s}]} = 54\,R_E\ . \tag{2}$$

The estimated path length indicates that the energy-dispersed ions were previously mirror reflected at lower altitudes.

Fig. 9a and b show two-dimensional slices of the ion distribution functions at 04:35:20 UT and 04:40:20 UT (also denoted by the dashed lines in Fig. 8). The bulk velocity perpendicular to the local magnetic field was subtracted from the original data. We focus on an observed ion beam in the anti-parallel direction corresponding to the energy dispersion in the E-t spectrogram. At 04:35:20 UT, the energy flux of this beam component had a peak around 490 km/s with an elongated shape in the perpendicular direction. The pitch angle of the ion beam ranged between 180° and $\sim$150° with a broadened distribution in a crescent-like form. We calculated lower cutoff velocities using the Burch's method for

several combinations of injection points and traveling durations to identify those with a good fit with the observed distribution functions. The estimated values are the injection point of $5\,R_E$ tailward of the MMS1 spacecraft and the injection event at 04:19:20 UT (i.e., a traveling time of 960 s). The rectangles in Fig. 9a denotes the cutoff velocities calculated for pitch angles at increments of 5° between 175° and 135° under the assumption of an injection point of $5\,R_E$ tailward of MMS1 along the magnetic field line and the injection event at 04:19:20 UT.

Five minutes later at 04:40:20 UT, there was a decrease in both peak and cutoff speeds to 340 km/s and 280 km/s, respectively. A combination of the same injection point as above and a traveling time of 1260 s gave cutoff velocities that well fitted the observations (Fig. 9b). This travelling time corresponds to the injection event at 04:19:20 UT, which roughly matches the event time estimated from the V^{-1}-t slope. The path length of the mirror reflected ions (i.e., from the injection source via the mirror point to the observed location) is strongly contingent on the pitch angle. A calculation of path length using the T96 model for a pitch angle of 175° at the MMS1 spacecraft gives $54\,R_E$, which is consistent with the estimation by the V^{-1}-t slope. These ions were mirror reflected at $(-0.72, 0.88, 2.6)\,R_E$ in GSM where the magnetic field strength was 2510 nT. On the other hand, the path length for a pitch angle of 150° was calculated to be $38\,R_E$: the location and the magnetic field strength of the mirror point were $(-6.7, 4.7, 5.2)\,R_E$ in GSM and 76 nT, respectively. The path length in this estimation is dependent solely on the location of the mirror point, as the same injection point is assumed for all pitch angles. We assumed that the pitch angle is precisely equal to 180° when the path length from the V^{-1}-t slope in the anti-parallel direction was estimated. No contradiction exists between the shorter path length estimated for a pitch angle of 150° and the entire scenario of the injection and mirror reflection.

It is likely that the energy dispersion of low-energy ions generally occurs in the well-developed CDPS several hours after the start of the strongly northward IMF. The CDPS dominated by B_Z is consistent with the plasma sheet thickening and an increase in the total plasma content (Nishino et al., 2002; Fuselier et al., 2015). The prolonged presence of a large B_Z in the CDPS under the strongly northward IMF suggests that the magnetic field lines of the near-Earth magnetotail shifted from a tail-like shape to a less-stretched shape, which was reported in previous research by Petrukovich et al. (2003). If the large B_Z of the CDPS in this event is the result of the plasma sheet thickening under the strongly northward IMF, it is interesting to note that plasma sheet thickening and thus increased magnetotail plasma content are simultaneously observed with low-energy ion transport by injection.

For most of the time, the bulk ion speed in the CDPS was as low as ∼50 km/s, which is consistent with previous statistical results (e.g., Angelopoulos et al., 1993) and event studies (e.g., Fujimoto et al., 1998). We note that even when energy dispersion occurs, both the parallel and perpendicular velocities are low. In the velocity moment calculation, since the parallel and anti-parallel components negate each other, the low parallel velocity does not contradict the observed ion transport in the field-aligned direction.

4 Summary and Discussion

We identified energy-dispersed low-energy ions in the CDPS in the duskside magnetotail under the strongly northward IMF and analyzed injection points in two ways, that is, by assuming the TOF effect and by using information of pitch angle dispersions. During the first event, the energy-dispersed ions in the direction parallel to the magnetic field were deemed to have originated from the tail flank plasma sheet several R_E tailward of the MMS1 spacecraft's location. During the second event, a longer duration of the ion energy dispersion in the anti-parallel direction was evident, which indicates that these ions once

traveled along the magnetic field toward the ionosphere and were mirror reflected at a low altitude back to the magnetotail plasma sheet.

The energy-dispersed ions in the field-aligned directions are not inconsistent with the stagnant plasma flows in the CDPS under the northward IMF. This is because the ion velocities in the parallel and anti-parallel directions were negated and thus did not exist in the bulk velocity, i.e., the low bulk velocity obtained from the moment calculation did not necessarily indicate the dominance of diffusive plasma transport.

The observed energy dispersions mean that some acceleration mechanisms would work in the tail flank region. Possible candidates for the acceleration mechanism of the energy-dispersed ions are (1) magnetic reconnection in well-developed Kelvin-Helmholtz vortices (e.g., Takagi et al., 2006; Nishino, Fujimoto, Ueno, Mukai, & Saito, 2007; Nakamura et al., 2017), (2) tension force of the closed magnetic field lines (Fujimoto et al., 1996), and (3) additional mechanisms including small magnetic reconnection in the turbulent plasma sheet (Borovsky & Funsten, 2003).

During the events reported in this study, the magnetopause under the strongly northward IMF was likely to be Kelvin-Helmholtz unstable to generate vortical structures flowing tailward. The intervals of energy dispersive signatures were a few to several minutes, which is similar to the period of the Kelvin-Helmholtz vortices in the magnetotail flanks (e.g., Nishino et al., 2011). In previous studies, ion beams observed in the LLBL under the northward IMF have been interpreted in the context of Kelvin-Helmholtz instability (Nishino, Fujimoto, Ueno, Mukai, & Saito, 2007; Taylor & Lavraud, 2008). Stenuit et al. (2001, 2002) reported the detection of energy-dispersed ions in the LLBL at the low-altitude region under the northward IMF, and suggested that Kelvin-Helmholtz instability at the tail magnetopause is related to the generation of energy-dispersed ions. The speed of the ion beams in the LLBL that were possibly accelerated inside the Kelvin-Helmholtz vortices is estimated to be in the order of the reconnection Alfvén speed (e.g., Ma et al., 2017). The LLBL was not detected directly in this study, but the local Alfvén speed in the CDPS was around 180 km/s (for a density of $5\,\mathrm{cm}^{-3}$ and a magnetic field strength of 20 nT), which is below the observed maximum speed of the energy-dispersed ions (typically, 400–500 km/s). However, if magnetic reconnection occurs in the lower density region closer to the plasma sheet boundary layer, the higher Alfvén speed may explain the maximum speed of the ion beams.

A scenario of the tension force of the closed field lines in the LLBL or in the CDPS adjacent to the LLBL is considered. The closed field lines in the LLBL/CDPS are stretched tailward by viscous interactions with the magnetosheath plasma, and finally return toward the Earth by the magnetic tension force (Fujimoto et al., 1996). This process may accelerate the ions toward the Earth and would be evidenced by the occurrence of fast bulk flows. However, because fast earthward flows were undetected by MMS during the events in this study, it is unlikely that magnetic tension force is instrumental in generating the observed energy-dispersed structures.

Considering the origins of the cold-dense plasma, although double-lobe reconnection is the most plausible mechanism for capturing the magnetosheath plasma into the Earth's magnetosphere, formation of the lobe/mantle region is also a potential candidate for the entry process. MMS1 data before 01:58 UT confirm the entry of large amounts of cold ions into the magnetotail via the lobe/mantle region during the northward IMF with an enhanced IMF B_Y. It is possible that the low-energy ions from the lobe/mantle region are the partial source of the energy-dispersed ions detected in the plasma sheet after 01:58 UT, since the detection of the CDPS by MMS1 started in the outer plasma sheet close to the northern lobe, as indicated by the large B_X component.

We discuss the possible relationship between energy-dispersed ions and the magnetosphere-ionosphere coupling under the northward IMF. Stenuit et al. (2002) proposed a connection

between the energy-dispersed ions at a low altitude and the Kelvin-Helmholtz instability at the tail magnetopause and demonstrated outflows of ionospheric oxygen ions under the northward IMF. Wang et al. (2019) examined the CDPS events observed by MMS in the magnetotail and DMSP-F18 in a low-altitude orbit and found increases in the density of oxygen ions (O^+) of ionospheric origin at both locations under the northward IMF. Their research revealed signatures of kinetic Alfvén waves that are capable of accelerating electrons in the field-aligned direction, and they discussed that observed electrons injected from the magnetosphere into the ionosphere playing a key role in the outflow of oxygen ions from the ionosphere to the CDPS. The events in the current study was also analyzed by Wang et al. (2019), i.e., the energy-dispersed ions in the CDPS coincided with the increase in the oxygen ions from the ionosphere. It is worth noting that both kinetic Alfvén waves and ion injection can be caused by magnetic reconnection in the Kelvin-Helmholtz vortices. The major carrier of field-aligned current may be electrons accelerated by kinetic Alfvén waves, which is consistent with the present study's observation of the low ion bulk speed in the parallel direction. Yokoyama et al.'s (2020) recent observational study analyzed low-altitude satellite data and proposed a generation mechanism of mesoscale field-aligned currents in the LLBL on the duskside during northward IMF periods. Their observation of the 630-nm auroral emission in the upward field-aligned current regions indicates that the major carrier of the field-aligned currents under the northward IMF is electrons precipitating into the ionosphere. However, because the present study was conducted for the stagnant CDPS and not for the LLBL with tailward flows, further investigations are required.

The energy dispersion of the low-energy ions in the current study occurred under a condition of high-density solar wind. Although the effect of solar wind density on the occurrence of the energy dispersion of the low-energy ions remains unclear, other CDPS events with ion energy dispersion under conditions of the strongly northward IMF and moderate solar wind density (data not shown here) have been identified. Therefore, the authors consider that the field-aligned transport of low-energy ions in the near-Earth plasma sheet generally occurs under the strongly northward IMF. However, further study is required into detailed mechanisms of ion acceleration under the strongly northward IMF and plasma transport under the weakly northward IMF. Further research will also explore the low-energy ion signatures in the CDPS in the dawn magnetotail as well as in the dawn LLBL under the strongly northward IMF.

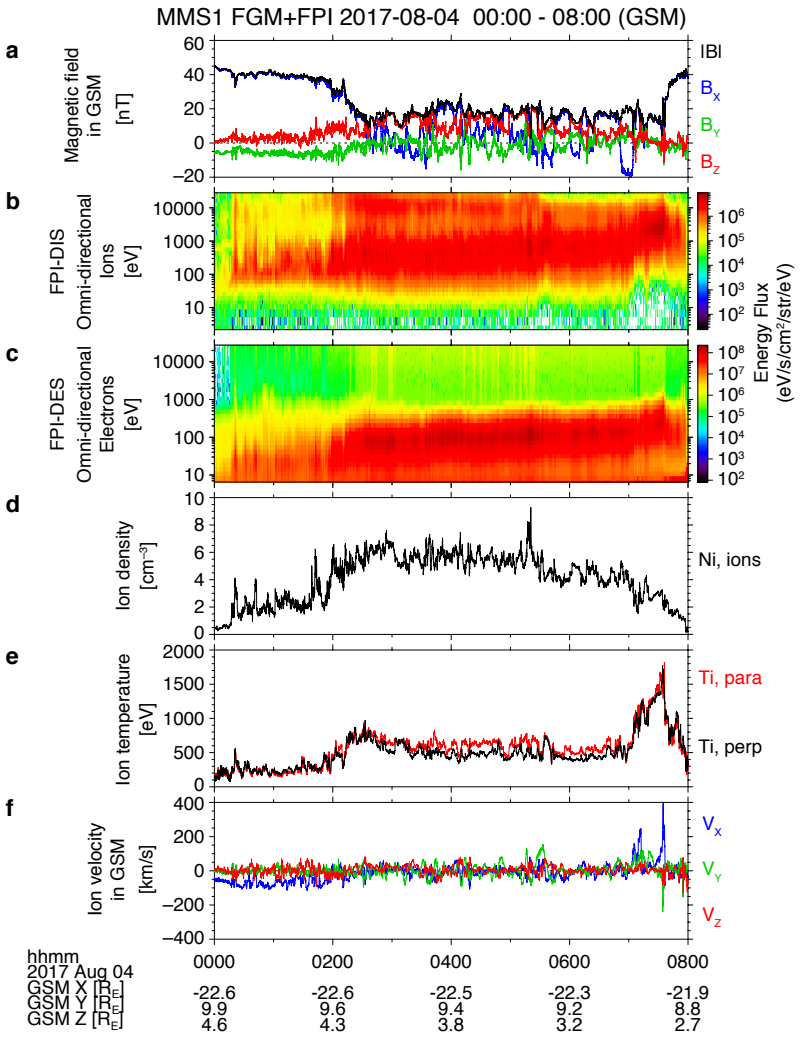

Figure 1. An overview of MMS1 observations between 00:00–08:00 UT on August 4, 2017. From the top: (a) magnetic field, (b) omnidirectional ion energy-time spectrogram, (c) omnidirectional electron energy-time spectrogram, (d) ion density, (f) parallel (red) and perpendicular (black) ion temperatures, and (g) ion velocity.

Acknowledgments

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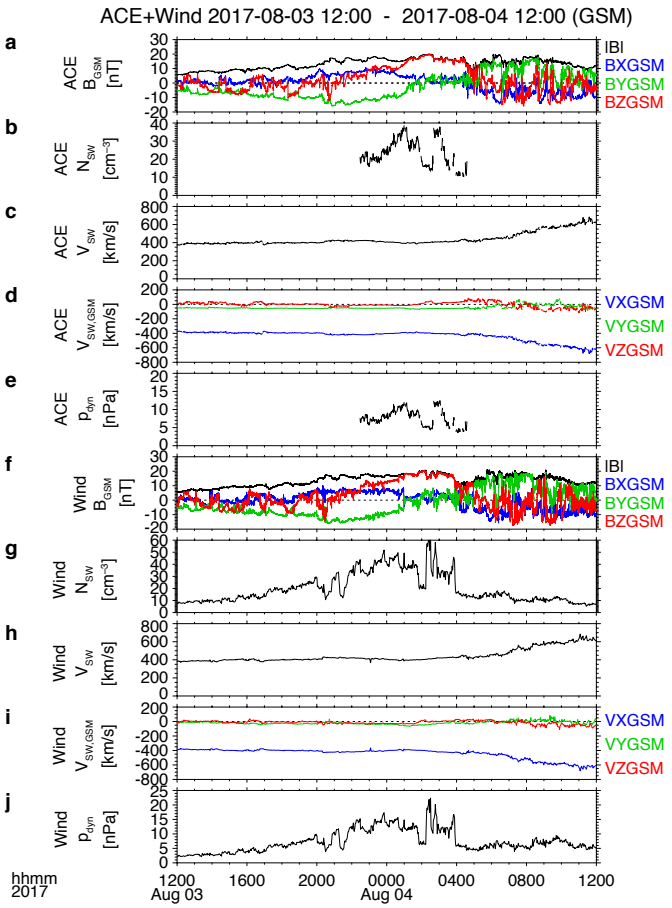

Figure 2. Solar wind data from ACE and Wind for 24 hours from 12:00 UT on August 3, 2017. From the top, (a) magnetic field, (b) ion density, (c) ion bulk speed, (d) ion flow vector, and (e) dynamic pressure from ACE. (f-j) Data from Wind are plotted in the same format as the ACE data.

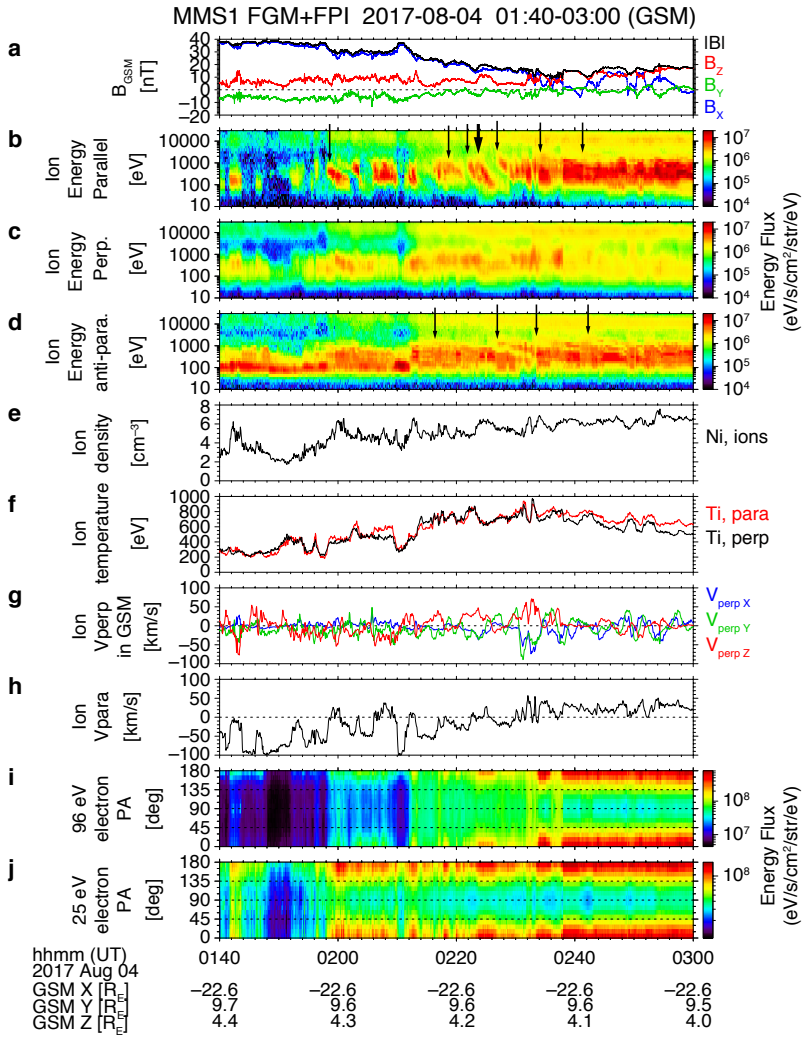

Figure 3. MMS1 observations between 01:40–03:00 UT on August 4, 2017. (a) Magnetic field, (b-d) ion energy-time spectrograms parallel, perpendicular, and anti-parallel to the magnetic field, (e) ion density, (f) ion parallel and perpendicular temperatures, (g) bulk ion velocity in the direction perpendicular to the local magnetic field, (h) bulk ion velocity in the parallel direction, (i) 96-eV electron pitch-angle distribution and (j) 25-eV electron pitch-angle distribution. Each arrow in the ion energy-time spectrograms indicates the beginning of energy dispersion. The thick arrow corresponds to the dispersion event analysed in detail in the main text.

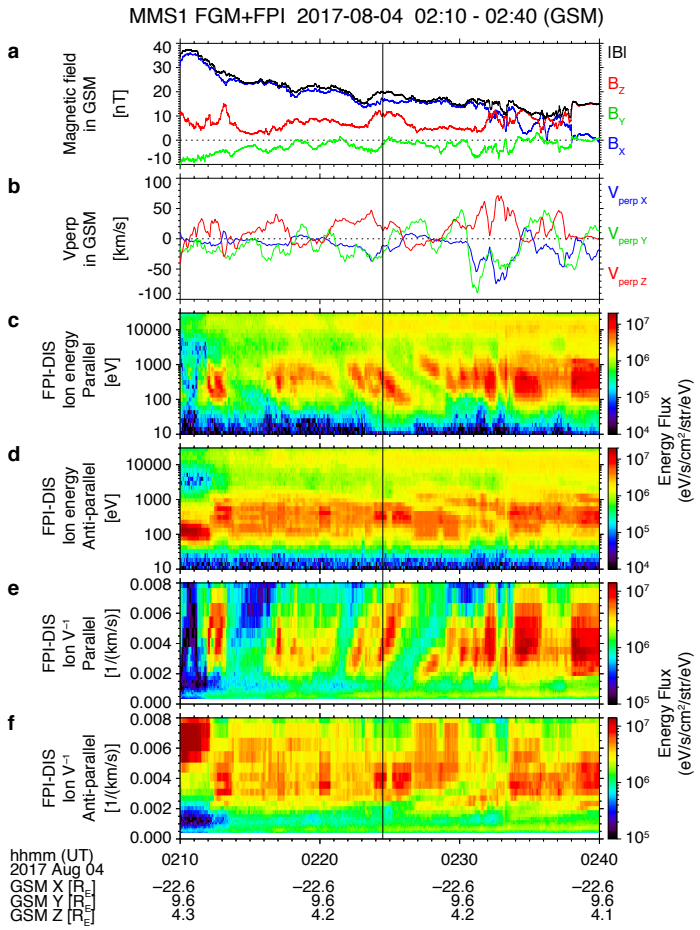

Figure 4. Energy-time spectrograms and reciprocal speed (V^{-1})-time spectrograms between 02:10–02:40 UT. (a) Magnetic field, (b) bulk ion velocity perpendicular to the magnetic field, (c and d) ion E-t spectrograms parallel and anti-parallel to the magnetic field, (e and f) reciprocal speed-time spectrograms in parallel and anti-parallel directions. A vertical dashed line marks the time when a two-dimensional slice of ion distribution function in Fig. 5 was taken.

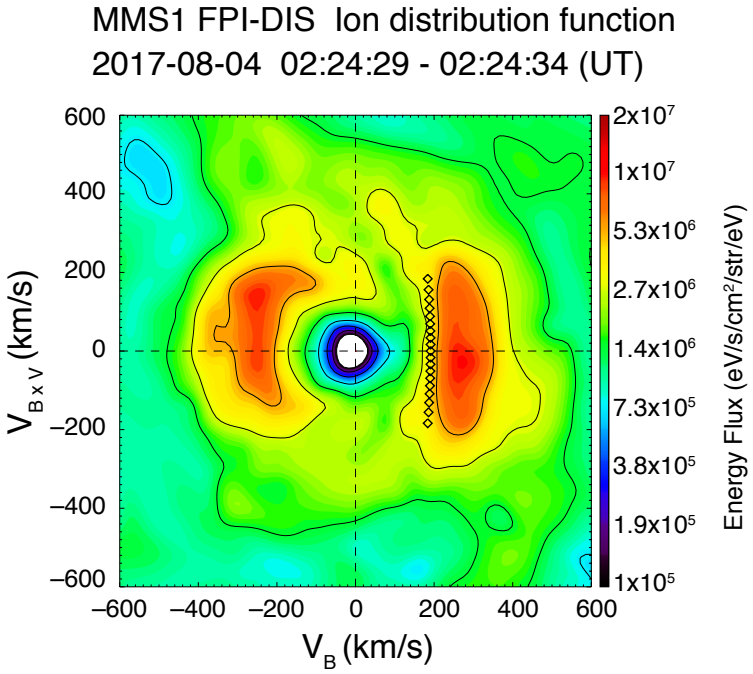

Figure 5. Two-dimensional slice of ion distribution function between 02:24:29–02:24:34 UT. The horizontal axis is the local magnetic field direction. The black rectangles show the lower cutoff of the distribution function of the ion beam for the pitch angles every 5° from 0° to 45° calculated using the Burch's method (Burch et al., 1982).

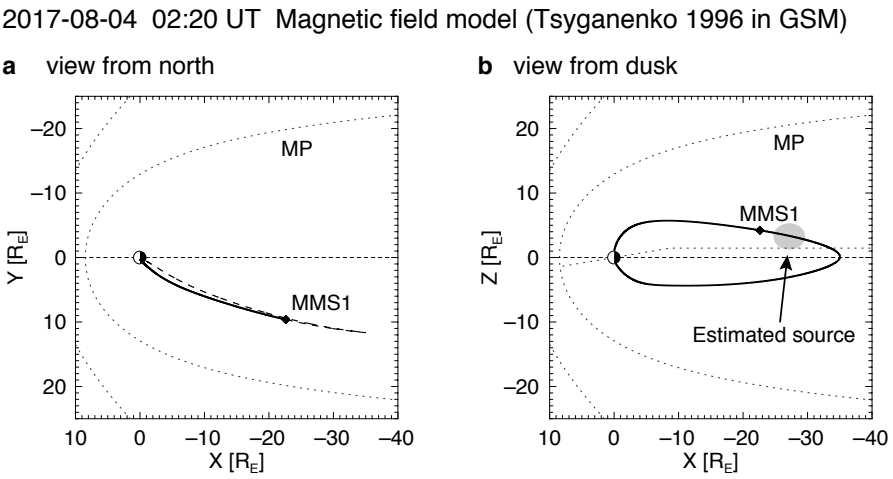

Figure 6. Traced magnetic field line at MMS1 using the T96 model at 02:20 UT. In the left panel, a solid (dotted) curve shows the magnetic field line traced from the MMS1 location toward the northern (southern) polar region. A dotted parabolic curve indicated by 'MP' is the modelled magnetopause location under a high solar wind dynamic pressure of 7.0 nPa (Shue et al., 1998). A gray region illustrates a roughly estimated source of the energy-dispersed ions.

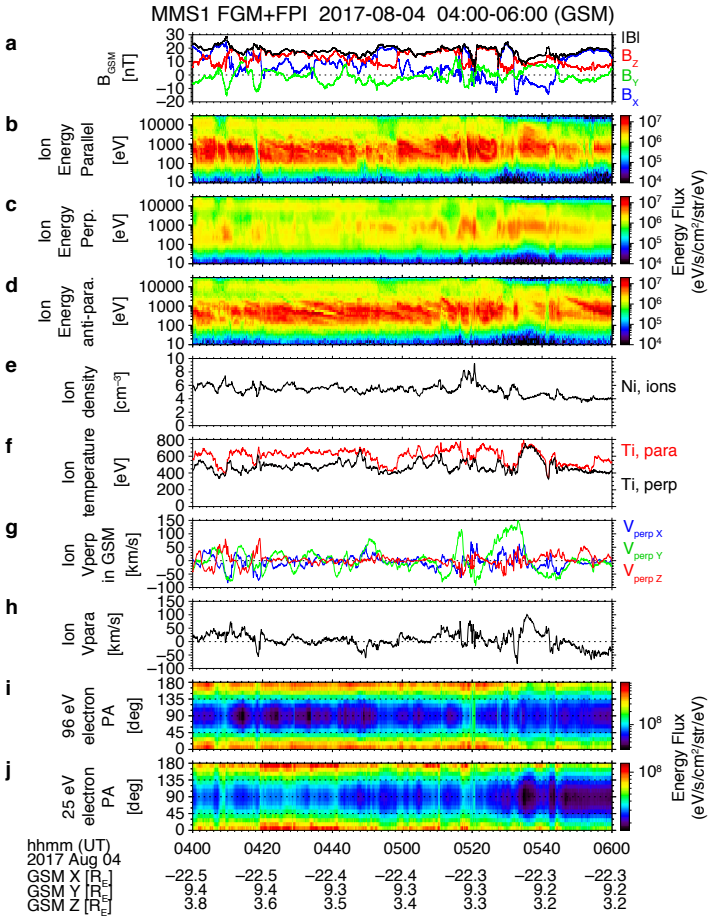

Figure 7. MMS1 observations between 04:00–06:00 UT on August 4, 2017 in the same format as Fig. 3.

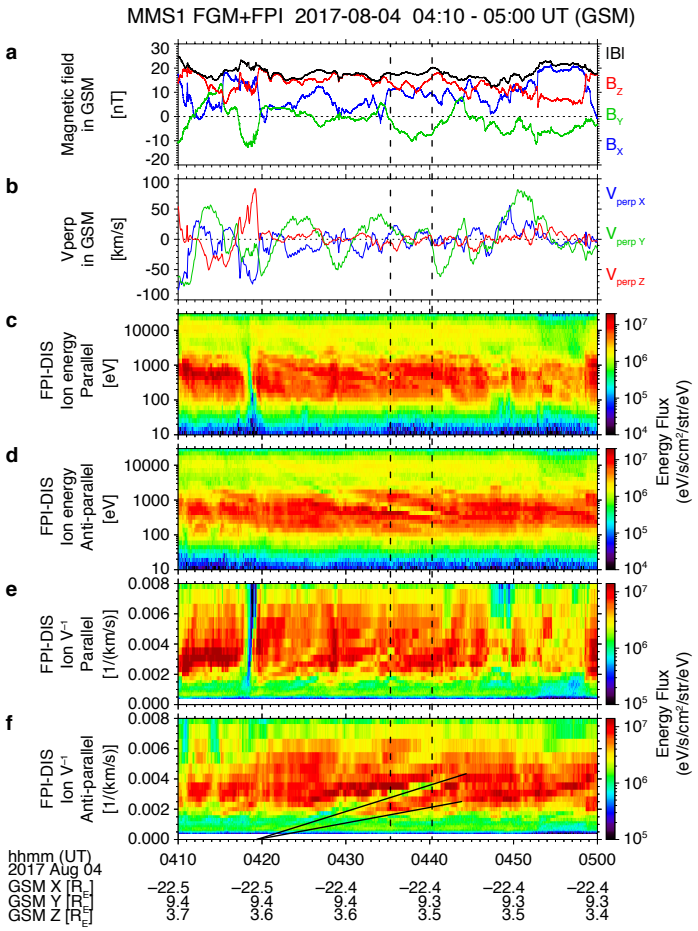

Figure 8. MMS1 data between 04:10–05:00 UT in the same format as Fig. 4. Two vertical lines correspond to the data presented in Fig. 9.

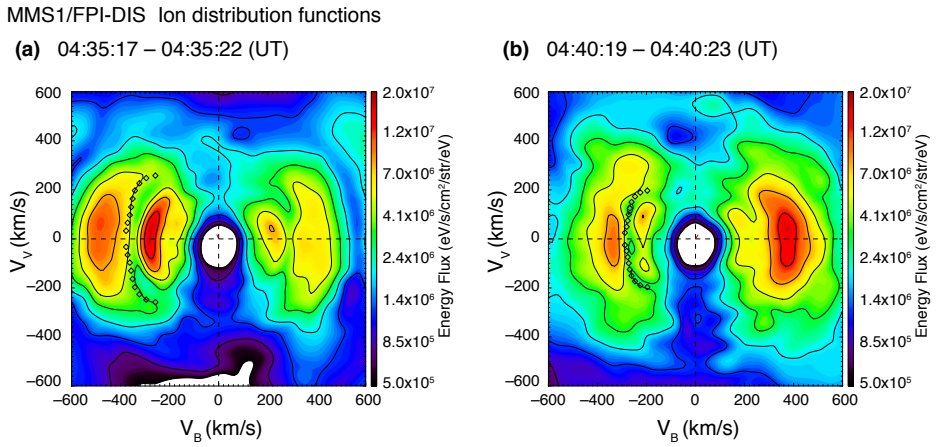

Figure 9. Two-dimensional slices of the ion distribution functions (a) between 04:35:17–04:35:22 UT and (b) between 04:40:19–04:40:23 UT. The black rectangles show the lower-energy cutoff of the distribution function of the ion beam for the pitch angles every 5° from 175° to 135° calculated using the Burch's method (Burch et al., 1982).

MMS data are available from https://lasp.colorado.edu/mms/sdc/public/. Solar wind data from ACE and Wind were provided by NASA's CDAWeb (https://cdaweb.gsfc.nasa.gov/). Data analysis was performed using SPEDAS V3.1 (see Angelopoulos et al. (2019) in detail).

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