

Abstract

Flux transfer events (FTEs) are a type of magnetospheric phenomena that exhibit distinctive observational signatures from the in-situ spacecraft measurements across the Earth’s magnetopause. They are generally believed to possess a magnetic field configuration of a magnetic flux rope and formed through magnetic reconnection at the dayside magnetopause, sometimes accompanied with enhanced plasma convection in the ionosphere. We examine two FTE events under the condition of southward interplanetary magnetic field (IMF) with a dawn-dusk component at the magnetopause by applying the Grad-Shafranov (GS) reconstruction method to the in-situ measurements by the Magnetospheric Multiscale (MMS) spacecraft to derive the magnetic flux contents associated with the FTE flux ropes. In particular, given a cylindrical magnetic flux rope configuration derived from the GS reconstruction, the magnetic flux content can be characterized by both the toroidal (axial) and poloidal fluxes. We then estimate the amount of magnetic flux (i.e., the reconnection flux) encompassed by the area “opened” in the ionosphere, based on the ground-based Super Dual Auroral Radar Network (SuperDARN) observations. We find that for event 1, the FTE flux rope is oriented in the approximate dawn-dusk direction, and the amount of its poloidal magnetic flux agrees with the corresponding reconnection flux. For event 2, the agreement among the estimates of the magnetic fluxes is uncertain. We provide a detailed description about our interpretation for the topological features of the FTE flux ropes, based on a formation scenario of sequential magnetic field reconnection between adjacent field lines, consistent with our results.

Plain Language Summary

The outer boundary of the Earth’s own magnetic field extends into space and is shaped by the constant outflow of ionized particles from the Sun, i.e., the so-called solar wind, into a bullet shape. The blunt side facing the Sun is called the dayside magnetopause where the Sun’s magnetic field carried along by the solar wind interacts with the Earth’s magnetic field. Under the condition of the Sun’s magnetic field possessing a southward component, the interaction becomes more intense and energetic, often leading to a continuous change of topology/connectivity between the two fields. Such a process, dubbed magnetic reconnection, is also accompanied with enhanced particle motion, of which signatures can manifest in the in-situ spacecraft measurements. Correspondingly such enhanced disturbances may map nearly simultaneously along the Earth’s magnetic field lines onto the Earth’s upper atmosphere and observed by the ground-based radars. By analyzing and correlating these observations at different but inter-connected sites, we carry out a study to characterize and relate the physical quantity of magnetic flux accumulated through the reconnection process. We also illustrate in detail the formation of one type of commonly associated magnetic field structure at the dayside magnetopause.

1 Introduction

Flux transfer events (FTEs) are recognized as signatures of intermittent magnetic reconnection from in-situ spacecraft measurements during the crossings of the Earth’s magnetopause (Russell & Elphic, 1978; Elphic, 1990; Zhang et al., 2022). They generally possess the signatures of bipolar magnetic field component in the direction normal to the local plane of the magnetopause current sheet, and sometimes elevated magnetic field magnitude and bursty plasma flows. The polarity of this normal field component follows certain pattern with respect to the locations of their occurrence, owing to the nominal field directions across the magnetopause. They have typical duration around 1 minute and occur most often and sometimes repeatedly under the southward interplanetary magnetic field (IMF) or magnetosheath magnetic field (shocked IMF) conditions. Additional plasma and particle signatures support the generation mechanism of magnetic reconnection.

tion and the magnetic field topology of a magnetic flux rope (Elphic, 1990; Raeder, 2006; Hasegawa, 2012; Guo et al., 2021) for FTEs. Interestingly, in Elphic (1990), it was indicated that “What Russell and Elphic [1978] suggested, in effect, was a magnetopause analog to solar flares”. For solar flares, magnetic reconnection always plays a critical role, often leading to the formation of magnetic flux ropes on the Sun (Forbes & Lin, 2000; Forbes et al., 2006; Chen, 2011). We will further digress on this aspect and offer our view on this analogy with greater details in Section 4. In this aspect for FTEs at the Earth’s magnetopause, a flux rope topology is conceived to be formed through the process of single or multiple X line reconnection (Fear et al., 2017; Lee & Fu, 1985; Hasegawa et al., 2010). For the latter, the flux rope may possess a more pronounced non-vanishing axial field component, thus exhibiting a configuration of helical magnetic field lines (e.g., Fu et al., 1990).

Magnetic flux ropes are a common and important type of structures occurring across space plasma regimes and magnetic reconnection is believed to play a major role in the formation of flux ropes (Russell et al., 1990). They are observed on the Sun, in the interplanetary space, at the Earth’s magnetopause, as well as in the magnetotail, from both in-situ and remote-sensing observations. In particular, for the in-situ spacecraft measurements, the Grad-Shafranov (GS) reconstruction method has been widely applied to derive the configuration of magnetic flux ropes in various space plasma regimes and with a wide range of scale sizes, including FTEs at the Earth’s magnetopause (Hasegawa, 2012; Hu, 2017). In these applications to FTEs, the method has been validated by using multi-spacecraft measurements and the results were interpreted in the context of approximately two and a half dimensional ($2\frac{1}{2}$ -D) flux ropes formed through magnetic reconnection (Hasegawa et al., 2004; Hasegawa et al., 2006). In Hasegawa et al. (2006), two groups of possibly recurring FTEs were examined by the optimal GS reconstruction technique by employing multiple Cluster spacecraft datasets, which enabled the most accurate characterization of the FTE flux rope configurations. It was found that the cross section size of an FTE flux rope can reach the order of ~ 1 Earth radius (R_E), and they all possess a strong core (axial) field. The results indicated consistency with the usual single-spacecraft based GS reconstruction results. In addition, the flux contents of the FTE flux ropes were also quantified, in terms of the axial flux and the “total transverse magnetic flux” (equivalent to the poloidal flux as we refer later). Most noteworthy, those authors were able to derive the reconnection rate (in the order of < 0.1 in normalized unit) for the FTE formation based on the realization that the “total reconnected flux” is equal to the poloidal flux of the flux rope. Part of their analysis result is to be cited in Section 3 for reference. Another inspiration is the series of recent works by Zou et al. (2022, 2021, 2018), albeit not directly addressing FTEs. Those authors have carried out detailed and correlated analysis of both in-situ spacecraft measurements and ground-based observations under the “space-ground conjunction”. The dayside magnetopause reconnection processes were studied especially in terms of the reconnection rates at the conjugate sites of reconnected field lines with one end connecting to the ionosphere. In the present study, we also seek out events of such conjunctions with correlated in-situ and ground-based observations, but focus on the utilization of single-spacecraft dataset to derive the critical parameters for FTE flux ropes in order to correlate with the associated physical quantities derived from the corresponding radar observations in the ionosphere. We intend to further elucidate the process of magnetic reconnection at the magnetopause, leading to the formation of FTE flux rope in detail, from a topological point of view.

FTEs have also been studied by using optical/radar observations in addition to in-situ spacecraft measurements. Poleward Moving Auroral Forms (PMAFs) are a type of auroral structure that is observed remotely and occurs in the ionosphere (Vorobev et al., 1975; Sandholt et al., 1986). PMAFs are caused by the reconnection of magnetic field lines in the magnetosphere and the magnetosheath or the boundary layers across the magnetopause, which process forms FTEs. The ionospheric signatures of FTEs through mapped field lines from the magnetopause to the ionosphere can be observed optically as PMAFs.

124 There are corresponding signatures occurring at the footprints of newly opened magnetic
 125 field lines and are characterized by a poleward motion of the associated plasma struc-
 126 tures (Hwang et al., 2020). Such a connection was made by using both in-situ spacecraft
 127 measurements of an FTE at the magnetopause and the corresponding radar and camera
 128 observations in the ionosphere with enhanced plasma convection and auroral struc-
 129 tures near the conjugate sites that map to the FTE location (Elphic et al., 1990; Wild
 130 et al., 2003). The Super Dual Auroral Radar Network (SuperDARN) observations (Greenwald
 131 et al., 1995; Chisham et al., 2007; Nishitani et al., 2019) have been used to analyze the
 132 motion and estimate the area “opened” by such a magnetic reconnection process. For
 133 example, some previous studies (Lockwood et al., 1990; Milan et al., 2000) inferred the
 134 latitudinal and longitudinal extents of “opened” magnetic field region using radar and
 135 auroral observations. In turn, a connection can be made between the FTE formation at
 136 the magnetopause and the corresponding signatures in the ionosphere. In particular, cer-
 137 tain amount of flux for the reconnected field (hence the reconnection flux) can be esti-
 138 mated by using the radar observations to provide a quantitative characterization that
 139 can be compared with the corresponding FTE fluxes (Marchaudon, Cerisier, Bosqued,
 140 et al., 2004; Marchaudon, Cerisier, Greenwald, & Sofko, 2004; Oksavik et al., 2005; Fear
 141 et al., 2017). It was summarized by Fear et al. (2017) that the range of magnetic flux
 142 contents for the conjugate FTE events is approximately between 1 and 77 MWb.

143 In this study, we follow the overall approach of Fear et al. (2017), especially for an-
 144 alyzing the radar observations, but instead applying the GS reconstruction method to
 145 the in-situ spacecraft measurements of FTEs, in order to estimate the magnetic flux con-
 146 tents associated with FTE formation processes. We describe the data source and meth-
 147 ods employed in Section 2. The results for two events from the analysis of both in-situ
 148 spacecraft measurements and the associated radar observations are presented in Section 3.
 149 Based on these analysis results, we offer an interpretation for the FTE formation pro-
 150 cess at the magnetopause in Section 4 solely from the viewpoint of topological change
 151 of magnetic fields. Finally we conclude and discuss the implications and uncertainties
 152 associated with this analysis.

153 2 Data and Methods

154 Following Fear et al. (2017), we utilize both in-situ spacecraft measurements, pri-
 155 marily from the Magnetospheric Multiscale (MMS) spacecraft, at the magnetopause and
 156 the corresponding SuperDARN observations in the ionosphere to carry out the quanti-
 157 tative analysis of the magnetic flux contents associated with the FTE flux ropes and the
 158 reconnection flux “opened” in the polar region of the ionosphere. The MMS mission is
 159 a constellation of four spacecraft to study the Earth’s magnetosphere and the important
 160 process of magnetic reconnection through in-situ measurements of magnetic field and par-
 161 ticle populations. The magnetic field data are gathered through the use of a fluxgate mag-
 162 netometer (Russell et al., 2016), with a sampling rate of 128 Hz. The Fast Plasma In-
 163 vestigation (FPI) instrument (Pollock et al., 2016) is used to obtain the ion and electron
 164 distribution functions and to derive their associated moments. Only data obtained in
 165 burst mode are utilized in this study and are in the Geocentric Solar Magnetospheric
 166 (GSM) coordinate system from the MMS1 spacecraft.

167 SuperDARN is a global network of scientific radars located in both the Northern
 168 and Southern Hemispheres. The SuperDARN radar data are used to map high-latitude
 169 plasma convection and to display back scatter power and Doppler velocity for a selected
 170 beam along a particular line of sight in this study. The convection map is generated from
 171 the improved model of Thomas and Shepherd (2018) (TS18 model). The technique uses
 172 data from all the SuperDARN stations in one hemisphere and data from a statistical model
 173 for regions without real-time radar observations. We follow closely the procedures given
 174 by Fear et al. (2017) for quantifying the amount of flux in the polar cap region “opened”
 175 by the magnetic reconnection associated with the corresponding FTE formation at the

176 magnetopause. Namely, the longitudinal and latitudinal extents of the area “opened”
 177 are estimated by the extents of the enhanced plasma convection velocities and the pole-
 178 ward propagation of the enhanced back scatter power, respectively. The expansion of
 179 the enhanced radar scatter power is considered equivalent to the signatures of PMAFs
 180 in our analysis.

181 To characterize the magnetic flux contents of an FTE flux rope, we take a differ-
 182 ent and unique approach by employing the Grad-Shafranov (GS) reconstruction method
 183 based on in-situ data. The GS method has been applied to examine the magnetic field
 184 structures of FTEs at the Earth’s magnetopause (Sonnerup et al., 2004; Hasegawa et al.,
 185 2004; Hasegawa et al., 2006; Hasegawa, 2012; Hu, 2017), in the form of a cylindrical flux
 186 rope configuration composed of nested flux surfaces with arbitrary (2D) cross sections.
 187 Through this approach, the critical parameters characterizing a flux rope structure can
 188 be derived quantitatively, including the magnetic flux contents.

189 The GS reconstruction method employs the GS equation in a Cartesian coordinates
 190 which governs the magnetic flux function $A(x, y)$ in a 2D geometry (i.e., $\partial/\partial z = 0$),

$$\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = -\mu_0 \frac{dP_t(A)}{dA}. \quad (1)$$

191 Here, due to the invariance along the z dimension (z being the cylindrical axis), the mag-
 192 netic field components are determined by the scalar magnetic flux function, via, $B_x =$
 193 $\partial A/\partial y$, $B_y = -\partial A/\partial x$, and $B_z = B_z(A) \neq 0$. On the right-hand side, the total deriva-
 194 tive with respect to A involves the so-called transverse pressure $P_t(A) = p(A) + B_z^2(A)/2\mu_0$,
 195 which is a single-variable function of A and the sum of the plasma pressure and the ax-
 196 ial magnetic pressure. Therefore a solution $A(x, y)$ to the GS equation fully character-
 197 izes a cylindrical magnetic field configuration with all three field components including
 198 the non-vanishing axial component known over the cross-section plane perpendicular to
 199 the z axis.

200 The GS reconstruction procedures proceed by integrating the flux function from
 201 the initial spacecraft path at $y = 0$ where the initial values are known from the space-
 202 craft measurements once an optimal z axis orientation is determined (Hu & Sonnerup,
 203 2002) together with a proper frame of reference in which the structure is in approximate
 204 magnetohydrostatic equilibrium. The reference frame is chosen as the deHoffmann-Teller
 205 (HT) frame with the frame velocity \mathbf{V}_{HT} which is determined from the magnetic field
 206 and plasma velocity measurements (Paschmann & Sonnerup, 2008; Khrabrov & Sonnerup,
 207 1998). The quality of the HT frame is assessed by a correlation coefficient cc_{HT} (1 be-
 208 ing ideal) and the Walén test slope (0 being ideal). The latter evaluates the relative mag-
 209 nitude of the remaining plasma flow in the HT frame with respect to the local Alfvén
 210 speed. One essential step involves an analytic function fitting to the quantities P_t ver-
 211 sus A in order to make the right-hand side of the GS equation (1) explicitly known, i.e.,
 212 by obtaining an analytic functional form $P_t(A)$ through curve fitting. The same proce-
 213 dure is applied for obtaining $B_z(A)$. The end result is a 2D array of $A(x, y)$ over a rect-
 214 angular domain, together with the distribution of B_z . Thus all three components of the
 215 magnetic field are obtained as functions of (x, y) . In addition to a number of standard
 216 output quantities, the solution can be specifically utilized to calculate the axial (toroidal)
 217 magnetic flux Φ_z and the poloidal magnetic flux Φ_p of a flux rope configuration in a pre-
 218 cise way (Qiu et al., 2007; Hu et al., 2014):

$$\Phi_z = \int_S B_z dS, \quad (2)$$

219 and

$$\Phi_p = |A_m - A_b| \cdot L = \phi_p \cdot L. \quad (3)$$

220 Here an area S is chosen over the cross section plane, within which the axial flux can be
 221 summed up for the central region of a magnetic flux rope. A physical choice of the bound-
 222 ary for such an area is $A = A_b$ based on the $P_t(A)$ or $B_z(A)$ fitting, which indicates

Table 1. Event parameters for the two FTEs and the corresponding GS reconstructions.

Event	1	2
Date	27 November 2016	19 December 2016
Time interval (UT)	08:39:08 - 08:40:05	09:15:40 - 09:17:46
MMS1 location (GSM) [R_E]	(10.3, 3.6, -1.4)	(11.8, 1.8, 0.3)
Optimal z axis (GSM)	(-0.161, 0.825, 0.542)	(0.057, 0.064, -0.996)
HT frame velocity [km/s]	(-93, 212, -114)	(-22, 92, -48)
Walén test slope	-0.19	-0.28
cc_{HT}	0.89	0.72
Chirality	right-handed	left-handed
Axial flux Φ_z [MWb]	3.4	5.3
Unit poloidal flux ϕ_p [MWb/ R_E]	0.684	0.763

223 that the solution within this boundary (as highlighted by the white contour in Figure 3a)
 224 is judged to satisfy the GS equation under certain threshold conditions (e.g., for a fit-
 225 ting residue of $P_t(A)$, $R_f \ll 1$). In this way, a boundary is specified by a flux surface
 226 that has an arbitrary cross section shape resulting in a truly 2D structure, as we will il-
 227 lustrate in the following event studies, based on in-situ spacecraft data.

228 More straightforwardly, owing to the definition of the flux function for a 2D geom-
 229 etry, the flux function A itself directly characterizes distinct flux surfaces. The differ-
 230 ence in A between a pair of such distinct surfaces represents the amount of unit poloidal
 231 flux ϕ_p enclosed by a rectangular area intercepting and bounded by these two surfaces
 232 with a unit axial length in the z dimension. Therefore for a flux rope of axial length L
 233 and a boundary at $A = A_b$, the amount of poloidal flux is given by equation (3) where
 234 the flux function value at the center of the flux rope (corresponding to the extremum
 235 in A inside the flux rope boundary) is denoted A_m .

236 3 Analysis Results

237 3.1 Event 1: 27 November 2016

238 Figure 1 shows an overview plot of the in-situ measurements from MMS1 over a
 239 ~ 12 hour time period on 27 November 2016. It shows mostly typical magnetosheath
 240 conditions but with a final transition into the magnetosphere around 16:00 UT. The FTE
 241 interval, based on the event list provided by Fargette et al. (2020), is marked in the top
 242 panel, which has a duration ~ 1 minute. The zoomed-in FTE interval is shown in Fig-
 243 ure 2 with the same set of panels, but for a much shorter time period surrounding the
 244 interval selected for the GS reconstruction. Such an interval, as marked, shows clear sig-
 245 natures for a possible magnetic flux rope structure. The magnetic field magnitude is rel-
 246 atively stronger than the surrounding field, and two field components, B_Z and B_X , show
 247 gradual rotations, while the B_Y component is unipolar and is significant in magnitude.
 248 The plasma β value decreases below 1.0 near the central portion of the interval. These
 249 magnetic field signatures hint at a magnetic flux rope configuration. The structure is likely
 250 oriented horizontally in the dawn-dusk direction at the magnetopause, given the space-
 251 craft location and the relative spacecraft path across such a structure along the $-\mathbf{V}_{HT}$
 252 direction, as listed in Table 1. Figure 2 shows southward and duskward enhancements
 253 of the ion velocity (signature of reconnection jets, the second panel). The HT velocity
 254 is southward and duskward (consistent with the expected motion of an FTE flux rope),
 255 and the electron temperatures are higher than in the surrounding magnetosheath region.
 256 In the pristine magnetosheath, the electron perpendicular temperature tends to be higher
 257 than the parallel temperature (not always though; Phan et al. (1994)), but for the event

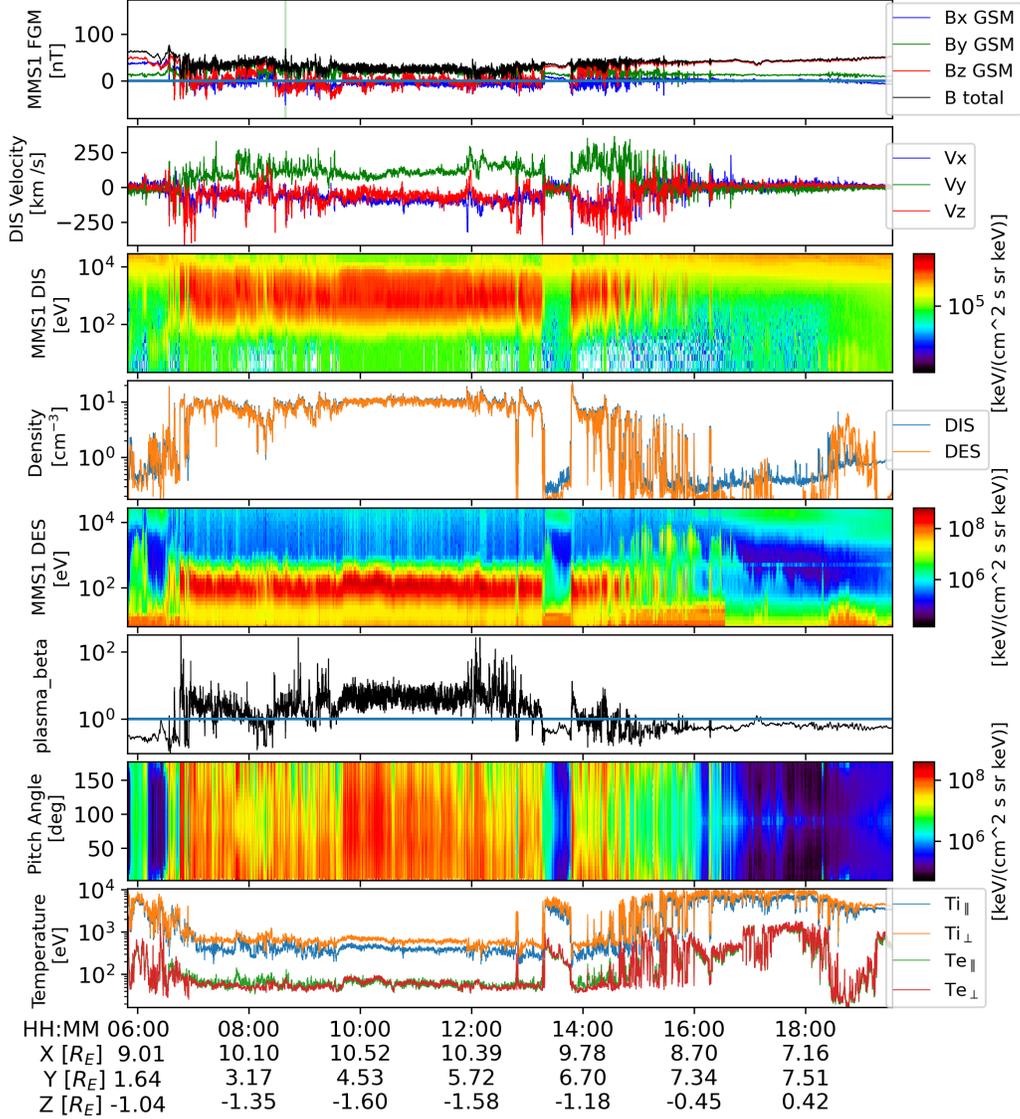


Figure 1. Times-series measurements from the MMS1 spacecraft for event 1 on 27 November 2016. From the top to the bottom panels are the GSM components of the magnetic field and the field magnitude, the ion velocity from the dual ion spectrometers (DIS), the ion energy spectrogram, the number density from DIS and the dual electron spectrometers (DES), the electron energy spectrogram, the plasma β , the electron pitch angle distribution (ePAD) for the 0.2-2 keV electrons, and the perpendicular and parallel temperature for ions and electrons. See the legends and labels for details. The MMS1 spacecraft locations in the GSM coordinates are also listed beneath the time tick labels. The light green vertical lines in the top panel mark the time interval of the FTE flux rope for event 1.

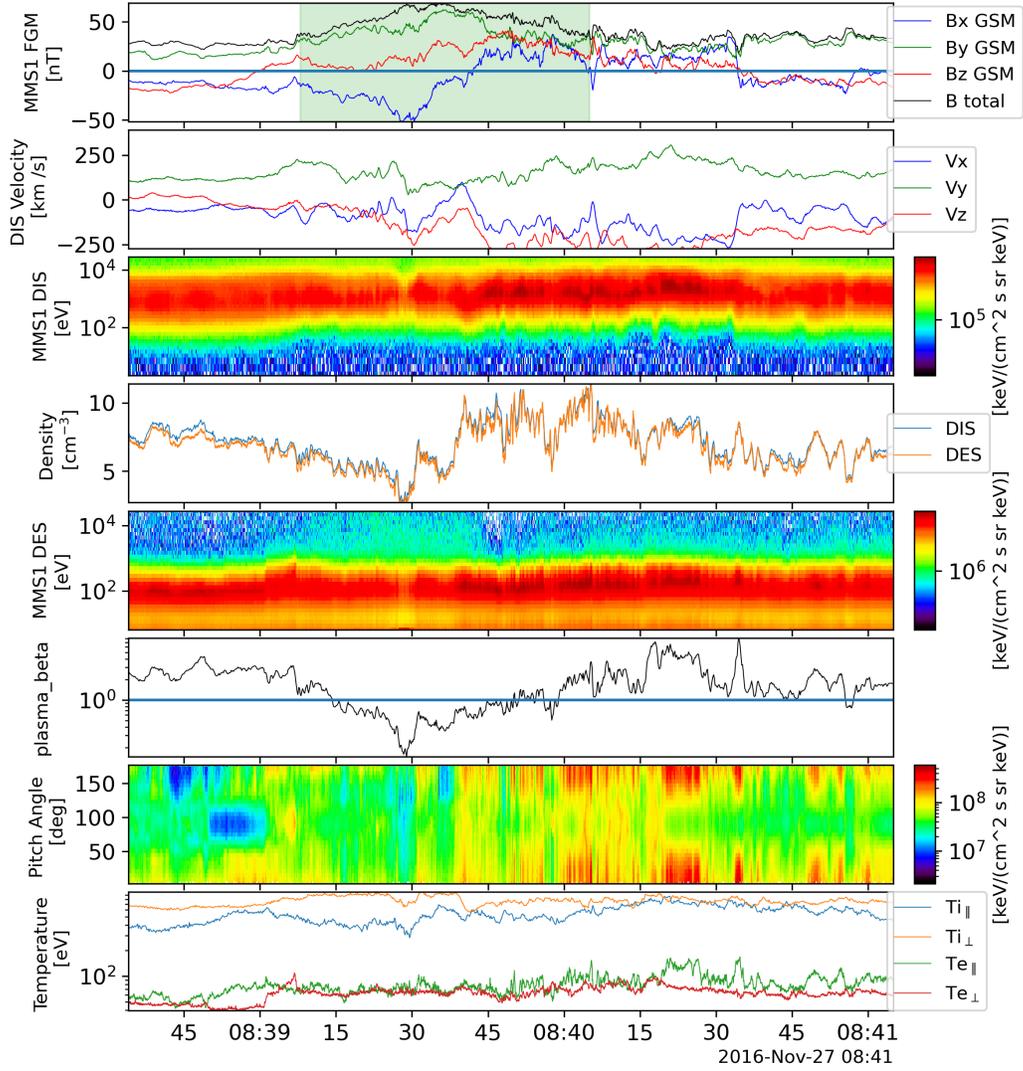


Figure 2. The same time-series stack plot as Figure 1 but for a much shorter time period surrounding the FTE interval, which is marked in the top panel by the light green shaded area.

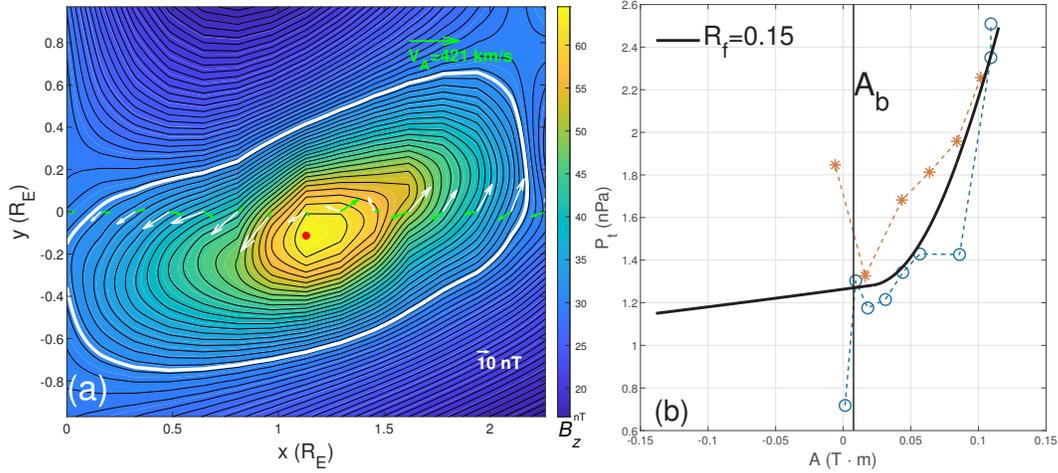


Figure 3. The GS reconstruction result for the event 1 FTE interval based on MMS1 spacecraft measurements. (a) The cross section of the magnetic field structure on a plane perpendicular to the z axis reconstructed from the spacecraft measurements along its path ($y = 0$). The black contours are the contours of the flux function A (also the transverse field lines on the plane), and the color represents the B_z distribution as indicated by the color bar. The red dot marks the location of the maximum B_z value. The white (green) arrows along $y = 0$ indicate the measured transverse magnetic field (remaining plasma flow velocity in the HT frame). Reference vectors are given near the bottom and top right corners, as denoted by a magnitude of 10 nT for the magnetic field and the average local Alfvén speed V_A for the velocity, respectively. The length of the reference vector for the magnetic field is equivalent to $0.20V_A$. (b) The corresponding P_t versus A measurements along the spacecraft path (circle and star symbols) and the associated fitting curve $P_t(A)$ in black. A fitting residue, R_f , is calculated to indicate the quality of fitting as denoted. The vertical line marks the choice of a particular flux function value A_b which defines a boundary of the flux rope structure as highlighted by the white thick contour where $A = A_b$ in (a).

258 1 interval, the parallel temperature tends to be higher, which is a signature of reconnected
 259 field lines. The ePAD plot also shows enhanced bi-directional field-aligned streaming mag-
 260 netosheath electrons heated by the magnetopause reconnection (Hasegawa et al., 2010).
 261

262 The GS reconstruction is carried out, yielding a z axis orientation mostly along the
 263 GSM-Y direction. A cross-section map of the magnetic field configuration is presented
 264 in Figure 3a, together with the corresponding $P_t(A)$ plot in (b). The flux rope config-
 265 uration is seen as represented by the closed contours of the flux function $A(x, y)$ (i.e.,
 266 equivalent to nested flux surfaces in this view down the z axis), bounded by the white
 267 contour at which $A = A_b$. Such a boundary as highlighted indicates that within this
 268 cylindrical ($2\frac{1}{2} D$) flux surface, the cylindrical flux rope configuration with nested flux
 269 surfaces is more reliably reconstructed because those surfaces are crossed by the space-
 270 craft along its path with actual measurements returned as the data points given in Fig-
 271 ure 3b. Therefore the reconstruction result obtained within this flux rope boundary is
 272 mostly consistent with the spacecraft measurements for this event, as judged in part by
 273 an acceptable fitting residue value $R_f = 0.15$ (for the corresponding fitting of $B_z(A)$,
 274 $R_f = 0.08$). The flux rope possesses right-handed chirality (positive sign of magnetic
 275 helicity). The magnetic flux contents are estimated based on the GS reconstruction re-

276 sult and are given in Table 1. The axial flux is a summation of the axial flux element
 277 over an area enclosed by the flux rope boundary, within which $A > A_b$ for this event.
 278 The total poloidal flux is subject to the determination of the axial length, L , of the flux
 279 rope along the z dimension. It is determined in coordination with the corresponding radar
 280 observations in the ionosphere as to be described below.

281 The analysis of the corresponding radar observations is carried out following the
 282 general procedures described in Fear et al. (2017), under the assumption that the sig-
 283 natures of FTE formation, in the form of reconnected field line footpoints motion, map
 284 to the polar cap region of the ionosphere nearly simultaneously. Figure 4 shows the cor-
 285 responding convection map in the Southern Hemisphere above the 65° magnetic latitude
 286 in its usual format. Ionospheric flows between 08:38 and 08:40 UT on 27 November 2016
 287 are plotted on the altitude adjusted corrected geomagnetic (AACGM) coordinates (Shepherd,
 288 2014). The plasma convection pattern with two cells in the Earth’s ionosphere is con-
 289 sistent with the southward directed IMF. The footprint of MMS1 is traced along the mag-
 290 netic field line according to the Tsyganenko (1996) model down to the ionosphere and
 291 is marked by the red dot which is at (13.0 MLT, -76.2° MLAT). Nearby a region with
 292 enhanced flow on the dayside is observed in the post-noon sector at a latitude around
 293 -80° and is within the ZHO coverage. The dashed black curve marks the longitudinal
 294 range of the enhanced flow region at this latitude. To determine the longitudinal extent
 295 of the “opened” flux region, we plot in Figure 5a the magnitudes of the flow velocity and
 296 its gradient along this particular latitude. The extent is taken as the range between the
 297 two vertical lines, about 38° in longitude, and is marked by the red dashed curve at the
 298 same latitude as the red dot in Figure 4.

299 The back scatter power and line-of-sight velocity measured by beam 15 of ZHO are
 300 displayed in Figure 5b. The latitudinal expansion equivalent to the PMAFs is shown by
 301 the dashed line. There is a time difference of 4 minutes between the FTE flux rope in-
 302 terval and the onset of PMAFs. Depending on the propagation time between the FTE
 303 location at the magnetopause and the conjugate field-line footpoints in the ionosphere,
 304 it is possible to have a time difference of a few minutes (Wild et al., 2003). The PMAFs
 305 start at -76° latitude, and move poleward to -81° latitude. The line-of-sight velocities
 306 of the PMAFs reach about 900 m/s away from the ZHO station. The PMAFs are thus
 307 observed to have propagated by 5° of magnetic latitudes into the polar cap, correspond-
 308 ing to a poleward distance of ~ 500 km. The area of the polar cap opened by the cor-
 309 responding FTE formation via magnetic reconnection is the product of the linear lengths
 310 of the above estimated latitudinal and longitudinal extents, which is approximately 0.56
 311 Mm^2 . The radial ionospheric magnetic field strength is 5×10^{-5} T. Following Fear et
 312 al. (2017), we assume that the uncertainties in the MLT extent and in the latitudinal
 313 direction are ± 1 h and $\pm 2^\circ$, respectively. The reconnection flux Φ_R calculated using the
 314 radar data is 28 ± 16 MWb for this event.

315 One unique advantage of combining the two sets of observations at the magnetopause
 316 and in the ionosphere is to help refine the analysis of the flux rope configuration by ad-
 317 dressing the uncertainty associated with determining the axial length of a cylindrical flux
 318 rope for the FTE event. Similar to Fear et al. (2017), by establishing a mapping between
 319 the extent of the “opened” region in the ionosphere to the magnetopause, a finite ax-
 320 ial length can be determined. However our approach is different in that we start the map-
 321 ping from the magnetopause based on the GS reconstruction result by selecting a series
 322 of points, separated by $1 R_E$ in this case, extending along the flux rope axial direction
 323 from the locations on the spacecraft path corresponding to the beginning and ending times
 324 of the interval, respectively. These points along the straight lines are then projected onto
 325 the magnetopause interface given by the Shue et al. (1998) model by simply propagat-
 326 ing them along the -GSM-X direction. They are then traced along the magnetic field lines
 327 based on the Tsyganenko (1996) model to the ionosphere. The series of stars (and nearly
 328 overlapping crosses) plotted in Figure 4 represent these mapped points. They locate around

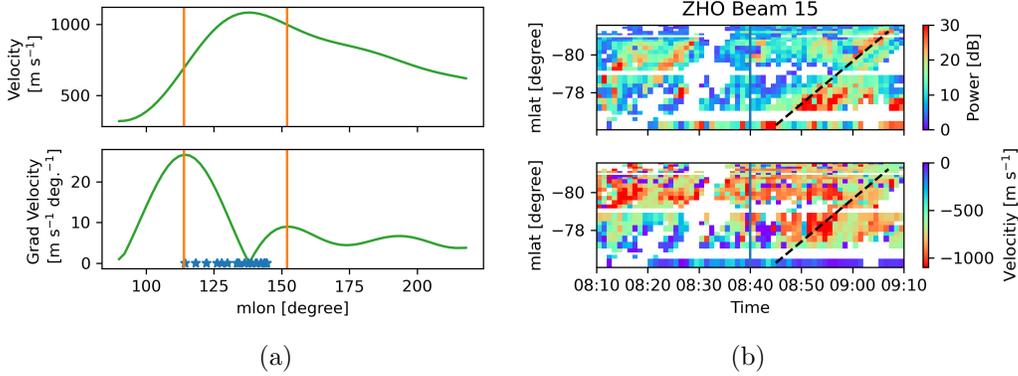


Figure 5. Analysis of the longitudinal and latitudinal extents of the opened flux region in the ionosphere for event 1. (a) Upper panel: the magnitude of velocities along the dashed black curve in Figure 4. Lower panel: the absolute value of the gradient of the velocities. Vertical lines mark the peaks in the magnitude of the gradient. The range between the vertical lines is taken as the longitudinal extent of the “opened” flux region. Blue stars belong to the same set of symbols marked in Figure 4, but are lined up within the marked range of longitudes only. (b) Radar observation from Beam 15 of the Zhongshan station (ZHO) as a function of time and magnetic latitudes. Upper panel: the radar back scatter power. Dashed black line shows a guideline for the propagating feature with enhanced scattering around the time of the FTE interval. Lower panel: the line-of-sight velocity. The vertical blue lines mark the beginning time of the FTE interval observed by the MMS1 spacecraft.

329 the mapped MMS1 spacecraft position and are also near the region with enhanced pole-
 330 ward flow. There are a total of 20 points confined within the range of the longitudinal
 331 extent of the “opened” flux region spanned by the red dashed curve (see also Figure 5a).
 332 Therefore for this event, the axial length of the flux rope at the magnetopause is estimated
 333 to be $19 R_E$.

3.2 Event 2: 19 December 2016

334
 335 For event 2 on 19 December 2016, the same analysis is carried out. The time series
 336 plots are shown in Figures 6 and 7. The flux rope interval marked in Figure 7 shows
 337 the magnetic field components with less pronounced rotations in direction, although the
 338 field magnitude is elevated. The plasma flow and particle signatures comply with a typical
 339 background condition on the magnetosheath side of the magnetopause. The GS reconstruction
 340 result for the FTE interval is summarized in Table 1 and the cross section map is given
 341 in Figure 8a. The results show a flux rope configuration with the z axis mostly
 342 pointing southward (i.e., being vertical) in the GSM coordinates. The cross section map
 343 consists of closed loops of the contours of the flux function with the increasing B_z value
 344 toward the center. The spacecraft path is crossing the edge of the flux rope, corresponding
 345 to the insignificant rotation in the field direction. The corresponding P_t versus A curve
 346 is shown in Figure 8b, where the fitted functional curve $P_t(A)$ extends significantly beyond
 347 both limits of the range of measurements (i.e., beyond the data points represented
 348 by the symbols). The part extrapolated toward the more negative values of A corresponds
 349 to the central portion of the flux rope structure enclosed within the white contour shown
 350 in Figure 8a.

351 In contrast to event 1, the ion velocity and spectrum in Figure 7 show no signature
 352 of reconnection, the HT velocity in Table 1 is too slow to be an encounter with a

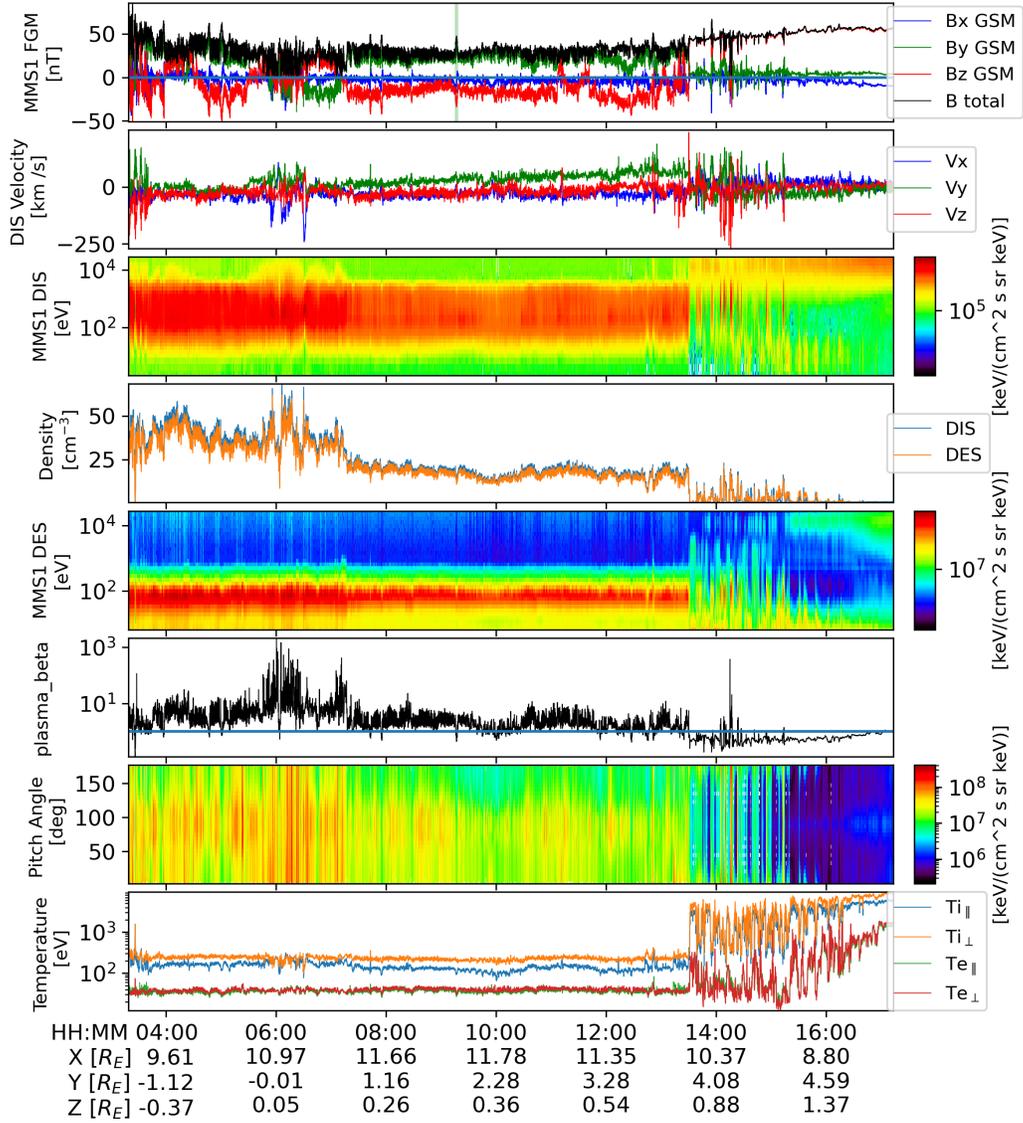


Figure 6. Time-series measurements from the MMS1 spacecraft for event 2 on 19 December 2016. Format is the same as Figure 1.

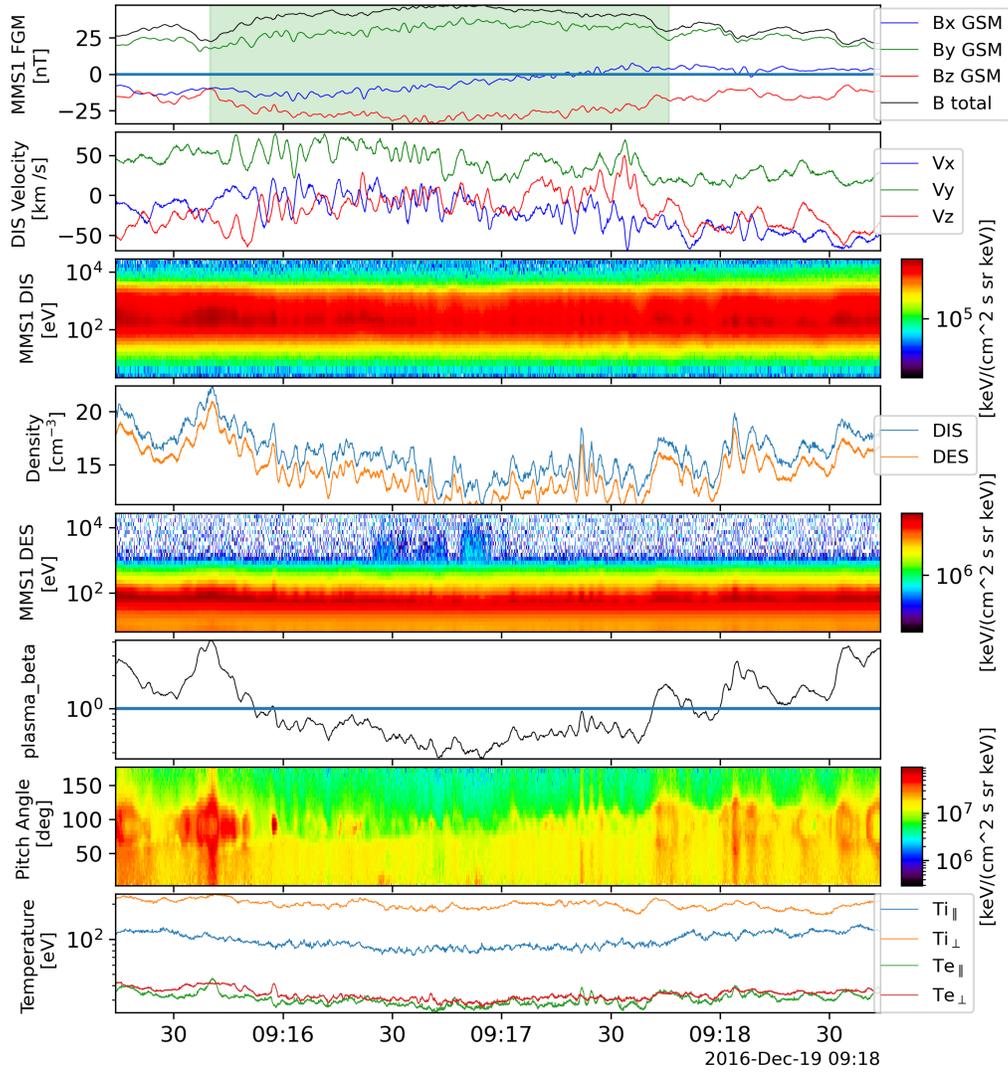


Figure 7. Same as Figure 6, but zoomed in to show the details of the FTE interval, which is marked by the green shaded area in the top panel.

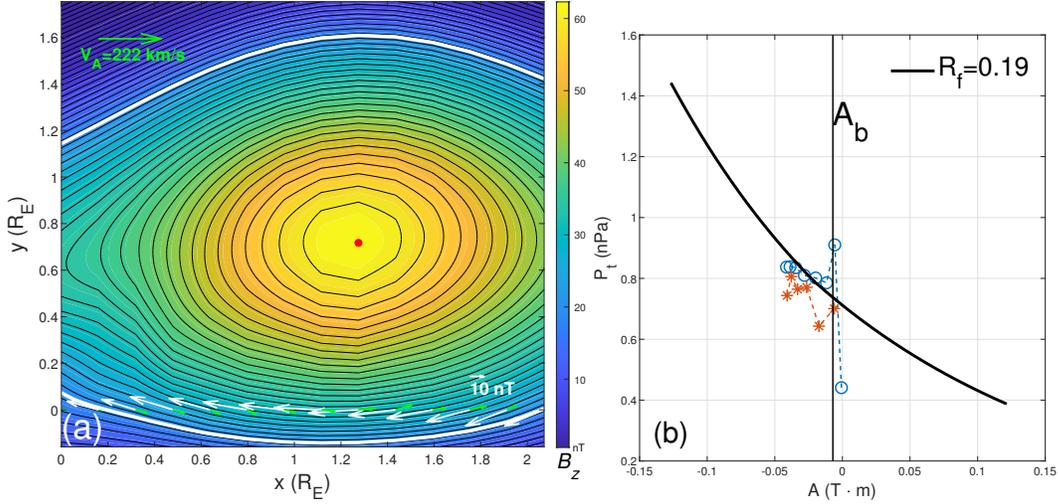


Figure 8. The GS reconstruction result for event 2 based on the MMS1 measurements at the magnetopause. Format is the same as Figure 3. The length of the reference vector for the magnetic field is equivalent to $0.25V_A$.

353 flux rope part of the FTE, and the electron perpendicular temperature is higher than
 354 the parallel temperature. The ePAD lacks clear indication of bi-directional streaming
 355 of electrons along the field lines. All these features suggest that MMS1 detected only the
 356 magnetosheath field lines draping around the FTE flux rope or tube (thus a remote or
 357 grazing encounter). Although such an in-direct encounter for this FTE event is consistent
 358 with the GS reconstruction result, given that the flux rope configuration from the
 359 GS reconstruction is mostly based on a significant extrapolation of the in-situ data, as
 360 described above, the results are thus deemed highly uncertain.

361 The convection map again from the ZHO station is shown in Figure 9, where the
 362 poleward enhanced plasma motion is seen near the mapped MMS1 spacecraft position
 363 on the ionosphere (12.2 MLT, -76.1° MLAT) at the time. The mapped footpoints origi-
 364 nating along the flux rope axis from the magnetopause to the ionosphere span a rela-
 365 tively narrow range in longitudes, but extend over $\sim 7^\circ$ in latitudes. The analysis based
 366 on the radar observations of the back scatter power and the gradient in the convection
 367 velocity, shown in Figure 10, yields a longitudinal extent of 36° and a latitudinal extent
 368 of only 2° for the “opened” area in the polar cap region. Correspondingly, the estimate
 369 for the “opened” flux with uncertainty is 11 ± 12 MWb, following the same analysis ap-
 370 proach as event 1.

371 3.3 Summary of GS Reconstruction Results

Table 2. Analysis results based on the GS reconstruction of the FTE flux rope interval at the magnetopause and the corresponding radar observations in the ionosphere for event 1^a.

Φ_z [MWb]	ϕ_p [T·m]	L [R_E]	Φ_p [MWb]	Φ_R [MWb]	$\tilde{\phi}_p$ [T·m]	$\tilde{\Phi}_z$ [MWb]
3.4	0.107	19	13	28 ± 16	0.0268 - 0.0621	1.05 - 3.59

^aThe last two columns are the ranges of fluxes cited from Hasegawa et al. (2006) for 5 FTEs at the magnetopause by applying the optimal GS reconstruction method to the Cluster spacecraft data.

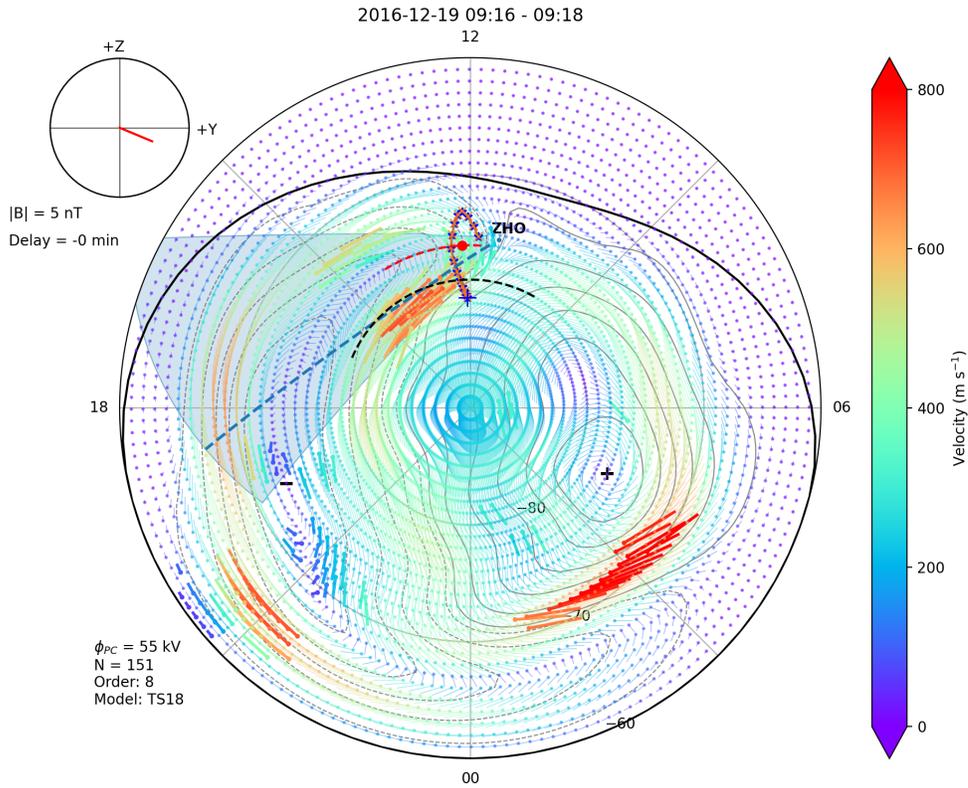


Figure 9. Convection map on the ionosphere for event 2. Format is the same as Figure 4. Points along the axial direction of the reconstructed flux rope projected to the ionosphere are marked as blue stars and red crosses. Each point along the reconstructed flux rope axial direction is $2 R_E$ apart from its neighboring points. The end point marked by the blue plus sign corresponds to the end point along the flux rope axis in the southward direction at the magnetopause.

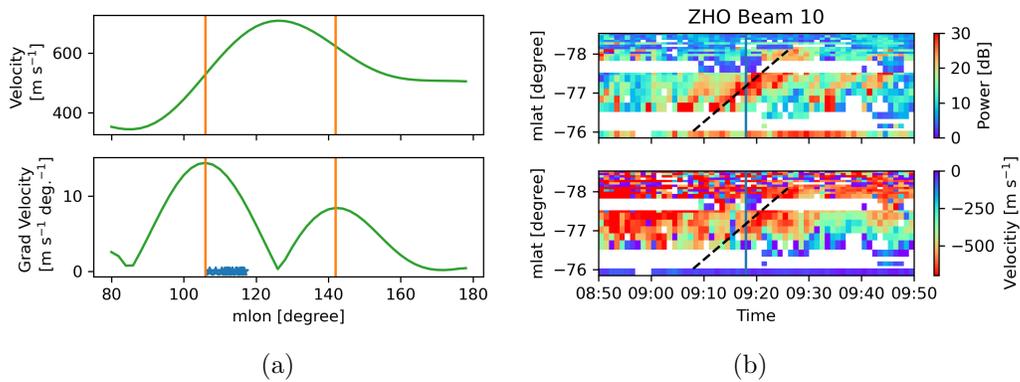


Figure 10. Analysis of the longitudinal and latitudinal extents of the “opened” flux region for event 2, based on radar observations from the Zhongshan (ZHO) station. The format is the same as Figure 5.

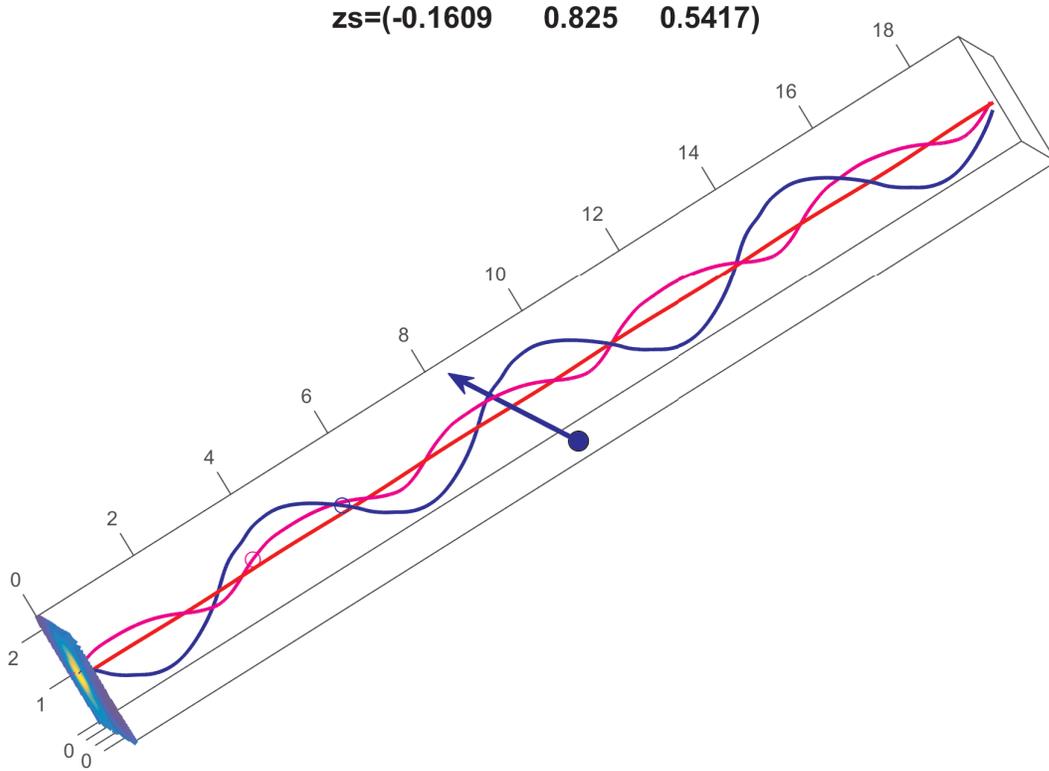


Figure 11. A 3D rendering of the field-line configuration for event 1 in a view angle toward Earth, i.e., down the GSM-X axis. The GSM-Z axis is straight up and the GSM-Y axis is horizontally to the right. The blue dot and arrow denote the location of MMS1 spacecraft at the beginning of the FTE interval and the direction of $-\mathbf{V}_{HT}$, respectively. The tickmark labels are in R_E . Three field lines are drawn in red, magenta and blue colors within the cylindrical volume of axial length $L = 19R_E$ based on our analysis results for event 1. The cross section map is shown on the bottom plane where the field lines are rooted and the optimal z axis orientation in the GSM coordinates is denoted on top.

372 We summarize the GS reconstruction results, mainly the magnetic flux estimates
 373 in Table 2 for event 1 only, because those results are judged to be reliable based on the
 374 analysis results presented in Section 3.1. The ranges of the unit poloidal flux and the
 375 axial flux for five FTE intervals examined by Hasegawa et al. (2006) are also shown for
 376 comparison, where the maximum values for both fluxes are from one FTE interval. The
 377 axial flux of event 1 is within the range of those estimates, although closer to the upper
 378 limit. The unit poloidal flux is about 50% larger than the upper limit of the range of the
 379 corresponding estimates from Hasegawa et al. (2006).

380 The largest uncertainty in the estimate of the total poloidal flux Φ_p is generally
 381 believed to lie in the uncertainty of the axial length, L , of a cylindrical flux rope model
 382 (Hu et al., 2014, 2015). In this analysis, we lack a feasible means to provide an estimate
 383 of the uncertainty associated with L . If we adopt the same assumption as we made for
 384 the similar analysis of the interplanetary magnetic flux ropes (Hu et al., 2014, 2015), the
 385 uncertainty in Φ_p could amount to 100% toward the estimate of the upper limit of the
 386 total poloidal flux.

387 To further put our GS reconstruction result in the context of a better character-
 388 ization of the magnetic field configuration of an FTE flux rope from a quasi-3D point
 389 of view, we show in Figure 11 a rendering of the 3D field line plot for event 1. It is the
 390 solution to the GS equation within the solution domain of a cylinder (or a cuboid) with
 391 the axial length $L = 19R_E$. The cylinder is oriented along the z axis direction as viewed
 392 toward the Earth with the dawn-dusk direction pointing horizontally to the right. The
 393 MMS1 spacecraft is traversing the structure along the blue arrow at the time with the
 394 velocity, $-\mathbf{V}_{HT}$, given in Table 1. In other words, the structure is moving with the ve-
 395 locity \mathbf{V}_{HT} relative to the spacecraft in the opposite direction of the blue arrow. Three
 396 selected field lines are drawn. The straight line in red originates from the red dot in Fig-
 397 ure 3a, where B_z reaches the maximum. The magenta and blue lines are spiraling along
 398 the z axis around the central line with varying degrees of twist. On average, the unit field
 399 line twist can be estimated by taking the ratio between ϕ_p and Φ_z (Hu et al., 2014), which
 400 yields about 0.2 turns/ R_E for event 1. Therefore for the flux rope configuration shown
 401 in Figure 11 with $L = 19R_E$, the average total number of twist or turns of the field lines
 402 for the FTE flux rope is approximately 4.

403 **4 Interpretation for the formation of magnetic flux ropes at the mag-** 404 **netopause**

405 Based on these analysis results, we would like to describe in detail our view on the
 406 FTE flux rope formation as this is the main motivation for this study. The basic pro-
 407 cess to be proposed for the formation of magnetic flux ropes at the Earth's magnetopause,
 408 i.e., in the form of FTEs, is largely based on the well-known scenario of flux rope for-
 409 mation on the Sun through magnetic reconnection as manifested in solar flares (Longcope
 410 et al., 2007; Qiu et al., 2007; Hu et al., 2014). An analogy between the topological change
 411 of the underlying magnetic field lines during a solar flare and that during the FTE for-
 412 mation can be made because the magnetic reconnection is responsible for these changes
 413 in both cases. As a result, a common magnetic flux rope structure is formed in both cases,
 414 albeit it is drastically different in size and strength (or magnetic flux content). In ad-
 415 dition, these changes, as reflected by the reconnected magnetic field line footpoints mo-
 416 tion, can be both characterized by remote-sensing observations. For solar flares, they are
 417 generally represented by the flare ribbon brightenings primarily observed on the chro-
 418 mosphere where the reconnected field lines map to and exhibit enhanced brightening
 419 in patches during a flare. For FTEs, the reconnected field line footpoints may map to
 420 the ionosphere, causing enhanced convection flows that can be measured by, e.g., the Su-
 421 perDARN radar network in polar regions. We provide, in this study, an interpretation
 422 of the FTE formation at the Earth's magnetopause based on such an analogy between
 423 the magnetic field topologies of the two processes.

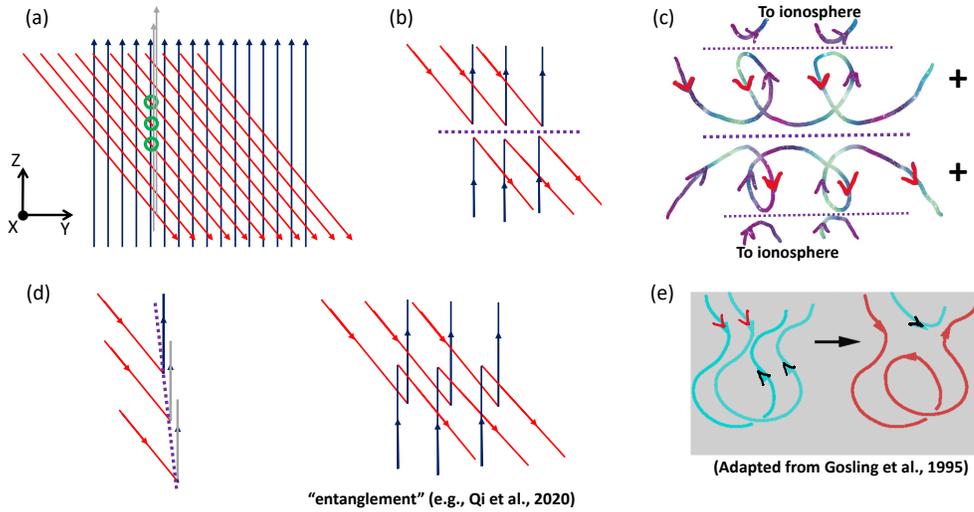


Figure 12. Schematics for the formation of magnetic flux ropes at the Earth’s magnetopause. (a) The magnetic field lines in the magnetosheath (red lines) and the magnetosphere (black lines) as viewed toward Earth (along $-X$) at the magnetopause for a general IMF condition of $B_Z < 0$ and $B_Y > 0$ where the X , Y , and Z denote the unit directional vectors of the GSM coordinates. This view can also be considered equivalent to an LMN coordinate system, e.g., with $L \equiv Z$, $M \equiv -Y$, and $N \equiv X$. (b) One scenario of magnetic reconnection between the field lines in the magnetosheath and in the magnetosphere, forming a primary X line as denoted by the thick dotted line. (c) The subsequent reconnection between adjacent field lines along the secondary X lines (thin dotted lines) forming twisted magnetic flux rope structures which are right-handed as denoted by the “+” sign. The other sets of reconnected field lines as represented by shorter loops may connect to the ionosphere. (d) One distinctive scenario of an approximately north-south oriented primary X line, and an alternative scenario of flux “entanglement” (Qi et al., 2020) with the red line segments always crossing above the black line segments in this view (see text for details). (e) The detailed change of connectivity for the reconnection between one pair of adjacent field lines as originally depicted by Gosling et al. (1995). The viewpoint is the same for all panels except for (e), and the red arrowheads are consistently attached to the parts of field lines corresponding to the original red field lines in (a) and (b).

Figure 12 shows schematic illustrations of the possible scenario of FTE formation through a sequential reconnection process at the magnetopause under a southward IMF (or magnetosheath field) condition with $B_Y > 0$. A similar set can be generated for the similar IMF condition but with $B_Y < 0$. Such a process, especially as illustrated in panel (c), has a direct analogy to the formation of a flux rope with quasi-3D geometry in solar flares (Longcope et al., 2007; Qiu et al., 2007; Hu et al., 2014). Figure 12a shows the relative orientations of the fields in the magnetosheath (red lines) and the magnetosphere (black lines). In general magnetic reconnection may proceed between any pair of the red and black field lines, forming an arbitrary primary X line. Figure 12b shows a typical case with an approximately dawn-dusk (horizontally) oriented primary X line along which two sets of reconnected field lines are aligned in a crisscross pattern approximately in the same horizontal direction. Subsequently, as illustrated in (c), additional reconnection may ensue for either or both sets of field lines separated by the primary X line, especially in a sequence that happens between adjacent field lines and proceeds either from dawn toward dusk direction or vice versa.

For example, for the set of field lines north of the primary X line illustrated in Figure 12b, assume that reconnection proceeds from dawn to dusk (left to right), the black end of the first field line may approach the red end of the adjacent field line and reconnect, forming a twisted field line. Such a process is further shown in Figure 12e (Gosling et al., 1995), which has long been recognized as a building block for the formation of a magnetic flux rope configuration with field lines of multiple turns, as depicted in (c), as a result of such a sequential reconnection process between adjacent field lines. If a “guide field” can be assumed to be determined by the B_Y component, dictating the formation of an axial field near the center of such a flux rope configuration, the handedness (the sign of magnetic helicity, or chirality) of the magnetic flux rope topology can be inferred as right-handed (being positive in chirality, “+”) for either set of field lines separated by the primary X line in Figure 12c and for either direction of the reconnection sequence. It can also be shown that for the other condition $B_Y < 0$, a left-handed magnetic flux rope (negative chirality, “-”) may form in a similar manner with an approximately horizontal orientation. These findings about handedness rules of FTE flux ropes are consistent with the recent studies of the sign of helicity of FTEs (Kieokaew et al., 2021; Dahani et al., 2022). They concluded that “Right-handed (left-handed) FTE flux ropes are mostly preceded by positive (negative) interplanetary magnetic field (IMF) B_Y ” as one of their key points (Kieokaew et al., 2021). Furthermore, it was pointed out by Dahani et al. (2022) that a weaker B_Y component corresponding to the lack of a “guide field” may lead to greater uncertainty in the aforementioned chirality rule, although those authors attributed such uncertainty to microscopic (Hall) effect (see, also, Eriksson et al., 2020). However we would argue that the complexity in a more general 3D magnetic field topology may disrupt the chirality rule when the field configuration becomes complex and deviates from a 2D geometry.

Topologically, Figure 12d illustrates such a special case or an exception to the aforementioned chirality rule, corresponding to a case with a north-south (vertically) oriented primary X line. For this case, it is not clear how a “guide field” contributes to the formation of the axial field of a 2D magnetic flux rope. Such a configuration shown to the left may be formed through consecutive reconnection at the locations marked by the green circles in (a), where the reconnection proceeds between the red field lines and the corresponding black lines at the sites aligned vertically with the black field lines replenished from the magnetosphere as indicated by the additional gray lines. Whereas perhaps a more common scenario, given to the right in (d), is the flux “entanglement” (Qi et al., 2020), or inter-laced/linked field lines (Fargette et al., 2020), due to the fact of the prevalent intercepting X points originating from (a). Both configurations impose significant difficulty for the GS reconstruction method (see, e.g., Hasegawa et al., 2007). Additionally, in a more general 3D topology that goes beyond the current most commonly invoked 2D framework, the uncertainty in the handedness is probably intrinsic to the complex-

ity in the field topology, leading to further complications in characterizing the magnetic flux contents as well.

In summary, as a consequence of such a reconnection sequence in a quasi-3D geometry, in the case of flares, the amount of magnetic flux enclosed by regions swept by the flare ribbons (so-called the reconnection flux) usually matches the poloidal flux of thus formed magnetic flux rope (Qiu et al., 2007; Hu et al., 2014). In direct analogy, the same applies for the connection between the FTE flux rope and the region in the ionosphere where the reconnected field lines sweep through. Specifically, from Figure 12c and e, it can be understood that one unit of magnetic flux injected into the coiled loop structures adding one turn of the ensuing flux rope is equal to the amount closed down into the reconnected short loop with one end tracing to the ionosphere. Therefore, the amount of poloidal flux of thus formed FTE flux rope corresponds to the amount of flux “opened” (i.e., the reconnection flux Φ_R) in the corresponding polar cap region where the reconnected field line footpoints are rooted.

5 Conclusions and Discussion

In conclusion, we have presented two event studies of the FTE flux ropes at the Earth’s magnetopause based on the MMS1 in-situ measurements and the corresponding mapped field-line footpoint motion in the high-latitude ionosphere in the Southern Hemisphere based on the simultaneous SuperDARN radar observations. The GS reconstruction method is applied to the in-situ measurements of FTE flux ropes to derive the magnetic field configuration in a cylindrical geometry, which yields the quantitative characterizations of the magnetic flux contents of the flux rope structure, in terms of the toroidal (axial) and poloidal magnetic fluxes. In turn, the corresponding reconnection flux in an area is estimated by examining the correlated enhanced plasma convection pattern mapped along the magnetospheric field lines to the polar cap region, following the approach of Fear et al. (2017). The area “opened” through the magnetic reconnection at the day-side magnetopause, forming the FTE, and mapped to the ionosphere is estimated by calculating the longitudinal and latitudinal extents based on the SuperDARN observations of nearly concurrent enhancement of poleward plasma convection motion during the FTE interval.

We find that for event 1, the FTE flux rope configuration is well reconstructed with the spacecraft path cutting across the center of a helical magnetic field structure. It possesses right-handed chirality and is oriented largely in the dawn-dusk direction at the magnetopause. The flux rope length is estimated to be about $19 R_E$. The GS reconstruction results yield the corresponding magnetic flux contents as listed in Table 2. The poloidal flux of the FTE flux rope, $\Phi_p = 13$ MWb, falls within the range of the estimated reconnection flux, $\Phi_R = 28 \pm 16$ MWb, from the SuperDARN radar observations, but the toroidal (axial) flux is significantly lower. Considering the possible uncertainty in the estimation of the flux rope length, L , and its variability (e.g., in Fear et al. (2017), such a length for one event was estimated to be as large as $38 R_E$), the agreement between the poloidal flux of the FTE flux rope and the reconnection flux for this event is likely supported by these analysis results.

For event 2, as indicated in Table 1, the FTE flux rope possesses an axial orientation that is in the North-South direction and left-handed chirality, despite the fact that the spacecraft path is near the edge of the flux rope cross section, as shown in Figure 8a. Both the axial and the poloidal fluxes are comparable to the values for event 1. However, they are considered less reliable due to the fact that the flux rope configuration is derived mainly by extrapolations to the in-situ spacecraft data. There also exists significant uncertainty in the estimate of the reconnection flux from radar observations. Additional source of uncertainty is associated with the estimate of the axial length of the flux rope. Since the flux rope is mostly oriented vertically at the magnetopause from a

529 viewpoint toward the Earth in the GSM coordinates, the mapped field line footpoints
 530 from the flux rope to the ionosphere, as shown in Figure 9, tend to congregate around
 531 the same longitude, resulting in a larger uncertainty in the flux rope length, L . There-
 532 fore, all these aforementioned uncertainties for event 2 prohibit a quantitative compar-
 533 ison among the various flux estimates.

534 Motivated by the conceptual analogy to solar flares, we offer an interpretation of
 535 the formation of the FTE flux rope through the magnetic reconnection at the dayside
 536 magnetopause, as presented in Section 4. Figure 12 illustrates a scenario for the IMF
 537 $B_Y > 0$, which is consistent with the results for events 1 summarized above. In par-
 538 ticular, it provides a more detailed explanation for the chirality rule of FTE flux ropes
 539 (e.g., Dahani et al., 2022; Kieokaew et al., 2021) based on the topology change of FTE
 540 flux ropes through magnetic reconnection. The distinction of this scenario from the oth-
 541 ers (e.g., Lee & Fu, 1985, and others) is perhaps the emphasis on the intermediate pro-
 542 cess (i.e., that generating the shorter loops marked by “To ionosphere” in Figure 12c),
 543 corresponding to the reconnection sequence between adjacent reconnecting field lines from
 544 one end to the other. The entire sequence may generate the corresponding signatures
 545 in the ionosphere, not just at the two ends. Therefore we conclude that the flux rope for-
 546 mation at the magnetopause may proceed in a quasi-3D manner via a sequential mag-
 547 netic reconnection process between adjacent field-line loops. Such a sequence may dic-
 548 tate the topological properties of the thus formed magnetic flux rope, governed by the
 549 IMF condition and other spatial features, such as the orientations of the multiple X-lines
 550 (see Figure 12). The results from event 1, especially in terms of the agreement between
 551 the poloidal flux and the reconnection flux and the correct handedness, support this con-
 552 clusion, while for event 2, it is much uncertain. It indicates the importance of detailed
 553 investigation of magnetic field topology into two or three dimensions that has to go be-
 554 yond a relatively simple time-series analysis often limited to one spatial dimension.

555 To further elucidate these points, we will extend the current study which is lim-
 556 ited by the small number of event studies. A survey of additional FTE events with con-
 557 jugate signatures in the ionosphere by employing the approaches described here (or the
 558 ones with refined analysis to reduce uncertainties) can be carried out in the future. In
 559 addition, it has been increasingly realized that in a more general 3D topology, the re-
 560 connection sequence may indicate a correlation between the axial flux of the flux rope
 561 and the reconnection flux (see, e.g., He et al., 2022; Hu et al., 2022). Therefore it is worth
 562 investigating further the correlation between the reconnection flux and the flux encom-
 563 passed in FTE events, as this study and other previous studies have attempted to do,
 564 through multiple observational and theoretical approaches.

565 Data Availability Statement

566 SuperDARN data can be found at [https://www.frdr-dfdr.ca/repo/collection/](https://www.frdr-dfdr.ca/repo/collection/superdarn)
 567 [superdarn](https://www.frdr-dfdr.ca/repo/collection/superdarn). SuperDARN data has been processed using the Radar Software Toolkit de-
 568 veloped by the SuperDARN Data Analysis Working Group (Burrell et al., 2022) and vi-
 569 sualized by the pyDARN package developed by the SuperDARN Data Visualization Work-
 570 ing Group (Martin et al., 2023; Shi et al., 2022). The MMS spacecraft data are accessed
 571 via the MMS Science Data Center (<https://lasp.colorado.edu/mms/sdc/public/>).
 572 A Python package, pyGS, developed by Dr. Yu Chen for performing the GS reconstruc-
 573 tion, is publicly available at <https://github.com/PyGSDR/PyGS/>.

574 Acknowledgments

575 We acknowledge the use of SuperDARN data. The Zhongshan (ZHO) SuperDARN radar
 576 is maintained and operated by the Polar Research Institute of China with partial sup-
 577 port from the Chinese Meridian Project. SuperDARN is a network of radars funded by
 578 national scientific funding agencies of Australia, Canada, China, France, Italy, Japan,

579 Norway, South Africa, the United Kingdom, and the United States of America. SW, YZ
 580 and QH acknowledge partial support of NASA grant 80NSSC21K0003. XS is supported
 581 by NSF grants AGS-1935110 and AGS-2025570, and NASA grant 80NSSC21K1677. The
 582 work by H.H. was supported by JSPS Grant-in-aid for Scientific Research KAKENHI
 583 21K03504.

584 References

- 585 Burrell, A., Thomas, E., Schmidt, M., Bland, E., Coco, I., Ponomarenko, P., ...
 586 Walach, M.-T. (2022, April). *Superdarn radar software toolkit (rst) 4.7*.
 587 Zenodo. Retrieved from <https://doi.org/10.5281/zenodo.6473603> doi:
 588 10.5281/zenodo.6473603
- 589 Chen, P. F. (2011, April). Coronal Mass Ejections: Models and Their Observational
 590 Basis. *Living Reviews in Solar Physics*, 8(1), 1. doi: 10.12942/lrsp-2011-1
- 591 Chisham, G., Lester, M., Milan, S. E., Freeman, M. P., Bristow, W. A., Grocott,
 592 A., ... Walker, A. D. M. (2007, January). A decade of the Super Dual
 593 Auroral Radar Network (SuperDARN): scientific achievements, new tech-
 594 niques and future directions. *Surveys in Geophysics*, 28(1), 33-109. doi:
 595 10.1007/s10712-007-9017-8
- 596 Dahani, S., Kieokaew, R., Génot, V., Lavraud, B., Chen, Y., Michotte de Welle, B.,
 597 ... Burch, J. (2022). The helicity sign of flux transfer event flux ropes and
 598 its relationship to the guide field and hall physics in magnetic reconnection at
 599 the magnetopause. *Journal of Geophysical Research: Space Physics*, 127(11),
 600 e2022JA030686. Retrieved from [https://agupubs.onlinelibrary.wiley](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022JA030686)
 601 [.com/doi/abs/10.1029/2022JA030686](https://doi.org/10.1029/2022JA030686) (e2022JA030686 2022JA030686) doi:
 602 <https://doi.org/10.1029/2022JA030686>
- 603 Elphic, R. C. (1990, January). Observations of flux transfer events - Are FTEs flux
 604 ropes, islands, or surface waves? *Geophysical Monograph Series*, 455-471.
- 605 Elphic, R. C., Lockwood, M., Cowley, S. W. H., & Sandholt, P. E. (1990, Novem-
 606 ber). Flux transfer events at the magnetopause and in the ionosphere. *Geo-*
 607 *physical Research Letters*, 17(12), 2241-2244. doi: 10.1029/GL017i012p02241
- 608 Eriksson, S., Souza, V. M., Cassak, P. A., & Hoilijoki, S. (2020). Nascent flux rope
 609 observations at earth's dayside magnetopause. *Journal of Geophysical Re-*
 610 *search: Space Physics*, 125(10), e2020JA027919. Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020JA027919)
 611 [agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020JA027919](https://doi.org/10.1029/2020JA027919)
 612 (e2020JA027919 2020JA027919) doi: <https://doi.org/10.1029/2020JA027919>
- 613 Fargette, N., Lavraud, B., Øieroset, M., Phan, T. D., Toledo-Redondo, S., Kieokaew,
 614 R., ... Smith, S. E. (2020, March). On the Ubiquity of Magnetic Reconnec-
 615 tion Inside Flux Transfer Event-Like Structures at the Earth's Magnetopause.
 616 *Geophysical Research Letters*, 47(6), e86726. doi: 10.1029/2019GL086726
- 617 Fear, R. C., Trenchi, L., Coxon, J. C., & Milan, S. E. (2017, December). How Much
 618 Flux Does a Flux Transfer Event Transfer? *Journal of Geophysical Research*
 619 *(Space Physics)*, 122(12), 12,310-12,327. doi: 10.1002/2017JA024730
- 620 Forbes, T. G., & Lin, J. (2000, November). What can we learn about reconnection
 621 from coronal mass ejections? *Journal of Atmospheric and Solar-Terrestrial*
 622 *Physics*, 62, 1499-1507. doi: 10.1016/S1364-6826(00)00083-3
- 623 Forbes, T. G., Linker, J. A., Chen, J., Cid, C., Kóta, J., Lee, M. A., ... Riley, P.
 624 (2006, March). CME Theory and Models. *Space Sci. Rev.*, 123(1-3), 251-302.
 625 doi: 10.1007/s11214-006-9019-8
- 626 Fu, Z. F., Lee, L. C., & Shi, Y. (1990, January). A three-dimensional MHD simu-
 627 lation of the multiple X line reconnection process. *Geophysical Monograph Se-*
 628 *ries*, 58, 515-519. doi: 10.1029/GM058p0515
- 629 Gosling, J. T., Birn, J., & Hesse, M. (1995, April). Three-dimensional magnetic
 630 reconnection and the magnetic topology of coronal mass ejection events. *Geo-*
 631 *physical Research Letters*, 22(8), 869-872. doi: 10.1029/95GL00270

- 632 Greenwald, R. A., Baker, K. B., Dudeney, J. R., Pinnock, M., Jones, T. B., Thomas,
633 E. C., ... Yamagishi, H. (1995, February). Darn/Superdarn: A Global View of
634 the Dynamics of High-Latitude Convection. *Space Sci. Rev.*, *71*(1-4), 761-796.
635 doi: 10.1007/BF00751350
- 636 Guo, J., Lu, S., Lu, Q., Lin, Y., Wang, X., Huang, K., ... Wang, S. (2021, June).
637 Re-Reconnection Processes of Magnetopause Flux Ropes: Three-Dimensional
638 Global Hybrid Simulations. *Journal of Geophysical Research (Space Physics)*,
639 *126*(6), e29388. doi: 10.1029/2021JA029388
- 640 Hasegawa, H. (2012, August). Structure and Dynamics of the Magnetopause and Its
641 Boundary Layers. *Monographs on Environment, Earth and Planets*, *1*(2), 71-
642 119. doi: 10.5047/meep.2012.00102.0071
- 643 Hasegawa, H., Nakamura, R., Fujimoto, M., Sergeev, V. A., Lucek, E. A., Rème, H.,
644 & Khotyaintsev, Y. (2007). Reconstruction of a bipolar magnetic signature in
645 an earthward jet in the tail: Flux rope or 3d guide-field reconnection? *Journal*
646 *of Geophysical Research: Space Physics*, *112*(A11). Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007JA012492)
647 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007JA012492 doi:
648 <https://doi.org/10.1029/2007JA012492>
- 649 Hasegawa, H., Sonnerup, B., Dunlop, M., Balogh, A., Haaland, S., Klecker, B., ...
650 Rème, H. (2004, April). Reconstruction of two-dimensional magnetopause
651 structures from Cluster observations: verification of method. *Annales Geophys-*
652 *icae*, *22*, 1251-1266. doi: 10.5194/angeo-22-1251-2004
- 653 Hasegawa, H., Sonnerup, B. U. O., Owen, C. J., Klecker, B., Paschmann, G.,
654 Balogh, A., & Rème, H. (2006). The structure of flux transfer events
655 recovered from cluster data. *Annales Geophysicae*, *24*(2), 603-618. Re-
656 trieved from <https://angeo.copernicus.org/articles/24/603/2006/> doi:
657 10.5194/angeo-24-603-2006
- 658 Hasegawa, H., Sonnerup, B. U. Ö., Owen, C. J., Klecker, B., Paschmann, G.,
659 Balogh, A., & Rème, H. (2006, March). The structure of flux transfer events
660 recovered from Cluster data. *Annales Geophysicae*, *24*(2), 603-618. doi:
661 10.5194/angeo-24-603-2006
- 662 Hasegawa, H., Wang, J., Dunlop, M. W., Pu, Z. Y., Zhang, Q.-H., Lavraud, B., ...
663 Bogdanova, Y. V. (2010). Evidence for a flux transfer event generated by mul-
664 tiple x-line reconnection at the magnetopause. *Geophysical Research Letters*,
665 *37*(16). Retrieved from [https://agupubs.onlinelibrary.wiley.com/doi/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010GL044219)
666 [abs/10.1029/2010GL044219](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010GL044219) doi: <https://doi.org/10.1029/2010GL044219>
- 667 He, W., Hu, Q., Jiang, C., Qiu, J., & Prasad, A. (2022, August). Quantitative Char-
668 acterization of Magnetic Flux Rope Properties for Two Solar Eruption Events.
669 *ApJ*, *934*(2), 103. doi: 10.3847/1538-4357/ac78df
- 670 Hu, Q. (2017, June). The Grad-Shafranov Reconstruction in Twenty Years: 1996 -
671 2016. *Sci. China Earth Sciences*, *60*, 1466-1494. doi: doi:10.1007/s11430-017-
672 -9067-2
- 673 Hu, Q., Qiu, J., Dasgupta, B., Khare, A., & Webb, G. M. (2014, September). Struc-
674 tures of Interplanetary Magnetic Flux Ropes and Comparison with Their Solar
675 Sources. *ApJ*, *793*, 53. doi: 10.1088/0004-637X/793/1/53
- 676 Hu, Q., Qiu, J., & Krucker, S. (2015, June). Magnetic field-line lengths inside inter-
677 planetary magnetic flux ropes. *Journal of Geophys. Res.*, *120*, 1. doi: 10.1002/
678 2015JA021133
- 679 Hu, Q., & Sonnerup, B. U. Ö. (2002, July). Reconstruction of magnetic clouds
680 in the solar wind: Orientations and configurations. *Journal of Geophys. Res.*,
681 *107*, 1142. doi: 10.1029/2001JA000293
- 682 Hu, Q., Zhu, C., He, W., Qiu, J., Jian, L. K., & Prasad, A. (2022, July). Validation
683 and Interpretation of a Three-dimensional Configuration of a Magnetic Cloud
684 Flux Rope. *ApJ*, *934*(1), 50. doi: 10.3847/1538-4357/ac7803
- 685 Hwang, K.-J., Nishimura, Y., Coster, A. J., Gillies, R. G., Fear, R. C., Fuselier,
686 S. A., ... Clausen, L. B. (2020). Sequential observations of flux transfer

- 687 events, poleward-moving auroral forms, and polar cap patches. *Journal of*
688 *Geophysical Research: Space Physics*, 125(6), e2019JA027674. Retrieved
689 from [https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JA027674)
690 [2019JA027674](https://doi.org/10.1029/2019JA027674) (e2019JA027674 2019JA027674) doi: [https://doi.org/10.1029/](https://doi.org/10.1029/2019JA027674)
691 [2019JA027674](https://doi.org/10.1029/2019JA027674)
- 692 Khrabrov, A. V., & Sonnerup, B. U. Ö. (1998). DeHoffmann-Teller Analysis. *ISSI*
693 *Scientific Reports Series*, 1, 221-248.
- 694 Kieokaew, R., Lavraud, B., Fargette, N., Marchaudon, A., Génot, V., Jacquey, C.,
695 ... Burch, J. (2021). Statistical relationship between interplanetary magnetic
696 field conditions and the helicity sign of flux transfer event flux ropes. *Geo-*
697 *physical Research Letters*, 48(6), e2020GL091257. Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020GL091257)
698 [agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020GL091257](https://doi.org/10.1029/2020GL091257)
699 (e2020GL091257 2020GL091257) doi: <https://doi.org/10.1029/2020GL091257>
- 700 Lee, L. C., & Fu, Z. F. (1985, February). A theory of magnetic flux transfer at the
701 Earth's magnetopause. *Geophysical Research Letters*, 12(2), 105-108. doi: [10](https://doi.org/10.1029/GL012i002p00105)
702 [.1029/GL012i002p00105](https://doi.org/10.1029/GL012i002p00105)
- 703 Lockwood, M., Cowley, S. W. H., Sandholt, P. E., & Lepping, R. P. (1990, Octo-
704 ber). The ionospheric signatures of flux transfer events and solar wind dynamic
705 pressure changes. *Journal of Geophys. Res.*, 95(A10), 17113-17135. doi:
706 [10.1029/JA095iA10p17113](https://doi.org/10.1029/JA095iA10p17113)
- 707 Longcope, D., Beveridge, C., Qiu, J., Ravindra, B., Barnes, G., & Dasso, S. (2007,
708 August). Modeling and Measuring the Flux Reconnected and Ejected by the
709 Two-Ribbon Flare/CME Event on 7 November 2004. *Sol. Phys.*, 244, 45-73.
710 doi: [10.1007/s11207-007-0330-7](https://doi.org/10.1007/s11207-007-0330-7)
- 711 Marchaudon, A., Cerisier, J., Bosqued, J., Dunlop, M., Wild, J., Décréau, P., ...
712 Laakso, H. (2004, January). Transient plasma injections in the dayside mag-
713 netosphere: one-to-one correlated observations by Cluster and SuperDARN.
714 *Annales Geophysicae*, 22(1), 141-158. doi: [10.5194/angeo-22-141-2004](https://doi.org/10.5194/angeo-22-141-2004)
- 715 Marchaudon, A., Cerisier, J. C., Greenwald, R. A., & Sofko, G. J. (2004,
716 May). Electrodynamics of a flux transfer event: Experimental test of the
717 Southwood model. *Geophysical Research Letters*, 31(9), L09809. doi:
718 [10.1029/2004GL019922](https://doi.org/10.1029/2004GL019922)
- 719 Martin, C., Shi, X., Schmidt, M., Day, E. K., Bland, E., Khanal, K., ... Krieger, K.
720 (2023, March). *Superdarn/pydarn: pydarn v3.1.1*. Zenodo. Retrieved from
721 <https://doi.org/10.5281/zenodo.7767590> doi: [10.5281/zenodo.7767590](https://doi.org/10.5281/zenodo.7767590)
- 722 Milan, S. E., Lester, M., Cowley, S. W. H., & Brittnacher, M. (2000, July). Con-
723 vection and auroral response to a southward turning of the IMF: Polar UVI,
724 CUTLASS, and IMAGE signatures of transient magnetic flux transfer at
725 the magnetopause. *Journal of Geophys. Res.*, 105(A7), 15741-15756. doi:
726 [10.1029/2000JA900022](https://doi.org/10.1029/2000JA900022)
- 727 Nishitani, N., Ruohoniemi, J. M., Lester, M., Baker, J. B. H., Koustov, A. V.,
728 Shepherd, S. G., ... Kikuchi, T. (2019, March). Review of the accom-
729 plishments of mid-latitude Super Dual Auroral Radar Network (Super-
730 DARN) HF radars. *Progress in Earth and Planetary Science*, 6(1), 27. doi:
731 [10.1186/s40645-019-0270-5](https://doi.org/10.1186/s40645-019-0270-5)
- 732 Oksavik, K., Moen, J., Carlson, H. C., Greenwald, R. A., Milan, S. E., Lester, M.,
733 ... Barnes, R. J. (2005, October). Multi-instrument mapping of the small-
734 scale flow dynamics related to a cusp auroral transient. *Annales Geophysicae*,
735 23(7), 2657-2670. doi: [10.5194/angeo-23-2657-2005](https://doi.org/10.5194/angeo-23-2657-2005)
- 736 Paschmann, G., & Sonnerup, B. U. O. (2008). Proper Frame Determination and
737 Walen Test. *ISSI Scientific Reports Series*, 8, 65-74.
- 738 Phan, T. D., Paschmann, G., Baumjohann, W., Scokopke, N., & Lühr, H. (1994).
739 The magnetosheath region adjacent to the dayside magnetopause: Ampte/irm
740 observations. *Journal of Geophysical Research: Space Physics*, 99(A1), 121-
741 141. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/>

- 10.1029/93JA02444 doi: <https://doi.org/10.1029/93JA02444>
- Pollock, C., Moore, T., Jacques, A., Burch, J., Gliese, U., Saito, Y., ... Zeuch, M. (2016, March). Fast Plasma Investigation for Magnetospheric Multiscale. *Space Sci. Rev.*, *199*(1-4), 331-406. doi: 10.1007/s11214-016-0245-4
- Qi, Y., Russell, C. T., Jia, Y.-D., & Hubbert, M. (2020). Temporal evolution of flux tube entanglement at the magnetopause as observed by the mms satellites. *Geophysical Research Letters*, *47*(23), e2020GL090314. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020GL090314> (e2020GL090314 2020GL090314) doi: <https://doi.org/10.1029/2020GL090314>
- Qiu, J., Hu, Q., Howard, T. A., & Yurchyshyn, V. B. (2007, April). On the Magnetic Flux Budget in Low-Corona Magnetic Reconnection and Interplanetary Coronal Mass Ejections. *ApJ*, *659*, 758-772. doi: 10.1086/512060
- Raeder, J. (2006, March). Flux Transfer Events: 1. generation mechanism for strong southward IMF. *Annales Geophysicae*, *24*(1), 381-392. doi: 10.5194/angeo-24-381-2006
- Russell, C. T., Anderson, B. J., Baumjohann, W., Bromund, K. R., Dearborn, D., Fischer, D., ... Richter, I. (2016, March). The Magnetospheric Multiscale Magnetometers. *Space Sci. Rev.*, *199*(1-4), 189-256. doi: 10.1007/s11214-014-0057-3
- Russell, C. T., & Elphic, R. C. (1978, December). Initial ISEE Magnetometer Results: Magnetopause Observations (Article published in the special issues: Advances in Magnetospheric Physics with GEOS- 1 and ISEE - 1 and 2.). *Space Sci. Rev.*, *22*(6), 681-715. doi: 10.1007/BF00212619
- Russell, C. T., Priest, E. R., & Lee, L. C. (1990, January). Physics of magnetic flux ropes. *Washington DC American Geophysical Union Geophysical Monograph Series*, *58*. doi: 10.1029/GM058
- Sandholt, P. E., Deehr, C. S., Egeland, A., Lybekk, B., Viereck, R., & Romick, G. J. (1986, September). Signatures in the dayside aurora of plasma transfer from the magnetosheath. *Journal of Geophys. Res.*, *91*(A9), 10063-10079. doi: 10.1029/JA091iA09p10063
- Shepherd, S. G. (2014). Altitude-adjusted corrected geomagnetic coordinates: Definition and functional approximations. *Journal of Geophysical Research: Space Physics*, *119*(9), 7501-7521. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2014JA020264> doi: <https://doi.org/10.1002/2014JA020264>
- Shi, X., Schmidt, M., Martin, C. J., Billett, D. D., Bland, E., Tholley, F. H., ... McWilliams, K. (2022). pydarn: A python software for visualizing superdarn radar data. *Frontiers in Astronomy and Space Sciences*, *9*. Retrieved from <https://www.frontiersin.org/articles/10.3389/fspas.2022.1022690> doi: 10.3389/fspas.2022.1022690
- Shue, J. H., Song, P., Russell, C. T., Steinberg, J. T., Chao, J. K., Zastenker, G., ... Kawano, H. (1998, August). Magnetopause location under extreme solar wind conditions. *Journal of Geophys. Res.*, *103*(A8), 17691-17700. doi: 10.1029/98JA01103
- Sonnerup, B. U. Ö., Hasegawa, H., & Paschmann, G. (2004, June). Anatomy of a flux transfer event seen by Cluster. *Geophysical Research Letters*, *31*, 11803. doi: 10.1029/2004GL020134
- Thomas, E. G., & Shepherd, S. G. (2018). Statistical patterns of ionospheric convection derived from mid-latitude, high-latitude, and polar superdarn hf radar observations. *Journal of Geophysical Research: Space Physics*, *123*(4), 3196-3216. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2018JA025280> doi: <https://doi.org/10.1002/2018JA025280>
- Tsyganenko, N. A. (1996, October). Effects of the solar wind conditions in the global magnetospheric configurations as deduced from data-based field models

- 797 (Invited). In E. J. Rolfe & B. Kaldeich (Eds.), *International conference on*
798 *substorms* (Vol. 389, p. 181).
- 799 Vorobev, V. G., Starkov, G. V., Gustafsson, G., Feldshtein, I. I., & Shevnina, N. F.
800 (1975, February). Dynamics of day and night aurora during substorms.
801 *Planet. Space Sci.*, *23*(2), 269-278. doi: 10.1016/0032-0633(75)90132-4
- 802 Wild, J. A., Milan, S. E., Cowley, S. W. H., Dunlop, M. W., Owen, C. J., Bosqued,
803 J. M., ... Rème, H. (2003, August). Coordinated interhemispheric Super-
804 DARN radar observations of the ionospheric response to flux transfer events
805 observed by the Cluster spacecraft at the high-latitude magnetopause. *Annales*
806 *Geophysicae*, *21*(8), 1807-1826. doi: 10.5194/angeo-21-1807-2003
- 807 Zhang, H., Zong, Q., Connor, H., Delamere, P., Facskó, G., Han, D., ... Yao,
808 S. (2022, August). Dayside Transient Phenomena and Their Impact on
809 the Magnetosphere and Ionosphere. *Space Sci. Rev.*, *218*(5), 40. doi:
810 10.1007/s11214-021-00865-0
- 811 Zou, Y., Walsh, B. M., Chen, L.-J., Ng, J., Shi, X., Wang, C.-P., ... Michael Ruo-
812 honiemi, J. (2022). Unsteady magnetopause reconnection under quasi-steady
813 solar wind driving. *Geophysical Research Letters*, *49*(1), e2021GL096583.
814 Retrieved from [https://agupubs.onlinelibrary.wiley.com/doi/abs/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021GL096583)
815 [10.1029/2021GL096583](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021GL096583) (e2021GL096583 2021GL096583) doi: [https://](https://doi.org/10.1029/2021GL096583)
816 doi.org/10.1029/2021GL096583
- 817 Zou, Y., Walsh, B. M., Nishimura, Y., Angelopoulos, V., Ruohoniemi, J. M.,
818 McWilliams, K. A., & Nishitani, N. (2018). Spreading speed of mag-
819 netopause reconnection x-lines using ground-satellite coordination. *Geo-*
820 *physical Research Letters*, *45*(1), 80-89. Retrieved from [https://agupubs](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017GL075765)
821 [.onlinelibrary.wiley.com/doi/abs/10.1002/2017GL075765](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017GL075765) doi:
822 <https://doi.org/10.1002/2017GL075765>
- 823 Zou, Y., Walsh, B. M., Shi, X., Lyons, L., Liu, J., Angelopoulos, V., ... Hender-
824 son, M. G. (2021). Geospace plume and its impact on dayside magnetopause
825 reconnection rate. *Journal of Geophysical Research: Space Physics*, *126*(6),
826 e2021JA029117. Retrieved from [https://agupubs.onlinelibrary.wiley](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021JA029117)
827 [.com/doi/abs/10.1029/2021JA029117](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021JA029117) (e2021JA029117 2021JA029117) doi:
828 <https://doi.org/10.1029/2021JA029117>