https://doi.org/10.5194/angeo-2021-58
Preprint. Discussion started: 22 October 2021

Annales Geophysicae Discussions

Dayside magnetopause reconnection and flux transfer events: BepiColombo earth-Flyby observations

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Abstract. This study analyzes the flux transfer event (FTE)-type flux ropes and magnetic reconnection around the dayside magnetopause during BepiColombo's Earth flyby. The magnetosheath corresponds to a high plasma β (~ 8) and the IMF has a significant radial component. Six flux ropes are identified. The motion of flux rope together with the maximum magnetic shear model suggests that the reconnection X-line swipes BepiColombo near the magnetic equator due to an increase of the radial IMF. The flux rope with the highest flux content contains a clear coalescence signature, i.e., two smaller flux ropes merging, supporting theoretical predictions the flux content of flux ropes can grow through coalescence. The secondary reconnection associated with coalescence exhibits a large normalized guide field and a reconnection rate comparable to the reconnection rate measured at the magnetopause (~ 0.1).

1. Introduction

Flux transfer events (FTEs) are frequently observed near the outer boundaries of planetary magnetospheres, including at the Earth (e.g., Russell and Elphic, 1978; Saunders et al., 1984; Wang et al., 2005), Mercury (Russell and Walker, 1985; Slavin et al., 2009; 2010; 2012; Imber et al., 2014; Sun et al., 2020), Saturn (Jasinski et al., 2016; 2021) and Jupiter (Walker and Russell, 1985; Lai et al., 2012). Some of the FTEs have magnetic flux ropes at their cores, which consist of helical magnetic field lines surrounding stronger magnetic fields paralleling their central axes (Paschmann et al., 1982; Lee et al., 1993). These FTE-type flux ropes are created by multiple X-line reconnections in the magnetopause during intervals of significant magnetic shear across this current sheet (Lee and Fu, 1985; Raeder, 2006). As a result, the FTE-type flux ropes signal not only the occurrence of magnetic reconnection but their direction of travel can be used to infer the relative location of the reconnection X-lines at the magnetopause.

https://doi.org/10.5194/angeo-2021-58
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FTEs contribute to the transport of magnetic flux from the dayside to the nightside magnetosphere that drives the Dungey cycle in dipolar planetary magnetospheres. In Mercury's magnetosphere, the FTE-type flux ropes transport majority of (>60%) the circulated flux (Slavin et al., 2010; Imber et al., 2014; Sun et al., 2020). In contrast, FTE-type flux ropes are estimated to transport only a small portion (<5%) of the circulated flux at Earth (Lockwood et al., 1995; Fear et al., 2017). And for the giant outer planetary magnetospheres at Jupiter and Saturn, they appear to transport a negligible magnetic flux (< 1%) for the solar wind-driven portion of their internal convection (Jasinski et al., 2021).

FTEs at Earth are most frequent during periods of the southward interplanetary magnetic field (IMF) when the magnetic shear angle across the magnetopause is larger than 90° (e.g., Rijnbeek et al., 1984; Kuo et al., 1995; Wang et al., 2006). The locations of magnetopause X-lines are closely related to the orientation of the IMF. For example, during the purely southward IMF, reconnections most likely occur on the magnetopause near the subsolar point (Dungey, 1961). During the purely northward IMF, reconnections occur on the magnetopause tailward of the cusp (Dungey, 1961; Song and Russell, 1992; Shi et al., 2009; 2013). Magnetic reconnection is also thought to occur at the dayside magnetopause under the strong radial IMF (B_x dominate) (Belenkaya, 1998; Luhmann et al., 1984; Pi et al., 2017; Tang et al., 2013), but the strong radial IMF conditions are less well studied.

Coalescence events, which refer to the merging of neighboring flux ropes, are thought to be an important process in space plasma physics (Biskamp and Welter, 1980; Dorelli and Bhattacharjee, 2009; Fermo et al., 2011; Hoilijoki et al., 2017). The merging of flux ropes is associated with secondary reconnection, and changes in magnetic field configuration caused by this secondary reconnection can energize particles, especially electrons (Drake et al., 2006). Furthermore, several studies have suggested that FTE-type flux ropes are initially formed at electron to ion scales. They then grow through coalescence, thereby, increasing their magnetic flux content (Fermo et al., 2011; Akhavan-Tafti et al., 2018). NASA's Magnetospheric Multiscale (MMS) Mission (Burch et al., 2016) has provided several observations between neighboring flux ropes, for example, Øieroset et al. (2016); Zhou et al. (2017); and Kacem et al. (2018).

This study investigates FTE-type flux ropes and reconnection at the Earth's dayside magnetopause during BepiColombo's flyby on 10 April 2020. The paper is arranged as follows. Section 2 introduces the BepiColombo mission and the measurements during the dayside magnetopause crossing. Section 3 analyzes the distribution of magnetopause reconnection with a strong radial IMF component, and the properties of the flux ropes, including a coalescence event. Section 4 provides a summary of our results.

2. BepiColombo Dayside Magnetopause Crossing

2.1. Spacecraft and Instrumentation

BepiColombo, which is a joint mission by the ESA and the JAXA, consists of two spacecraft, which are the Mercury Planetary Orbiter (MPO) and Mercury Magnetospheric Orbiter (MMO, or Mio). These spacecraft together will carry out detailed investigations of Mercury's interior, surface, exosphere, and magnetosphere (Milillo et al., 2020; Murakami et al., 2020; Benkhoff et al., 2010). The mission made its first planetary flyby maneuver at Earth on 10 April 2020 (Mangano et al., 2021), during which several instruments collected measurements.

https://doi.org/10.5194/angeo-2021-58
Preprint. Discussion started: 22 October 2021

This study uses measurements collected by the magnetometer (MAG) onboard MPO (Heyner et al., 2021), the low energy electron by Mercury Electron Analyzer (MEA) (Sauvaud et al., 2010), which is part of the Mercury Plasma Particle Experiment (MPPE) onboard Mio (Saito et al., 2021). The MPO/MAG includes one outbound sensor and one inbound sensor, and it has a sampling rate of 128 Hz. Mio/MEA has a sampling rate of 4 s. The IMF and solar wind conditions are obtained from the OMNI dataset (King and Papitashvili, 2005), which has a time resolution of 1 minute.

2.2. Overview of Magnetosheath and Magnetopause

Figure 1 shows an overview of the dayside magnetopause crossing during BepiColombo's Earth flyby. BepiColombo traveled from the magnetosheath into the dayside magnetosphere. It crossed the magnetopause at a distance of ~ 4.8 R_E dawnward from the subsolar magnetopause. During the 30 minutes interval around the magnetopause crossing (~00:05 to 00:35 UT) analyzed here, the IMF was southward with a strong radial component. The B_x was the dominant component (B_x/B_t > 0.7 in Figure 1f). The average electron density in the magnetosheath was estimated to be ~ 10 cm^{-3} based on the onboard-calculated partial moment from Mio/MEA between 00:05 and 00:28. The magnetosheath plasma β was high with a value of ~ 8.0, which was the ratio of the thermal pressure to the magnetic pressure. The thermal pressure in the magnetosheath was calculated by assuming that the pressure balance existed across the dayside magnetopause and that the thermal pressure inside the dayside magnetosphere was negligible compared to the magnetic pressure.

3. Magnetopause Reconnections and FTE-type Flux Ropes

3.1. Identification of FTE-type Flux Ropes

The FTEs were identified after the measured magnetic field was rotated into boundary normal coordinates (the LMN coordinates). The minimum variance analysis (MVA) (Sonnerup and Cahill Jr., 1967; Sonnerup and Scheible, 1998) was performed on the magnetic field measurements across the magnetopause current sheet from 00:32:30 to 00:33:25 UT. The MVA results produced L = [0.10, 0.24, 0.97] (maximum variance direction), M = [0.12, 0.96, -0.25] (intermediate variance direction), N = [0.99, -0.14, -0.06] (minimum variance direction), and the eigenvalue ratios $\lambda_{max}/\lambda_{int}$ ~ 54.3, $\lambda_{int}/\lambda_{min}$ ~ 3.9. Both of the ratios were larger than 3 indicating that the LMN coordinate of the magnetopause was well determined [*Sonnerup & Scheible*, 1998].

The FTEs are identified with bipolar signatures in the normal magnetic field (B_N) and clear magnetic field rotation (Russell and Elphic, 1978). The identification of FTEs with flux rope cores requires the additional signature of a strong magnetic field along their central axis, i.e. the intermediate variance direction [e.g. *Akhavan-Tafti et al.*, 2018]. Six FTE-type flux ropes were identified in this manner in the magnetosheath just upstream of the dayside magnetopause and marked with green arrows in Figure 1e and listed in Table 1.

The first FTE-type flux rope was observed at ~ 00:11:03 UT when the IMF clock angle was ~ 210°, and B_x/B_t ~ 0.75. This flux rope traveled southward as inferred from the polarities of the B_N variation. About 2 minutes later, the clock angle increased to ~ 260°. This IMF orientation persisted for about 12 minutes, during which no FTE-type flux ropes were observed. At ~ 00:26:06 UT, the clock angle decreased from ~ 260° to ~ 210° while the ratio of B_x/B_t

https://doi.org/10.5194/angeo-2021-58
Preprint. Discussion started: 22 October 2021

increased to ~ 0.90. At this point, 5 FTE-type flux ropes successively appeared up to the point where the magnetopause was crossed. The direction of travel for these 5 flux ropes was inferred to be northward, again based on the B_N variations. The first flux rope traveled southward indicating that the primary magnetopause X-line was initially located northward of the spacecraft. Later, the northward motion of the 5 flux ropes indicated that the primary magnetopause X-line(s) had shifted southward.

3.2. Reconnection X-lines from Maximum Magnetic Shear Model

To further investigate reconnection during BepiColombo's dayside magnetopause traversal, the maximum magnetic shear model (Trattner et al., 2007; 2017) was employed to deduce the location of the reconnection X-lines. The magnetic shear angle plots during the intervals centered at 00:09, 00:20, 00:28 UT are shown in Figure 2. Figures 2a and 2b correspond to a distorted feature of the anti-parallel reconnection region, which has recently been termed a "Knee" event (Trattner et al., 2021). The bent shape of the anti-parallel reconnection region is associated with the field line draping in the magnetosheath during the dominant B_x (significantly sunward) component during this period.

In Figure 2a, BepiColombo was located southward of the predicted X-line. From Figure 2a to Figure 2b, the predicted X-line crossed the location of BepiColombo and was then located to the south of BepiColombo. The changes of X-line locations from Figures 2a to 2b are due to the IMF clock angle decreased around 10° together with the B_x/B_t increased from 0.78 to 0.86.

The direction of motion for our FTE-type flux ropes was consistent with the predicted location of the reconnection X-line predicted by the maximum magnetic shear model during the changing solar wind conditions for this magnetopause encounter. Figure 2a corresponded to the only southward traveling FTE-type flux rope, while the other five northward traveling FTE-type flux ropes were observed during the conditions shown in Figures 2b and 2c. Although the maximum magnetic shear model faces challenges in determining the draping magnetic field lines in the magnetosheath during the intervals of the dominant B_x component (Trattner et al., 2007; 2012), the model predictions were consistent with our observations during BepiColombo's crossing.

3.3. FTE-type Flux Rope Modeling

This study employs a force-free flux rope model (Kivelson and Khurana, 1995) to fit the FTE-type flux ropes. This flux rope model starts from the periodic pinch solution (Schindler et al., 1973) of Ampere's law ($\nabla \times \vec{B} = \mu_0 \vec{J}$), where $\vec{B}$ is the magnetic field vector, $\vec{J}$ is the current density vector, and μ_0 is the magnetic permeability in the vacuum. Kivelson and Khurana (1995) include the axial magnetic field component (B_{int}). This model does not consider the gradient of the magnetic field along the axis of the flux rope. The self-consistent solution of the flux rope model is

https://doi.org/10.5194/angeo-2021-58
Preprint. Discussion started: 22 October 2021

Annales Geophysicae
Discussions

$$\begin{cases} B_{max} = \left(\frac{B_T}{\chi}\right)\sqrt{1+\epsilon^2}\sinh\left(\frac{x_{min}}{T}\right) \\ B_{int} = \left(\frac{B_T}{\chi}\right)\sqrt{1+\left(\frac{B_{int0}\chi}{B_T}\right)^2} \\ B_{min} = \left(\frac{B_T}{\chi}\right)\epsilon\sin\left(\frac{x_{max}}{T}\right) \end{cases} \quad (1)$$

In the equation, the parameter ε is associated with the shape of the flux rope. The x_{min} and x_{max} are the locations along with $\vec{n}_{min}$ and $\vec{n}_{max}$. The T is the vertical scale of flux rope and the B_T is the magnetic field intensity near the boundary of the flux rope along with the $\vec{n}_{min}$. The B_{int0} is the B_{int} in the background. In this study, the $\vec{n}_{min}$, $\vec{n}_{int}$ and $\vec{n}_{max}$ refer to the local coordinate of each flux rope. The χ is

$$\chi = \epsilon\cos\left(\frac{x_{max}}{T}\right) + \sqrt{1+\epsilon^2}\cosh\left(\frac{x_{min}}{T}\right) \quad (2)$$

The axial flux content (Φ_{axial}) is calculated by integrating the axial field (B_{int}) over the entire flux rope area,

$$\Phi_{axial} = \int B_{int}dS \quad (3)$$

During the fitting, we assume that the traveling speed of flux ropes was 100 km/s, which corresponds to the average Alfvén speed in the sub-solar magnetosheath. The least-squares of the minimization of the magnetic field differences (X^2) is employed to define the best fit, which is calculated from

$$\mathrm{X}^2 = \frac{\sum_{i=1}^{N_{point}}\sum_{j}^{max,int,min}\left[\left(B_j(i) - B_j'(i)\right)/B_t(i)\right]^2}{N_{point}} \quad (4)$$

where B_{max}, B_{int}, B_{min}, and B_t are the components and magnitude of the measured magnetic fields and B'_{max}, B'_{int}, and B'_{min} are the components from the model. The N_{point} is the number of data points. We set up a threshold of $\mathrm{X}^2 < 0.1$ to be the successful modeling.

Different from the circular profile of flux ropes resulted from the Lundquist force-free flux rope model (Lundquist, 1950), this force-free model gives a flattened profile of the flux rope. We use the semi-minor and semi-major to refer to the flatten features. This flux rope model is successfully applied for the flux ropes in the Earth's plasma sheet (Kivelson and Khurana, 1995), Earth's magnetopause (Zhang et al., 2008), and in Mercury's plasma sheet (Zhao et al., 2019).

Out of the 6 FTE-type flux ropes, 4 were successfully modeled. The modeling results were summarized in Table 1. In Figures 3a to 3d, the dashed lines overlapping with the solid measured magnetic fields represent the modeling curves from the flux rope model. The plasma density was ~ 10 cm^{-3} corresponding to an ion inertial length (d_i) of ~ 70 km. The two FTE-type flux ropes centered at 00:26:06 UT and 00:26:26 UT were in the scales of several d_i. The magnetic flux content of these two flux ropes was small (~ 20 kWb). In addition, these two flux ropes corresponded to the largest and smallest core fields.

The other two FTE-type flux ropes centered at 00:28:13 UT and 00:30:26 UT were in the scales of more than 10 d_i. These two flux ropes contained much higher magnetic flux (~ 300 kWb and ~ 188 kWb). The analysis of the flux rope centered at ~ 00:28:13 UT corresponding to the highest magnetic flux content is shown in the next.

3.4. Coalescence Event

Figure 3 shows that the magnetic field measurements of the FTE-type flux rope centered at ~ 00:28:13 UT in the LMN coordinate. Figure 3c showed the B_N included two successive bipolar signatures, which implied that two smaller scale flux ropes merging. Indeed, the hodogram in the B_{max}-B_{int} plane in Figure 3f confirmed the field rotations of two flux ropes, named “FR#A” and “FR#B”. Figure 3e further illustrated the merging of FR#A and FR#B, and the trajectory of BepiColombo. The magenta arrows and shaded region in Figure 3e indicated the secondary reconnection between FR#A and FR#B. This FTE-type flux rope with the highest flux content was cleared resulted from the coalescence of two smaller-scale flux ropes.

It needs to note that the coalescence signature is only observed in this FTE-type flux rope. We did not see similar successive bipolar signatures of the B_N in other 5 FTE-type flux ropes.

3.5. Magnetopause Reconnection and Secondary Magnetic Reconnection

In Figure 4, the reconnection properties of the secondary reconnecting current sheet in the coalescence event (Figure 3) and the magnetopause current sheet are studied. For the secondary reconnecting current sheet, the ratios of $\lambda_{max}/\lambda_{int}$ ~ 6.4, $\lambda_{int}/\lambda_{min}$ ~ 11.0 resulted from MVA were both larger than 3 indicating the local coordinate of the secondary reconnecting current was well built. The magnetic field measurements of the magnetopause current sheet were shown in the LMN coordinate.

In the reconnecting current sheet, the dimensionless reconnection rate can be determined from the ratio of normal magnetic field component (B_{normal}) to the reconnecting magnetic field (B_{inflow}) in the inflow region (Sonnerup, 1974; Sonnerup et al., 1981; Fuselier and Lewis, 2011; Phan et al., 2001). In the secondary reconnecting current sheet (Figures 4a to 4d), the B_{normal} was ~ 5 nT (the B_{min} averaged from 00:28:08.8 to 00:28:09.6 UT). Here the average B_t from 00:28:09.8 to 00:28:10.4 UT was taken as the B_{inflow} (~ 36 nT). The dimensionless reconnection rate was ~ 0.14. Meanwhile, the intensity of the guide field (B_{int}, Figure 4b) was ~ 32 nT across the current sheet, which was ~ 0.89 when normalized to the B_{inflow}. However, it needs to point out that the estimation of reconnection rate based on B_N/B_{inflow} could be imprecise. For example, the uncertainties of the normal direction and the fluctuations in the field strength could influence the accuracy of the reconnection rates.

In the magnetopause current sheet, the B_{normal} was 8.3 nT (averaged B_N from 00:32:56 to 00:33:05 UT, Figure 4g). The B_{inflow} in the magnetosphere side adjacent to the magnetopause was ~ 46.1 nT (average B_t from 00:33:06 to 00:33:15 UT, Figure 4h). Thus, the dimensionless reconnection rate was calculated to be ~ 0.18. The guide field across the magnetopause was ~ 13 nT, which was 0.28 normalized to the B_{inflow}.

4. Conclusions and Discussions

Our analysis of the subsolar magnetopause observations during BepiColombo’s Earth flyby was produced several conclusions.

First, the BepiColombo’s dayside magnetopause crossing corresponds to the magnetosheath with high plasma β (~ 8) and a significant radial component of the IMF (B_x/B_{tot} > 0.75). The traveling of the FTE-type flux rope suggests that the X-line crosses the location of BepiColombo, which is verified by the motion of the X-lines obtained from

https://doi.org/10.5194/angeo-2021-58
Preprint. Discussion started: 22 October 2021

the maximum magnetic shear model. The motion of the X-line is associated with the rotation and the increase in the B_x of the IMF. BepiColombo crosses the magnetopause near the magnetic equator, and 10 April 2020 is close to the spring equinox, which indicates a small dipole tilt influence. These observations of the crossing of the X-line provide clear evidence of magnetic reconnection near the magnetic equator under a strong radial IMF.

Second, the properties of the FTE-type flux ropes are determined by employing a flux rope model. The FTE-type flux ropes have scales ranging from several d_i to around 20 d_i, and the FTE-type flux rope with a large scale and the highest magnetic flux content corresponds to a clear coalescence signature. This observation strongly supports a key feature that the FTE-type flux rope can grow in scale and magnetic flux content through coalescence.

Third, the features of magnetic reconnection associated with the secondary reconnection in the coalescence event and the magnetopause current sheet are investigated. The reconnection rate of the secondary reconnection (0.14) is comparable with the reconnection rate on the dayside magnetopause (0.18). However, the secondary reconnection corresponds to a larger normalized guide field (0.89) than the magnetopause reconnection (0.28).

The large guide field is likely a common feature for the secondary magnetic reconnection during the coalescence. Using the MMS measurements, Zhou et al. (2017) reported a coalescence event with a strong guide field. We suggest that the large guide field shall be considered in the simulations, which investigate the particle energizations due to the coalescence. For example, the large guide field may influence the reconnection rate as suggested by Pritchett and Coroniti (2004) and Ricci et al. (2004), and therefore influences the energization of particles during the coalescence. Furthermore, a recent investigation also suggests that a large guide field might limit the ability of Fermi acceleration during the coalescence (Montag et al., 2017).

The FTE-type flux rope containing coalescence signature has a scale of ~20 d_i. Therefore, the secondary reconnecting current sheet embedded within the FTE-type flux rope is likely with scale much smaller than 20 d_i. We want to note that the secondary reconnection during the coalescence of flux ropes share some similarities with the electron-only reconnection the magnetosheath turbulence, whose reconnecting current sheet has scales (< 10 d_i) and a large guide field as revealed by MMS measurements (Phan et al., 2018; Stawarz et al., 2019) and simulations (Califano et al., 2020). Therefore, it is likely that the secondary reconnection associated with coalescence is also electron-only magnetic reconnection, which certainly deserves a detail study.

Data availability

The measurements from Mio/MEA and MPO/MAG analyzed in this study are available in the supporting information. The data archiving is underway. Mio/MEA data will be able to be accessed from the AMDA science analysis system (http://amda.cdpp.eu) provided by the Centre de Données de la Physique des Plasmas (CDPP) supported by CNRS, CNES, Observatoire de Paris, and Université Paul Sabatier Toulouse. MPO/MAG data will be available from https://archives.esac.esa.int/psa/#!Home%20View. OMNI dataset is available at https://omniweb.gsfc.nasa.gov/.

Author contributions

W. J. S. led the work, identified the events, conducted the data analysis of the dataset, and wrote the manuscript. W. J. S., J. A. S. and R. N. jointly designed the work. D. H. and J. Z. D. M. provided knowledge of the MPO-MAG instrument and the MPO-MAG data. S. A. and N. A. provided knowledge of the Mio-MEA instrument and the Mio-MEA data. K. J. T. provided Figure 3 and the relevant descriptions. J. T. Z. performed force-free fittings of the flux ropes. All authors discussed and contributed to the manuscript.

Competing interests

The authors declare no competing interests.

Acknowledgment

The BepiColombo project is supported by ESA and JAXA. W. J. S. and J. A. S. were supported by NASA Grants NNX16AJ67G and 80NSSC18K1137. N.A. and S.A. acknowledge the support of CNES for the BepiColombo mission. The research at LASP (K. J. T.) is supported by NASA grant NNG04EB99C and 80NSSC20K0688. W. J. S. thanks Dr. Gangkai Poh for helpful discussions.

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Figures and Tables

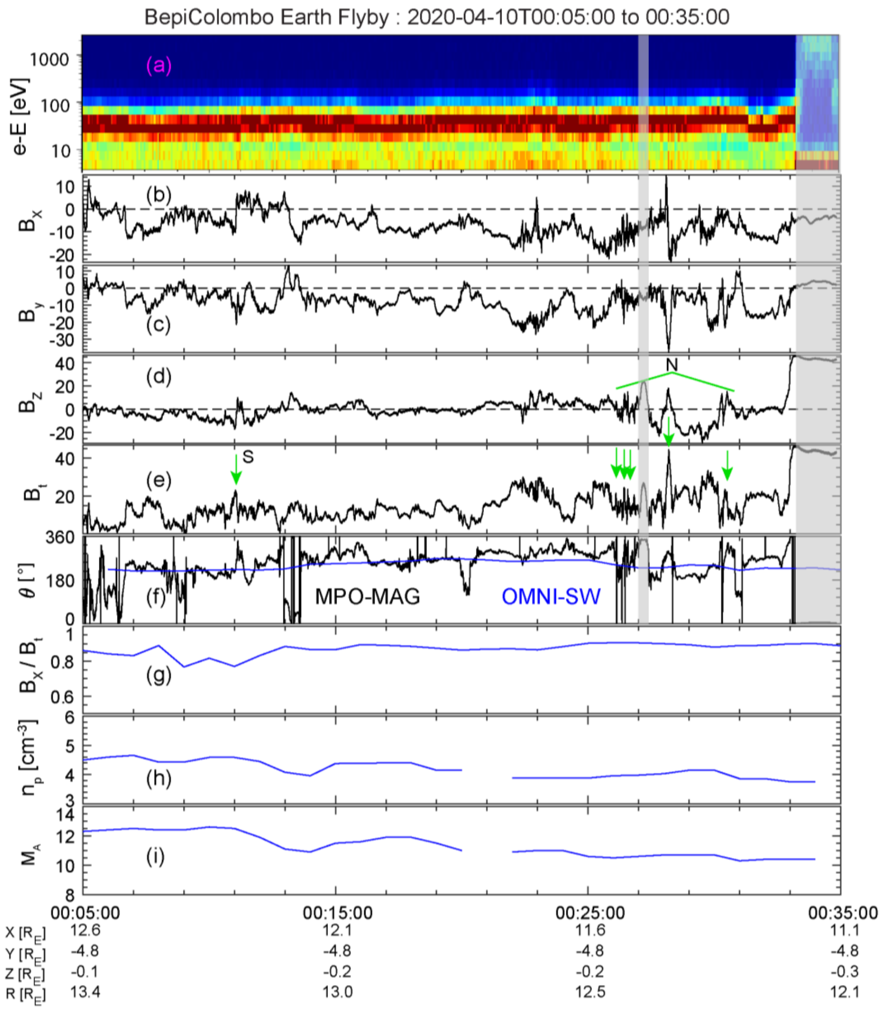

Figure 1. The electrons and magnetic field measurements of the dayside magnetopause. (a) the time-energy spectrogram of normalized electron counts from Mio/MEA, (b) B_x, (c) B_y, (d), B_z, (e) the magnetic field intensity, B_t, (f) the clock angle (θ), solar wind ratio of B_x/B_t (g), number density (n_p) (h), Alfvénic Mach number (M_A) (i). The black lines are from MPO/MAG, and the blue lines are from the OMNI. All quantities are in the Geocentric Solar Magnetospheric (GSM) coordinate. The θ in (f) is defined as arctan(B_y/B_z), ranging from 0° to 360°. The green arrows in (e) indicate the six FTE-type flux ropes. "S" indicates southward traveling and "N" northward traveling.

https://doi.org/10.5194/angeo-2021-58
Preprint. Discussion started: 22 October 2021

Table 1. List and properties of FTE-type flux ropes observed during BepiColombo's dayside magnetopause crossing

#	Time	Duration (s)	Travelling Direction	Core Field Intensity (nT)	Scale (km) [b]	Flux Content (kWb)	X^2
1	00:11:03	~ 12	Southward	— [a]	—	—	—
2	00:26:06	~ 7	Northward	~23.9	~462, 388	~13.7	~0.04
3	00:26:26	~ 6	Northward	~60.8	~565, 524	~22.5	~0.04
4	00:26:35	~ 4	Northward	—	—	—	—
5	00:28:13	~ 20	Northward	~41	~1745, 1281	~300	~0.08
6	00:30:26	~ 15	Northward	~45.2	~1853,1745	~188	~0.08

[a] "—" indicate that the values are not determined by the flux rope model. See the text for more information on the flux rope modeling.

[b] Scale contains semi-minor and semi-major to refer to the flatten profile. See the text for more information.

https://doi.org/10.5194/angeo-2021-58
Preprint. Discussion started: 22 October 2021

Annales Geophysicae
Discussions
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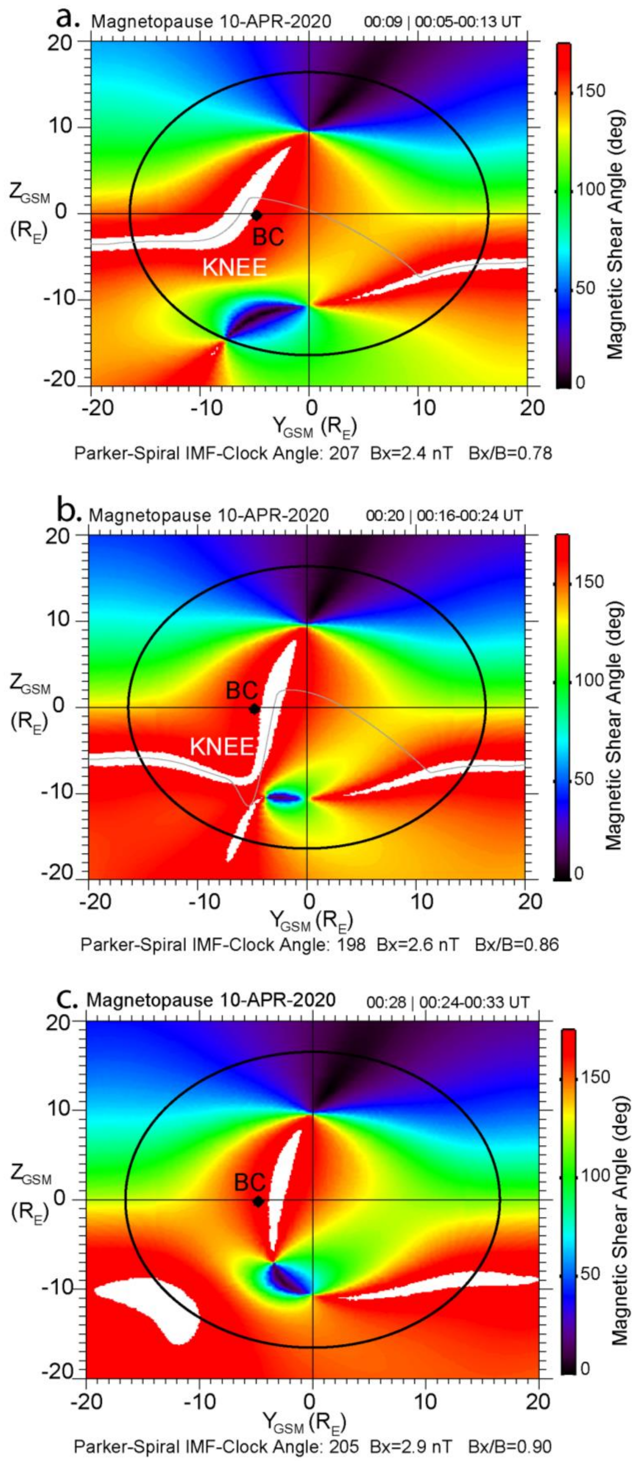
Figure 2. Magnetic shear angle plots on the magnetopause surface during BepiColombo's dayside magnetopause crossing, which are obtained through the maximum magnetic shear model [*Trattner et al.*, 2007]. (a), (b), (c) correspond to the IMF averaged from 00:05 to 00:13 UT, 00:16 to 00:24 UT and 00:24 to 00:33 UT, respectively. The black circle is the terminator plane separating the dayside magnetopause from the tailward magnetopause. The grey line is the predicted magnetopause reconnection line. White areas correspond to the magnetic shear angle is within 3° of 180°. The black dots are the location of BepiColombo ("BC"). The anti-parallel reconnection region shows a shape that is termed the "KNEE" event as it resembles a bent knee similar to an event discussed in *Trattner et al.* [2021].



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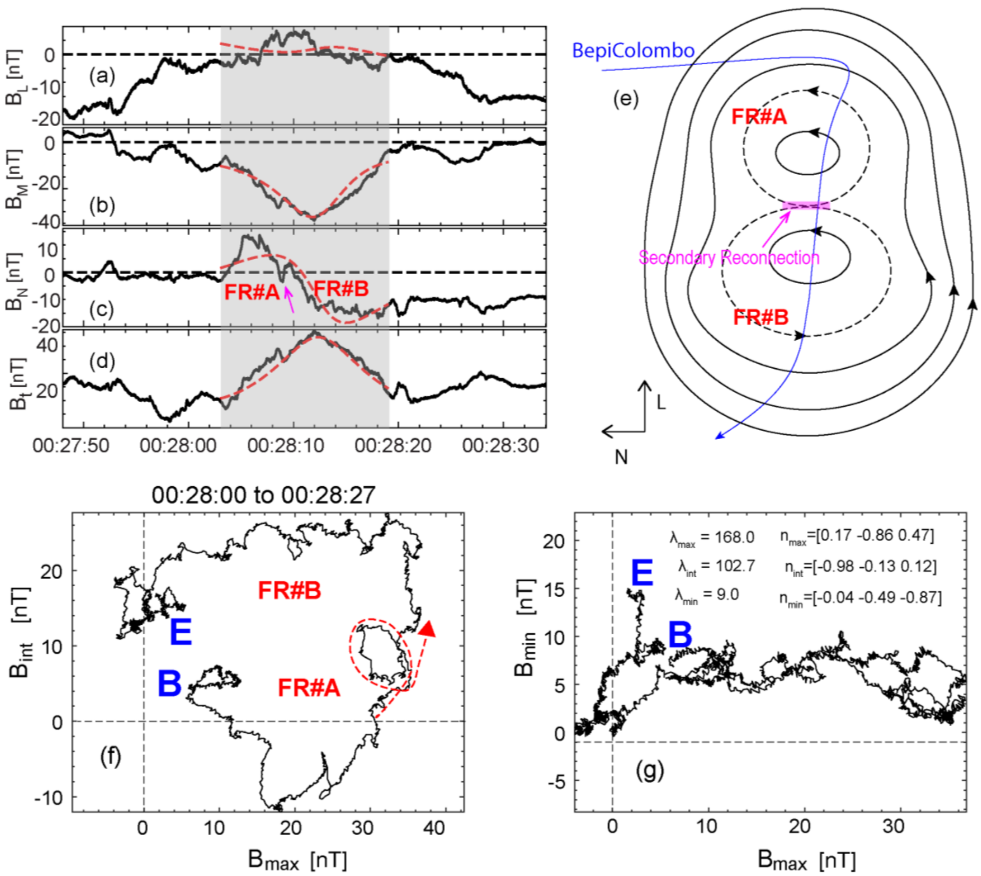

520 **Figure 3. Overview of the flux rope centered at ~ 00:28:13 UT with the coalescence feature.** (a) B_L, (b) B_M, (c) B_N, (d) B_t. The dashed lines are obtained from the flux rope model. This LMN is the local coordinate of the magnetopause. See the text for more information. (e) An illustration of the coalescence event and the BepiColombo's trajectory. The secondary reconnection site is marked by the magenta region in (e). (f) and (g) are the hodograms of the magnetic field measurements under the local coordinate of the flux rope. The "B" and "E"
525 indicate the beginning and the end of the data points. FR#A and FR#B are the two smaller flux ropes.

https://doi.org/10.5194/angeo-2021-58
Preprint. Discussion started: 22 October 2021

Annales Geophysicae Discussions

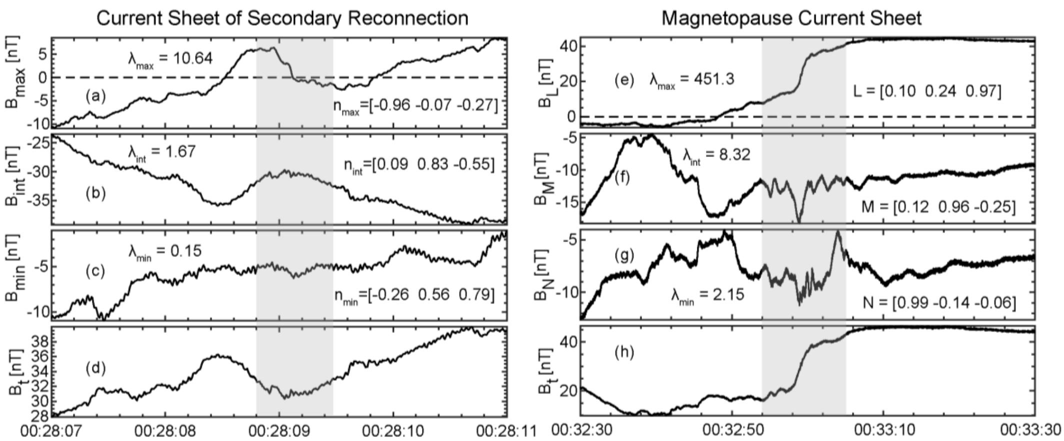

Figure 4. The magnetic field measurements under their separately local coordinate for the reconnecting current sheet of the coalescence event and the magnetopause current sheet. (a) to (d) are for the coalescence event, (e) to (h) are for the magnetopause current sheet. The eigenvalues and corresponding eigenvectors resulted from the MVA are shown.