

Spatial distribution of Mercury's flux ropes and reconnection fronts: MESSENGER observations

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Abstract. We perform a statistical study of flux ropes and reconnection fronts based on MESSENGER magnetic field and plasma observations to study the implications for the spatial distribution of reconnection sites in Mercury's near magnetotail. The results show important differences of temporal and spatial distributions as compared to Earth. We have surveyed the plasma sheet crossings between $-2 R_M$ and $-3 R_M$ down tail from the planet, i.e., the location of Near Mercury Neutral Line (NMNL). Plasma sheets were defined to be regions with $\beta \geq 0.5$. Using this definition, 39 flux ropes and 86 reconnection fronts were identified in the plasma sheet. At Mercury, the distributions of flux ropes and reconnection fronts show clear dawn-dusk asymmetry with much higher occurrence rate on the dawnside plasma sheet than on the duskside. This suggests that magnetic reconnection in Mercury's magnetotail occurs more frequently in the dawnside than in the duskside plasma sheet, which is different than the observations in Earth's magnetotail showing more reconnection signatures in the duskside plasma sheet. The distribution of plasma sheet thickness shows that plasma sheet near the midnight is the thinnest part and does not show obvious asymmetry. Thus, the reasons that cause magnetic reconnection to preferentially occur on the dawnside of the magnetotail at Mercury may not be the plasma sheet thickness and require further study. The peak occurrence rates of flux ropes and reconnection fronts in Mercury's plasma sheet are ~ 60 times higher than that of Earth's values, which we interpret to be due to the highly variable magnetospheric conditions at Mercury. Such higher occurrence rate of magnetic reconnection would generate more plasma flows in the dawnside plasma sheet than in the duskside. These plasma flows would mostly brake and initiate the substorm dipolarization on the postmidnight sector at Mercury rather than the premidnight substorm onset location at Earth.

Keywords. flux ropes, reconnection fronts, reconnection site, dawn-dusk asymmetry, Mercury's magnetotail, comparison with Earth

1. Introduction

Mercury is the closest to the Sun of the planets in the Solar System, with solar wind conditions quite different than those near Earth. Because the solar wind velocity does not vary a lot from the Mercury to the Earth, the stronger interplanetary magnetic field (IMF) intensity and higher solar wind density at Mercury would result in higher solar wind dynamic pressure than that at Earth [e.g., *Glassmeier, 1997*]. Observations from Mariner 10 and MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) [*Solomon et al., 2007*] revealed that Mercury's intrinsic magnetic field is closely aligned ($< 5^\circ$) with the planet's rotation axis, and exhibits the same polarity as the Earth, but the intensity of magnetic field near Mercury's surface is only $\sim 1\%$ of the Earth's surface field [e.g., *Ness et al., 1974; Alexeev et al., 2010; Anderson et al., 2010, 2011*]. It is because of the strong solar wind dynamic pressure and weak internal magnetic field that the subsolar standoff distance for Mercury's magnetopause is only $\sim 0.45 R_M$ away from the surface, where $R_M \approx 2440$ km is Mercury's radius [*Winslow et al., 2013; Zhong et al., 2015*]. Mercury's magnetosphere has been reported to be experienced many similar processes and structures dominated by magnetic reconnection as those at Earth, such as the flux transfer events (FTEs) near the magnetopause [*Russell and Walker, 1985; Slavin et al., 2009, 2010a, 2012a*], flux ropes and reconnection fronts in the magnetotail [*Slavin et al., 2009, 2012b; Sundberg et al., 2012a; DiBraccio et al., 2015*], and also the magnetospheric substorm processes [*Slavin et al., 2010b; Sun et al., 2015a, 2015b*]. Mercury's magnetospheric substorm at Mercury exhibits similar plasma sheet thinning process during growth phase and plasma sheet thicken during expansion phase, i.e., magnetospheric global reconfiguration during substorm [*Sun et al., 2015b*], but with a time scale (~ 2 to 3 minutes) much shorter than Earth's substorm (~ 2 to 3 hours) [*Slavin et al., 2010b; Sun et al., 2015b*].

Plasmoids were first proposed to be formed between the near and distant neutral lines during Earth's substorms with magnetic loop structures [Hones, 1977]. In order to generate magnetic loop topology, it would require anti-parallel ($\sim 180^\circ$) magnetic field lines between the neutral lines in the magnetotail. But the magnetic field in Earth's magnetotail is commonly observed to have strong B_y with the influence of IMF [e.g., Cowley, 1981]. This strong B_y would result in the formation of flux ropes containing helical field lines between neutral lines [e.g., Hughes and Sibeck, 1987; Mowdwin and Hughes, 1991]. The motion of plasmoids or flux ropes in the plasma sheet could compress the nearby lobe regions, which are called traveling compression regions (TCRs) [Slavin *et al.*, 1984]. Reconnection fronts (RFs, also called dipolarization fronts) were extensively studied in the Earth's plasma sheet [Runov *et al.*, 2009; Angelopoulos *et al.*, 2013; Liu *et al.*, 2013; Sun *et al.*, 2013], and are believed to be highly associated with magnetic reconnection [e.g., Sitnov *et al.*, 2009; Fu *et al.*, 2013; Ashour-Abdalla *et al.*, 2015]. The structure is identified as the leading edge of planetward propagating dipolarizing flux bundle (DFB, also called plasma bubble) [Liu *et al.*, 2013; Sun *et al.*, 2014]. The distributions of flux ropes, reconnection fronts and TCRs in Earth's magnetotail show clear dawn-dusk asymmetry with more events observed on the duskside than on the dawnside [Slavin *et al.*, 2005; Imber *et al.*, 2011; Liu *et al.*, 2013], which indicate that magnetic reconnection would more frequently occur in the duskside plasma sheet. This indication agrees with the distribution of reconnection generated flux bursts [e.g., Angelopoulos *et al.*, 1994; Raj *et al.*, 2002] and also the detected reconnection diffusion regions [e.g., Nagai *et al.*, 2013, 2015; Genestreti *et al.*, 2014] at Earth. Employing the observations from MESSENGER, Slavin *et al.* [2012b] and DiBraccio *et al.* [2015] studied the plasmoids, flux ropes and TCRs in Mercury's magnetotail. Slavin *et al.* [2012b] showed that plasmoids had the durations of ~ 1 to 3 s and

diameters of 500 to 1500 km. *DiBraccio et al.* [2015] conducted a statistical survey of flux ropes in Mercury's plasma sheet. Flux ropes were fitted to a force free model and the mean radius of them (~ 480 km) was shown to be comparable with the background proton gyro-radius (~ 380 km) indicating kinetic effects might be important for the flux ropes. *DiBraccio et al.* [2015] constrained the flux ropes in the region of $0.5 R_M$ centered at midnight, and therefore did not exhibit the dawn-dusk distribution of flux ropes. *Sundberg et al.* [2012a] carried out a study of reconnection fronts and DFBs in Mercury's magnetotail, which contained only five plasma sheet crossings from MESSENGER's orbits. In their study, reconnection fronts were observed to be well-defined one dimensional current sheets, which is consistent with the Earth's study [*Runov et al.*, 2009; *Liu et al.*, 2013; *Sun et al.*, 2014]. But the reconnection fronts and DFBs in Mercury's magnetotail only lasted ~ 2 s and ~ 10 s in average, respectively, which are shorter than those structures in Earth's plasma sheet [e.g., *Liu et al.*, 2013]. The relative short timescales of reconnection fronts and DFBs in Mercury's plasma sheet might reveal the plasma environment at Mercury is different to that at Earth.

Because of the high correlation between these structures (i.e., flux ropes and reconnection fronts in the plasma sheet) and magnetic reconnection, a larger statistical study of flux ropes and reconnection fronts could help us to understand the features of magnetic reconnection in Mercury's plasma sheet, especially the dawn-dusk distributions. The comparison with Earth's results would also increase our understanding of the dynamic processes in Mercury's magnetosphere. By using MESSENGER's magnetic field and plasma data, we have performed such a statistical survey of flux ropes and reconnection fronts in Mercury's magnetotail. We show the occurrence rates and dawn-dusk distribution of these structures, and discuss the near tail reconnection distributions at Mercury. We also compare the results with Earth's.

2. Data sources

This study utilizes plasma and magnetic field data from MESSENGER instruments. The Fast Imaging Plasma Spectrometer sensor (FIPS) [Andrews *et al.*, 2007] measures ions with an energy range from 50 eV/e to 13.7 keV/e in 10 s energy scan. FIPS had a field of view $\sim 1.4 \pi \cdot \text{sr}$ and an angular resolution of $\sim 15^\circ$. Ion moments (density and temperature) can be derived from average FIPS spectra under the assumption of nearly isotropic and highly subsonic plasma [Raines *et al.*, 2011; Gershman *et al.*, 2013]. In this work, plasma moments obtained from one-minute averaged spectra in the magnetotail are used. The Magnetometer (MAG) [Anderson *et al.*, 2007] provides magnetic field measurements at a sample rate of 20 vectors per second. Magnetic field is given in the Mercury Solar Magnetospheric (MSM) coordinates. This coordinate system is centered on the Mercury's magnetic dipole, which has a $\sim 0.2 R_M$ offset northward of the planet's center [e.g., Alexeev *et al.*, 2010; Anderson *et al.*, 2010]. In the coordinates, X_{MSM} axis is sunward, Z_{MSM} axis is northward and normal to the magnetic equatorial plane, and Y_{MSM} axis completes the right-handed coordinate system. Spacecraft position data are provided with the same resolution as magnetic field data and also in the MSM coordinates. We have transformed the spacecraft position into aberrated MSM coordinate system (MSM') in which X'_{MSM} is antiparallel to the average solar wind flow ($\sim 400 \text{ km/s}$), i.e., X_{MSM} and Y_{MSM} have been rotated according to Mercury's orbital motion and average solar wind velocity [e.g. Johnson *et al.*, 2012].

MESSENGER was inserted into orbit about Mercury on 18 March 2011. It entered into a highly eccentric orbit ($\sim 200 \text{ km} \times \sim 15\,300 \text{ km}$) with an inclination of 82.5° until 16 April 2012 when the apoapsis of the orbit was reduced to $\sim 10,000 \text{ km}$ and

the orbital period was changed from ~ 12 hour to ~ 8 hour. MESSENGER's orbits could be divided into "hot" and "warm" seasons during which the MESSENGER periapsis was located on the dayside and nightside, respectively. The positions where MESSENGER crossed the plasma sheet during hot season orbits were further downtail than the warm season orbits, which were resulted from the different periapsis locations. Before 16 April 2012, MESSENGER crossed the plasma sheet at a distance of $\sim -2 R_M$ to $-3 R_M$ downtail during hot seasons, which is consistent with the location of Near Mercury Neutral Line (NMNL) [Slavin *et al.*, 2012b; DiBraccio *et al.*, 2013]. Previous studies at Earth have revealed that the distributions of flux ropes [Imber *et al.*, 2011] and reconnection fronts [Zhou *et al.*, 2014] earthward of the Near Earth Neutral Line (NENL, $> -20 R_E$) is different to that in the NENL region. In order to remove this effect, we therefore only study the flux ropes and reconnection fronts in the NMNL region and also investigate the feature of Mercury's near tail reconnection site. In this study, we survey the plasma sheet crossings during the hot seasons before 16 April 2012. There are three hot seasons, which are from 17 August 2011 to 3 September 2011, 13 November 2011 to 29 November 2011, and 9 February 2012 to 23 February 2012. Figures 1a and 1b show the spatial distribution of orbits in MSM $X'-Z'$ and $X'-Y'$ planes for the hot season from 9 February 2012 to 23 February 2012. It can be seen that MESSENGER's orbits are evenly distributed in the magnetotail during this hot season without obvious bias.

3. Observations of plasma sheet

3.1. MESSENGER observations

Figures 1c and 1d depict two MESSENGER's orbits containing two plasma sheet crossings from one of the three hot seasons. During the intervals, MESSENGER entered into the southern lobe of the tail at the beginning (upper panel in Figure 1), and then crossed the equatorial region and moved into the northern lobe of the near tail. The orbits on 12 February 2012 (in blue, Event I) and 20 February 2012 (in green, Event II) crossed the dawnside and duskside plasma sheet in the tail, respectively. Figure 2 shows the plasma and magnetic field measurements from the two plasma sheet crossings. Vertical dashed lines mark the boundaries of plasma sheet for both events, which are defined to be the edges of high particle flux regions. The regions between two vertical dashed lines correspond to the thick portions on orbital trajectories in Figures 1c and 1d. B_x is negative and B_t almost constant (~ 40 nT for Event I and ~ 50 nT for Event II) before the first vertical lines in both events, indicating MESSENGER was located in the southern lobe. This was confirmed by plasma observation in the first panel showing tenuous particles during the intervals for both events. For both events, increasing particle flux at the first vertical lines, which are defined as the southern edges of plasma sheets, indicates that MESSENGER entered into the plasma sheet. The high proton number density ($n_p > 1 \text{ cm}^{-3}$), depression in B_t , increase in plasma β and magnetic elevation angle (θ) are consistent with features of the plasma sheet. The north boundaries of plasma sheet after the crossing of neutral sheet (reverses in B_x) for both events are marked by the second vertical dashed lines. The north boundary in Event II is located at $\sim [-2.19, 0.35, 0.11] R_M$, but plasma observations for Event I show that MESSENGER was still in the plasma sheet until $\sim 15:56:00$ UT when spacecraft was located at $\sim [-0.94, -0.59, -0.81] R_M$ indicating it encountered the high latitude, low altitude plasma sheet. Magnetic field intensity is much higher in the high latitude plasma sheet than the further downtail plasma sheet (as shown in Event I). Therefore, we will exclude the

high latitude, low altitude plasma sheet regions in this study. The durations in Figure 2 for both events are one hour. These plasma sheet observations indicate that the plasma sheet thicknesses for the two crossings are distinct. We then estimate the thicknesses of the plasma sheets from the locations of spacecraft during the plasma sheet crossing for both events.

In order to avoid the influence from high latitude, low altitude plasma sheet in the northern hemisphere, we only determine the half thickness of plasma sheet in the southern hemisphere. MESSENGER crossed the south edges of plasma sheet at $\sim [-2.63, -1.32, -1.07] R_M$ and $\sim [-2.49, 0.44, -0.22] R_M$ for Event I and Event II, respectively. The centers of the neutral sheets determined from the reverse in B_x during the plasma sheet crossings were at $\sim [-2.24, -1.13, -0.21] R_M$ and $\sim [-2.40, 0.41, -0.12] R_M$ for the two events. Thus the half thicknesses of plasma sheet for Event I and Event II are $\sim 0.86 R_M$ and $\sim 0.1 R_M$, respectively, which is assumed to be the difference between the south boundary of plasma sheet and the center of the neutral sheet. It needs to be noted that there could be multiple neutral sheet crossings (i.e., many B_x reversals) during one plasma sheet crossing. In this study, the center of neutral sheet is determined as the average position of the first and last B_x reversals similar to the study of Zhang *et al.* [2016]. The results show that the half thickness for Event I is about an order of magnitude (~ 8.6 times) thicker than Event II suggesting that the plasma sheet thickness could be extremely variable at Mercury. The proton density and temperature were $\sim 5 \text{ cm}^{-3}$ and $\sim 15 \text{ MK}$ for Event II, but were much denser ($\sim 15 \text{ cm}^{-3}$) and cooler ($\sim 4 \text{ MK}$) for Event I, which shows that thick plasma sheet contains denser and cooler plasma than the thin plasma sheet. In Event II, the proton gyro-radius was estimated to be in the range of 200 to 700 km, which is comparable to the determined plasma sheet thickness ($\sim 0.2 R_M$, $\sim 488 \text{ km}$). Therefore, we would expect intense kinetic effects in this plasma sheet, which is

confirmed by the fluctuations in magnetic field B_z and elevation angle shown in Figure 2. While in Event I, the proton gyro-radius was estimated to be in the range of 100 to 300 km, which is tens time smaller than the plasma sheet thickness ($\sim 1.72 R_M$, ~ 4200 km).

3.2 Plasma sheet identification

In previous studies of the Earth's plasma sheet, the magnetic elevation angle (θ) [e.g., Baumjohann *et al.*, 1990] and plasma β [e.g., Angelopoulos *et al.*, 1994] were commonly used in the separation of plasma sheet and lobes. In the lobe regions, B_x (sometimes B_y could be comparable with B_x) is generally much larger than B_z , and therefore, the magnetic elevation angle is small. As shown in Figure 2, θ is smaller than 15° in the southern lobes of both events, but is much higher in the plasma sheet. In addition, the lobe region contains tenuous plasma leading to a small plasma thermal pressure ($n_i k_B T_i + n_e k_B T_e$) and plasma β . But in the plasma sheet, plasma thermal pressure would be comparable or much larger than the magnetic pressure.

Subsequently, plasma β should be close to or much higher than one, which has been also confirmed in Event I and Event II.

In this study, we use plasma β_p (the ratio of proton thermal pressure to magnetic pressure) as the indicator to separate the plasma sheet and lobe. MESSENGER did not carry an instrument to measure low energy electron distributions, but the statistical results in Earth's plasma sheet had revealed that ion thermal pressure is commonly several times (~ 5 to 10) larger than electron thermal pressure [e.g., Baumjohann *et al.*, 1989]. And the main ion species is proton ($> 90\%$) in Mercury's plasma sheet [Gershman *et al.*, 2014]. Therefore, plasma β_p should be pretty close to plasma β .

We have employed both the plasma β_p and magnetic elevation angle as the criteria to separate the plasma sheet and lobe.

Figure 3 shows the samples of θ and β_p during the three hot seasons in the magnetotail regions containing 98 orbits. The magnetotail crossings with particles from magnetosheath, which contain higher particle flux and lower energy than the plasma sheet particles [e.g., Zurbuchen *et al.*, 2011], were excluded. The magnetotail data points are also constrained to be in the regions within $-1.0 R_M < Z_{MSM} < 0.4 R_M$. $Z_{MSM} < 0.4 R_M$ is used to remove the data points in high latitude, low altitude plasma sheet. Both θ and β_p are in one minute resolution, where magnetic field data are one minute averaged according to the duration of plasma data. Most of the samples in small β_p region correspond with times of small θ ($< 20^\circ$), which should be the lobe samples. The high β_p region incorporates most of the high θ samples, which is consistent with the features in plasma sheet. In order to find the plasma β_p corresponded to the boundary between plasma sheet and lobe, we have shown the average value of θ ($\bar{\theta}$, stars) and the corresponded standard deviation (bars) for each β_p bin in the figure. The value of $\bar{\theta}$ shows a clear jump around $\beta_p = 0.4$ to 0.5 . In the bin of $\beta_p = 0.5$, $\bar{\theta} \approx 14.5^\circ$ with a standard deviation of 15.0° . And in the bin of $\beta_p = 0.4$, $\bar{\theta} \approx 10.3^\circ$ with a standard deviation of 10.7° . Thus, we define that $\beta_p \geq 0.5$ corresponds to the plasma sheet region and $\beta_p < 0.5$ the lobe region. We take Event I (Figure 2a) and Event II (Figure 2b) as examples to evaluate this criterion. The horizontal lines in the β_p panels indicate that $\beta_p = 0.5$ generally coincide with the boundaries of plasma sheet for both events except the high latitude plasma sheet boundary in Event I. In Event I, the south boundary of plasma sheet was located between the points of $\beta_p = 0.1$ (in the lobe side) and 0.5 (in the plasma sheet side). In Event II, $\beta_p = 0.62$ and 1.01 in the plasma sheet side, and $\beta_p = 0.08$ and 0.06 in the

lobe side for the two vertical dashed lines, respectively. Observations from both of the events verify that $\beta_p \geq 0.5$ can be used to identify the plasma sheet. It needs to note that the boundary of high latitude plasma sheet in Event I is not consistent with the criterion $\beta_p \geq 0.5$. In this study, we only use $\beta_p \geq 0.5$ to determine the south boundaries of plasma sheets. During the hot seasons, MESSENGER always crossed the south boundaries of plasma sheet at a distance downtail further than $-2 R_M$.

4. Observations of flux ropes and reconnection fronts

4.1. Flux rope selection

Flux ropes could be formed between pairs of reconnection sites, and are proved to have helical magnetic field topologies [Moldwin and Hughes, 1992; Lepping *et al.*, 1995]. In the magnetotail, strong core fields are observed inside the flux ropes in dawn-dusk direction, which are believed to be highly related with large IMF B_y [Slavin *et al.*, 2003, 2005]. Both planetward and tailward traveling flux ropes were reported in the Earth's and Mercury's magnetotail [Moldwin and Hughes, 1994; Slavin *et al.*, 2003, 2012b; Zong *et al.*, 2004; DiBraccio *et al.*, 2015]. Figures 4a and 4b show two examples of planetward travelling flux rope (PFR) and tailward travelling flux rope (TFR) observed by MESSENGER in Mercury's plasma sheet. From this figure, we can see that the most prominent signatures for flux ropes are clearly south-then-north (SN, for PFR) or north-then-south (NS, for TFR) bipolar in the B_z component, which are accompanied by the enhancements in B_y and B_t . The maximum B_y and B_t generally coincide with the inflection point of B_z bipolar as marked by the vertical dashed lines in both cases.

The amplitude of B_z bipolar from peak to peak is ~ 50 nT for the PFR and ~ 60 nT for the TFR. The enhancements in B_y are ≥ 20 nT and B_t are ≥ 15 nT higher than the ambient field strengths for both cases. To further evaluate the flux ropes, we have applied the minimum (or maximum) variance analysis (MVA) [Sonnerup and Cahill, 1967; Sonnerup and Scheible, 1998] to the structures and show the result of planetward flux rope in Figure 4c. MVA provides three eigenvalues and three eigenvectors with the ratios between eigenvalues indicating the accuracy of the determined eigenvectors. The eigenvectors help us to understand the orientation of flux ropes with respect to Mercury. The maximum eigenvalues (λ_{max}) for both events are close to the intermediate eigenvalues (λ_{int} , $\lambda_{max}/\lambda_{int} \sim 3$), but are much larger than the minimum eigenvalues (λ_{min} , $\lambda_{int}/\lambda_{min} > 30$), which is the expected result when applying MVA to flux ropes [Sonnerup and Scheible, 1998; Xiao et al., 2004; DiBraccio et al., 2015]. For both events, the maximum variance vectors (\vec{n}_{max}) are primarily along the Z'_{MSM} direction, which are consistent with the of B_z bipolar and the minimum variance vectors (\vec{n}_{min}) along X'_{MSM} consistent with the observations that B_x is the least perturbed component. The intermediate variance vectors (\vec{n}_{int}) are almost in Y'_{MSM} direction showing the axial direction of the flux ropes are mainly along the Y'_{MSM} direction. These MVA results are consistent with the previous observations of flux ropes in both Earth's and Mercury's plasma sheet [e.g., Slavin et al., 1993; Zong et al., 1997; DiBraccio et al., 2015]. In B_{int} versus B_{max} hodograms (Figure 4c), the field rotations ($\geq 180^\circ$) further confirm the magnetic field topology of flux ropes.

Traveling compression regions (TCRs) were first observed to be the compressional regions in the lobes caused by the motion of flux ropes in the plasma sheet [Slavin et al., 1984, 2005]. At Mercury, the traveling of FTEs along the tail magnetopause were also observed to be accompanied with TCRs in the magnetotail [Slavin et al., 2012a].

Figure 5 shows a TCR detected by MESSENGER in the north lobe of Mercury's magnetotail. During this event, B_z is close to zero and B_x (~ 48 nT) is much larger than the B_z indicating MESSENGER was located in the lobe region, which is further confirmed by FIPS observations (not shown). The TCR exhibits the signatures of increase in B_x and B_t together with the highly asymmetric bipolar in B_z (left column in Figure 5), which are the typical features of TCRs as reported at Earth and Mercury [Slavin *et al.*, 2005, 2009, 2012b]. MVA results (right column in Figure 5) show that the ratios of λ_{max} to λ_{int} and λ_{int} to λ_{min} are ~ 5 and ~ 60 , respectively, suggesting that the MVA coordinates are well determined. For this TCR, \vec{n}_{max} is mainly along the Z'_{MSM} axis similar to the result of flux rope. But \vec{n}_{int} is along X'_{MSM} and \vec{n}_{min} along Y'_{MSM} , which is opposite to the flux rope with \vec{n}_{int} along Y'_{MSM} and \vec{n}_{min} along X'_{MSM} . This is because TCR consists of the compressed magnetic field lines without helical field topology. In this study, we only consider the flux ropes in the plasma sheet and exclude the TCRs by the above properties. The survey by DiBraccio *et al.* [2015] have revealed certain values of changes in B_z and B_t (ΔB_z and ΔB_t) for flux ropes in Mercury's magnetotail, i.e., $\Delta B_z \geq 20$ nT and $\Delta B_t \geq 10$ nT. In that study they exclude the events that MESSENGER crossed the outer edge of the flux rope. After surveying many events (~ 20 events), we have set $\Delta B_z \geq 15$ nT and $\Delta B_t \geq 5$ nT aiming to include more events. The durations for most flux ropes in that work are smaller than 1 s, but sometimes could be larger than 3 s [Slavin *et al.*, 2012b; DiBraccio *et al.*, 2015]. We have applied the following criteria to select flux ropes in this study:

- (i). Plasma sheet durations are selected based on $\beta_p > 0.5$, and the durations under extreme solar wind conditions [Slavin *et al.*, 2014] are excluded.

(ii). Magnetic field data within the plasma sheet are continuously scanned one data point at a time (t_0) with different intervals ($\pm\Delta t$) on either side of that point. We have set three values (i.e., 0.5 s, 1.25 s, 2.5 s) for Δt .

(iii). The minimum B_z ($B_{z\min}$, corresponding to t_{\min}) in the $t_0 - \Delta t$ to $t_0 + \Delta t$ time range should be smaller than 0. The maximum B_z ($B_{z\max}$, corresponding t_{\max}) should be greater than 0. And $B_{z\max} - B_{z\min}$ should be greater than 15 nT. For PFRs, $t_{\max} > t_{\min}$, while for TFRs, $t_{\max} < t_{\min}$. We note that TCRs in the plasma sheet generated by magnetopause FTE shower could be further avoided by this step as they usually are not accompanied with B_z reversals [Slavin *et al.*, 2012a].

(iv). The maximum B_y and B_t between t_{\min} to t_{\max} should be at least 5 nT larger than the average B_y and B_t in the $t_{\min} - 0.5$ to t_{\min} and t_{\max} to $t_{\max} + 0.5$ time ranges, individually. TCRs are commonly accompanied with Bx enhancements. This step could further exclude the TCRs in plasma sheet.

(v). Applying MVA on the selected events based on criteria (i) to (iv) to further pick up the events showing clear magnetic field rotation (angle $\geq 180^\circ$) in the newly formed coordinates.

(vi). In the newly formed coordinates, B_{\max} should show the bipolar signature, and the inflection point coincide with the local maxima in B_{int} .

4.2 Reconnection fronts selection

A reconnection front is defined as the leading edge of planetward propagating dipolarizing flux bundle (DFB, also called plasma bubble) [e.g., *Sergeev et al.*, 1996; *Angelopoulos et al.*, 2013; *Sun et al.*, 2014], which is believed to be highly related with magnetic reconnection [e.g., *Sitnov et al.*, 2009; *Ashour-Abdalla et al.*, 2015]. Figure 6a shows a typical DFB detected by MESSENGER in Mercury's plasma sheet,

which is defined to be the region between the two vertical dashed lines. The DFB contains stronger magnetic field ($B_t \sim 20$ nT) than the value in ambient plasma sheet ($B_t \sim 8$ nT). The leading edge of this DFB (the first vertical dashed line) is a well-defined reconnection front observed at $\sim 21:29:48$ UT, which shows a decrease in B_z (called magnetic dip) followed by a sharp increase in B_z (from ~ 5 nT to ~ 25 nT) and B_t (from ~ 8 nT to ~ 27 nT) in 0.8 s. Application of MVA on the reconnection fronts shows that the ratios of λ_{max} to λ_{int} and λ_{int} to λ_{min} are ~ 180 and ~ 5 , respectively, indicating it is a well-defined one dimensional structure. Figure 6b shows the magnetic field hodograms under MVA coordinates for the reconnection front. There is no clear field rotation in the hodograms, but the magnetic field perturbation mainly lies in \vec{n}_{max} , which further confirm that reconnection front is one-dimensional structure. This agrees with previous observations at Mercury [Sundberg et al., 2012a] and Earth [Angelopoulos et al., 2013; Liu et al., 2013; Sun et al., 2013]. This DFB ends at $\sim 21:29:55$ UT marked by the second vertical dashed line. This structure lasts ~ 7 s, which is comparable to the duration of DFB in previous observations (~ 10 s) at Mercury [Sundberg et al., 2012a], but much shorter than the duration of DFBs at Earth (~ 60 s) [e.g., Sergeev et al., 1996; Sun et al., 2014]. Another property of DFB is that it contains depleted plasma comparing with ambient plasma sheet [e.g., Chen and Wolf, 1993; Sergeev et al., 1996; Sun et al., 2014]. Since the duration of DFB (~ 10 s) is normally much shorter than the resolution of plasma moments (1 minute), we do not have density measurements within DFB. Therefore, we only employ magnetic field measurements to identify the reconnection fronts in this study. After surveying several tens of reconnection fronts (including those in Sundberg et al. [2012a]), we have set up the following criteria to select reconnection fronts

- (i). Based on the plasma sheet durations given in Section 4.1, magnetic field data inside the plasma sheet are continuously scanned one data point at a time (t_0) with an window of $\pm\Delta t = 1.5$ s on either side of that point, creating an interval of $[t_0 - \Delta t, t_0 + \Delta t]$.
- (ii). The time of maximum B_z (B_{zmax}) should be behind the minimum B_z (B_{zmin}) in the $t_0 - \Delta t$ to $t_0 + \Delta t$ time range. And $B_{zmax} - B_{zmin}$ should be greater than 15 nT.
- (iii). The averaged B_z (B_t) in the interval $[t_0 + \Delta t, t_0 + \Delta t + 1$ s] should be at least 10 nT (5 nT) greater than in the $[t_0 - \Delta t - 1$ s, $t_0 - \Delta t]$.
- (iv). Exclude the flux ropes listed in Section 4.1.

4.3. Statistical results

The examination of 68 plasma sheet crossings during the three hot seasons obtained 39 flux ropes and 86 reconnection fronts based on the criteria described in Sections 4.1 and 4.2. This section shows the statistical results of the flux ropes and reconnection fronts. The histograms in figure 7 show the distribution of MVA ratios of $\lambda_{max}/\lambda_{int}$ and $\lambda_{int}/\lambda_{min}$ for flux ropes and reconnection fronts. The average values of $\lambda_{max}/\lambda_{int}$ and $\lambda_{int}/\lambda_{min}$ for flux ropes are 5.0 and 17.2, respectively, implying most of the \vec{n}_{min} are well determined, which is consistent with the results of *DiBroccio et al.* [2015]. The ratios of $\lambda_{max}/\lambda_{int}$ and $\lambda_{int}/\lambda_{min}$ for reconnection fronts have the average values of 32.6 and 13.4, respectively, indicating that the structures are well defined one dimensional current sheet. This is also consistent with previous studies [e.g., *Liu et al.*, 2013; *Sun et al.*, 2013; *Sundberg et al.*, 2012a].

To further confirm the selection of flux ropes, Figure 8 shows the distribution of MVA eigenvectors with flux rope locations. In each case, the \vec{n}_{max} vector is rotated

to be positive along the Z'_{MSM} . The \vec{n}_{int} vector is positive along the Y'_{MSM} , and \vec{n}_{min} vector completes the right-handed coordinate system. It can be seen that \vec{n}_{max} are primarily along the Z'_{MSM} direction (left column in Figure 8), \vec{n}_{int} primarily along the Y'_{MSM} direction (middle column), and \vec{n}_{min} primarily along the X'_{MSM} direction (right column), respectively. These \vec{n}_{int} vectors confirm that most of the observed flux ropes have axial directions along Y'_{MSM} . The histograms below each vector projection show the distribution of separation angles between \vec{n}_{max} and Z'_{MSM} , i.e., $\psi(\vec{n}_{max}, \vec{z}_{MSM})$, \vec{n}_{int} and Y'_{MSM} , i.e., $\psi(\vec{n}_{int}, \vec{y}_{MSM})$, and \vec{n}_{min} and X'_{MSM} , i.e., $\psi(\vec{n}_{min}, \vec{x}_{MSM})$, respectively. The average values for the separation angles are small (28.1° , 36.3° , 31.7°) confirming the above results inferred from the distribution of MVA eigenvectors. It can be noticed that several of the \vec{n}_{int} vectors shown in the middle column appear tilt towards the X'_{MSM} . On one hand, this would suggest that the axial direction of these flux ropes are skewed in the $X'_{MSM} - Y'_{MSM}$ plane. This phenomenon has been reported in the Earth's magnetotail, which is believed to be due to one end of flux rope is released prior to the release of the other end [e.g., *Moldwin and Hughes*, 1992; *Kiehas et al.*, 2012]. On the other hand, this could be due to the deviations in the MVA determined \vec{n}_{int} .

Figure 9 shows the distributions of separation angles between MVA eigenvectors of reconnection fronts and the axes of MSM'. We have done the similar rotation for MVA eigenvectors of reconnection fronts as flux ropes. The \vec{n}_{max} for reconnection fronts are mostly aligned with Z'_{MSM} with the average value of $\psi(\vec{n}_{max}, \vec{z}_{MSM})$ 26.8° , which is consistent with the most prominent signature of reconnection front, i.e., sharp increase of B_z . But the separation angles between \vec{n}_{int} and Y'_{MSM} and between \vec{n}_{min} and X'_{MSM} are evenly distributed with the average value close to 45° . We suggest that this is due to the shape of reconnection front in the $X'_{MSM} - Y'_{MSM}$ plane being close to a semicircle [e.g., *Pritchett and Coroniti*, 2010; *Liu et al.*, 2013; *Sun et*

al., 2014]. And the reconnection fronts in this study are close to the region of NMNL, i.e., reconnection fronts are “young”. Thus, the DFBs should predominately move towards the planet with small Y'_{MSM} and Z'_{MSM} velocity components, which would result MESSENGER crossing any portion of the semicircle reconnection front in equal probability. As a result, the separation angles between the normal of reconnection front (\vec{n}_{min}) and X'_{MSM} are evenly distributed in the range of 0° to 90° .

5. Occurrence rate of flux ropes and reconnection fronts

The studies in the Earth’s tail have shown dawn-dusk asymmetry of near tail reconnection signatures, such as plasma flows, flux ropes and reconnection fronts, with the structures more frequently observed on the duskside than on the dawnside of the plasma sheet [e.g., *Slavin et al.*, 2005; *Imber et al.*, 2011; *McPherron et al.*, 2011; *Liu et al.*, 2013]. It is suggested that this asymmetry of near tail reconnection occurrences accounts for the substorm auroral onset normally observed on the premidnight (~ 23 MLT) sector of polar region at Earth [e.g., *Liou et al.*, 2001; *Frey et al.*, 2004]. In this section, we show the occurrence rate of flux ropes and reconnection fronts and its implication on near tail reconnection site in the Mercury’s plasma sheet. We also compare the results with the Earth’s observations.

5.1 Dawn-dusk distribution

The upper panel in Figure 10 shows the distribution of plasma sheet durations along Y'_{MSM} direction. Plasma sheet is thicker on the dawn and dusk flanks ($|Y'_{\text{MSM}}| > 1 R_M$) than on the midnight region, which will be further discussed in Figure 11. This phenomenon corresponds to the distribution in Figure 10 that MESSENGER spent

more time in the dawnside and duskside plasma sheet than in the near midnight region. The middle panel in Figure 10 displays the locations of flux ropes (red line, both PFRs and TFRs) and reconnection fronts (blue line). There are obvious asymmetries in these distributions, with more flux ropes and reconnection fronts observed on the dawnside plasma sheet than the duskside plasma sheet. Because the durations MESSENGER stayed in the plasma sheet are not uniform along Y'_{MSM} direction, we have normalized the distribution of flux ropes and reconnection fronts. The bottom panel displays the number of events observed per minute along the Y'_{MSM} location. Red line represents the occurrence rates of flux ropes, and blue line the reconnection fronts. Both the flux ropes and reconnection fronts present obvious asymmetries with occurrence rates higher on the dawnside plasma sheet than the duskside plasma sheet. The location of peak occurrence rate for both structures is $\sim Y'_{\text{MSM}} = -0.5 R_{\text{M}}$. The peak occurrence rate of flux ropes is ~ 0.070 events per minute, which is about half of the value (~ 0.15 events per minute) of reconnection fronts. The average occurrence rate of flux ropes is ~ 0.022 events per minute, which is also half of the occurrence rate of reconnection fronts (~ 0.044).

5.2. Comparison with results at Earth

The dawn-dusk asymmetric distributions of the flux ropes and reconnection fronts with events more frequently observed on the dawnside than the duskside plasma sheet at Mercury is different from that at Earth where flux ropes and reconnection fronts more frequently observed on the duskside plasma sheet [Slavin *et al.*, 2005; Imber *et al.*, 2011; Liu *et al.*, 2013]. The dawn-dusk asymmetry of the two structures indicates that the magnetic reconnection is preferentially occurred in the dawnside plasma sheet at Mercury, while the direct observations of ion diffusion region of magnetic

reconnection in the Earth's plasma sheet showed more frequently observed on the duskside plasma sheet than on the dawnside plasma sheet [Nagai *et al.*, 2013, 2015; Genestreti *et al.*, 2014].

In the study of Liu *et al.* [2013], the peak occurrence rate of reconnection fronts is ~ 2.5 events per 1000 minutes at Earth, i.e., $\sim 2.5 \times 10^{-3}$ events per minute. This value is ~ 60 times smaller than the occurrence rate of reconnection fronts (~ 0.15 events per minutes) at Mercury shown in this study. And Imber *et al.* [2011] showed the peak occurrence rate of flux ropes is ~ 0.070 events per hour, i.e., $\sim 1.2 \times 10^{-3}$ events per minute, which is also ~ 60 times smaller than the peak occurrence rate of flux ropes in this study.

A study of flux transfer event (FTE) shower near the magnetopause at Mercury showed the FTE shower had a period of 8 to 10 s [Slavin *et al.*, 2012a], which is also ~ 60 times shorter than the quasi-periodic FTEs at Earth with the mean period of ~ 8 min [e.g., Lockwood and Wild, 1993]. We note that this difference is consistent with the differences in occurrence rates for flux ropes and reconnection fronts between Mercury and Earth.

6. Discussion and Conclusions

We interpret the dawn-dusk asymmetric distributions of the flux ropes and reconnection fronts as the reconnection site being preferentially located on the dawnside plasma sheet at Mercury. This is different to the results at Earth showing reconnection site more frequently occurred on the duskside plasma sheet than on the dawnside [e.g., Nagai *et al.*, 2013, 2015; Genestreti *et al.*, 2014]. And there are observations of the clear dawn-dusk asymmetry of the thickness of Earth's plasma sheet with the duskside plasma sheet thinner than the dawnside plasma sheet [e.g.,

Fairfield, 1986; Rong *et al.*, 2011; Zhang *et al.*, 2016]. Therefore, we have estimated the half thickness of plasma sheet in the southern hemisphere for all the plasma sheet crossings based on criteria in section 3.1 to show the distribution of plasma sheet thickness along the Y'_{MSM} locations (Figure 11). We only determine the half thickness of plasma sheet in the southern hemisphere due to the north boundary of plasma sheet could be effected by the high latitude plasma sheet when MESSENGER travelled to the northern pole of Mercury.

Each gray circle in the top panel of Figure 11 represents the half thickness ($\Delta Z'_{\text{MSM}}$) of a plasma sheet. The red line is the averaged value of plasma sheet thickness in each bin with the gray lines representing the lower and upper quartiles. This panel shows that plasma sheet near the midnight region ($|Y'_{\text{MSM}}| < 0.8 R_{\text{M}}$) is thinner than the dawn and dusk flank regions ($|Y'_{\text{MSM}}| > 0.8 R_{\text{M}}$). The half thickness of plasma sheet ($\sim 0.3 R_{\text{M}}$) in the dawn flank region ($Y'_{\text{MSM}} < -0.8 R_{\text{M}}$) is thinner than the value ($\sim 0.5 R_{\text{M}}$) of dusk flank region ($Y'_{\text{MSM}} > 0.8 R_{\text{M}}$). Magnetic reconnection is believed to occur in thin plasma sheets with thickness comparable or thinner than background proton gyro-radius [e.g., Liu *et al.*, 2014a]. Therefore, Figure 11 shows the distribution of plasma sheet with thickness smaller than $0.4 R_{\text{M}}$ ($|\Delta Z'_{\text{MSM}}| < 0.2 R_{\text{M}}$, green line) and $0.2 R_{\text{M}}$ ($|\Delta Z'_{\text{MSM}}| < 0.1 R_{\text{M}}$, blue line), respectively. The $0.4 R_{\text{M}}$ (~ 980 km) and $0.2 R_{\text{M}}$ (~ 490 km) thicknesses of plasma sheet are comparable with the proton gyro-radius (~ 200 to 700 km) for the thin plasma sheet in Figure 2. It can be seen that most of the thin plasma sheets are in the near midnight region ($|Y'_{\text{MSM}}| < 0.8 R_{\text{M}}$), which is confirmed by the distribution of occurrence rate of the thin plasma sheet. There is not an obvious dawn-dusk asymmetry. Thus, it seems that the distribution of thin plasma sheet cannot explain the dawn-dusk asymmetric distributions of flux ropes and reconnection fronts in Mercury's plasma sheet. Research at Earth has shown that the thickness of plasma sheet could differ a lot between the southward and

northward IMF periods [Zhang *et al.*, 2016]. Since it is a primary study of plasma sheet thickness distribution in this paper, a further extensive research on the plasma sheet thickness distribution in Mercury's magnetotail is needed.

It should be noted that the heavy ions (Sodium, Na⁺, Oxygen, O⁺) have shown dawn-dusk asymmetry with them enhanced on the duskside plasma sheet in Mercury's magnetotail [Zurbuchen *et al.*, 2011; Raines *et al.*, 2013; Gershman *et al.*, 2014]. But the influence of heavy ions on the initiation of magnetic reconnection is still in debate. The temperature of sodium in Mercury's plasma sheet was investigated to be similar as proton [Gershman *et al.*, 2014]. Thus, the sodium gyroradius would be ~ 23 times larger than proton with a scale of several (~ 2 to 5) R_M, which is always larger than the thickness of plasma sheet as shown in Figure 11. But the study in the Earth's plasma sheet shows that heavy ions (O⁺) seems do not affect the scale of reconnecting current sheet even with a high O⁺ content ($n_{O^+}/n_{H^+} > 0.083$) [Liu *et al.*, 2014b]. Some studies had shown that outflow of O⁺ from the Earth's ionosphere could increase the occurrence of reconnection in the duskside plasma sheet, and therefore facilitate the occurrence of substorm [Baker *et al.*, 1982, 1985], while others indicated that higher O⁺/H⁺ ratio would suppress substorm occurrence [Nosé *et al.*, 2009]. Hence, whether the dawn-dusk asymmetry of magnetic reconnection in Mercury's plasma sheet is due to the influence of heavy ions remains unanswered. It has also been shown that the Kelvin-Helmholtz waves at Mercury are predominately observed on the duskside magnetopause, but is seldomly observed on the dawnside magnetopause [Sundberg *et al.*, 2012b; Liljeblad *et al.*, 2014; Gershman *et al.*, 2015]. Because the scale of KH waves at Mercury could be ~ 1 R_M [Boardsen *et al.*, 2010], therefore, there will be more solar wind plasma entry on the duskside plasma sheet than on the dawnside. The influence of solar wind plasma on the occurrence of magnetic reconnection at Mercury needs further study.

It has been shown that there is no conducting ionosphere at Mercury. The Region 1 field-aligned currents (FACs) might close through the regolith near Mercury's surface, which is quite distinct from the Earth [Anderson *et al.*, 2014]. The magnitude of Region 1 FACs at Mercury (tens of kA) is observed to be two orders smaller than that of Earth (several MA). But the strength varies with different disturbance levels [Anderson *et al.*, 2014], similar to the result at Earth [Alexeev *et al.*, 2000]. No Region 2 FAC signature was detected at Mercury. Mercury's magnetosphere is also different to the Earth's in many other aspects, such as, the scale of Mercury's magnetosphere is much smaller [e.g., Ness *et al.*, 1974; Alexeev *et al.*, 2008], the relative polar cap size of Mercury is larger [Alexeev *et al.*, 2008], and the relatively loaded magnetic flux during magnetospheric substorm is larger [Slavin *et al.*, 2010b; Sun *et al.*, 2015a]. How these differences influence the dynamics of Mercury's magnetosphere desire for further study.

The study from Earth showed close relation between plasmoids (and high speed flows) in the tail with auroral brightening in the polar region [e.g., Fairfield *et al.*, 1999; Ieda *et al.*, 2001]. And the premidnight onset location of Earth's substorm agrees with the average location of reconnection site in the magnetotail [e.g., Imber *et al.*, 2011]. The higher occurrence of flux ropes and reconnection fronts in the dawnside plasma sheet indicates magnetic reconnection more frequently occurred in the dawnside plasma sheet and, therefore, generate more plasma flows in the dawnside plasma sheet at Mercury. Thus, it would be expected that more fast flows brake and initiate substorm onset on the postmidnight sector at Mercury, which is different from the well determined premidnight onset locations of substorm at Earth [e.g., Liou *et al.*, 2001; Frey *et al.*, 2004]. Energetic electrons in Mercury's magnetosphere are more frequently detected on the premidnight sector than on the postmidnight sector

[Lawrence *et al.*, 2015; Baker *et al.*, 2016; Ho *et al.*, 2016; Lindsay *et al.*, 2016]. This is commonly believed to be due to the dawnward drift of electrons in the magnetosphere of Mercury. Our observations would indicate that this could also be due to that more flow bursts brake on the postmidnight sector than on the premidnight sector at Mercury. The substorm dipolarizations during flow brake would energize the electrons and result in more energetic electrons on the postmidnight sector. This process is schematically shown in Figure 12.

The occurrence rate of flux ropes and reconnection fronts in Mercury's magnetotail is ~ 60 times higher than the observations in Earth's magnetotail, which indicates that the occurrence rate of magnetic reconnection in the Mercury's plasma sheet is much higher than the Earth's plasma sheet. Considering that the ~ 2 to 3 minutes magnetic flux circulation time at Mercury, i.e., Dungey circulation or magnetospheric substorm [Slavin *et al.*, 2010b; Sun *et al.*, 2015b], is also ~ 60 times shorter than the duration (~ 2 to 3 hours) at Earth [e.g., Akasofu, 1964; Baker *et al.*, 1996], we conclude that the higher occurrence rate of magnetic reconnection at Mercury is due to its highly variable magnetospheric dynamics.

This study of flux ropes and reconnection fronts in Mercury's magnetotail and comparison with Earth's results have revealed a number of important features for Mercury's magnetosphere.

(1). The distribution of flux ropes and reconnection fronts shows a clear dawn-dusk asymmetry with higher occurrence rate on the dawnside than on the duskside in region of NMNL, which suggests the magnetic reconnection occurs more frequently on the dawnside than on the duskside in Mercury's magnetotail. This is different to the observations in Earth's magnetotail showing more reconnection on the duskside plasma sheet.

(2). The peak occurrence rates of flux ropes and reconnection fronts in Mercury's plasma sheet are ~ 60 times higher than that of Earth's. This could be due to highly variable magnetospheric conditions at Mercury with the time scale of global flux circulation the similar value faster than the Earth.

Furthermore, the results indicate that higher occurrence rate of magnetic reconnection would generate more flow bursts in the dawnside plasma sheet than in the duskside. As a result, flow bursts would mostly brake and initiate the substorm on the postmidnight sector at Mercury rather than the premidnight substorm onset location at Earth. We propose the observations of energetic electrons showing more events in the postmidnight sector than premidnight sector could be not only due to the dawnward drift of electrons, but also the postmidnight substorm initiation (i.e., substorm dipolarizations).

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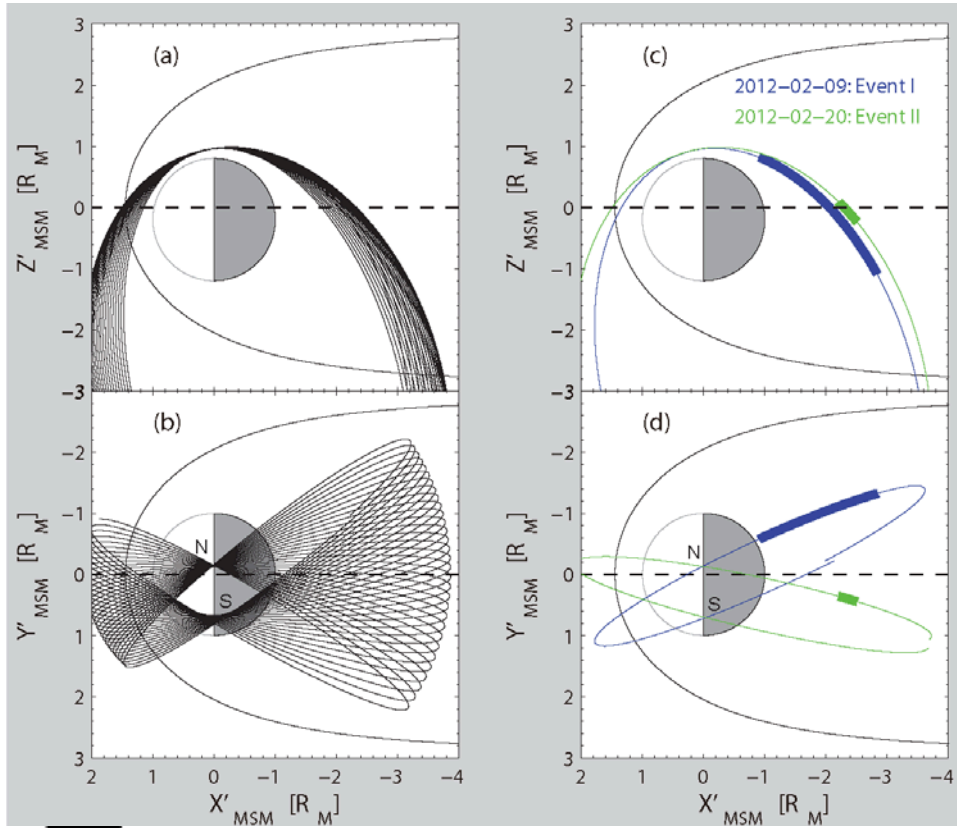


Figure 1 (a, b) MESSENGER orbits during the hot season from 9 February 2012 to 23 February 2012 in the MSM' $X'Z'$ and $X'Y'$ planes, respectively. (c, d) Two orbits from one of the MESSENGER's hot season on 12 February 2012 (blue lines, Event I) and 20 February 2012 (green lines, Event II) in the MSM' $X'Z'$ and $X'Y'$ planes, respectively. The thick portions in each orbit indicate the regions where MESSENGER was located in the plasma sheet.

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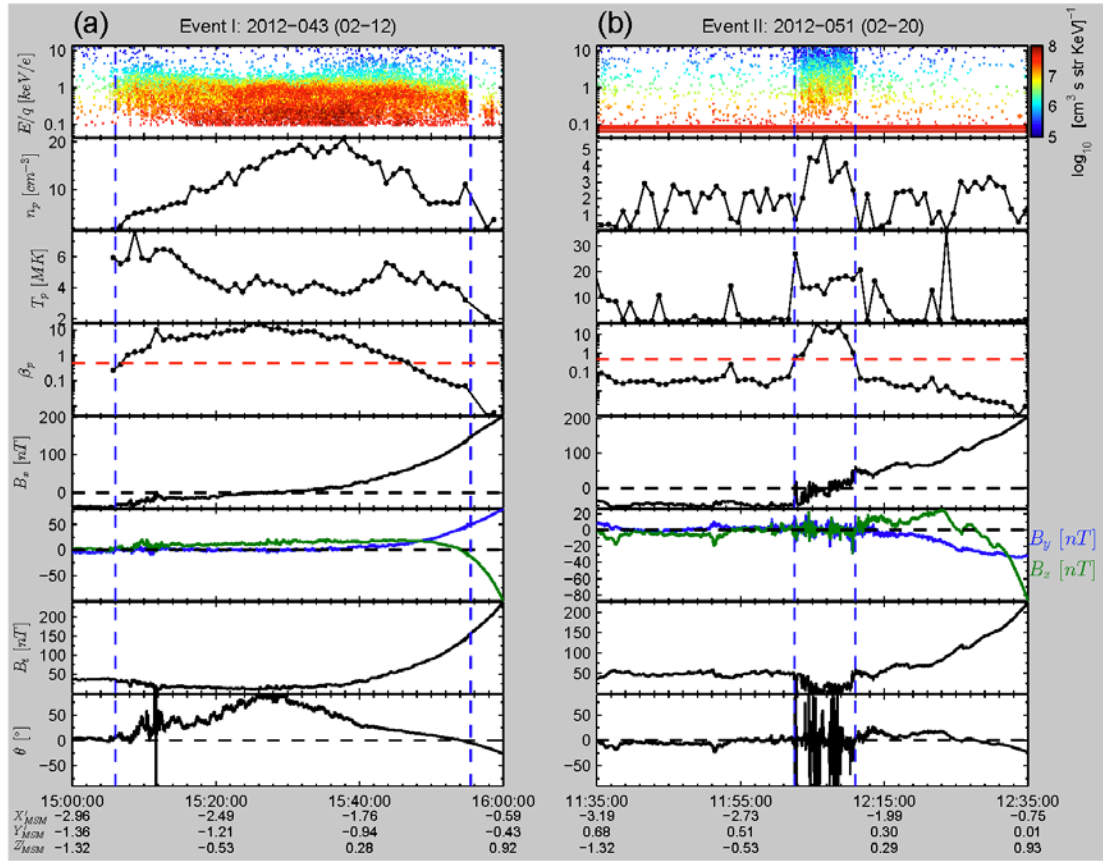


Figure 2 Plasma and magnetic field measurements taken from MESSENGER during plasma sheet crossings for Event I (12 February 2012, a) and Event II (20 February 2012, b). From top to bottom shows: proton energy spectrum; proton density; proton temperature; plasma β_p , $\beta_p = n_p k_B T_p / (B_t^2 / 2\mu_0)$ (Red horizontal lines indicate $\beta_p = 0.5$); magnetic field X component (B_x , in nT); magnetic field Y and Z components (B_y and B_z , in nT); magnetic field intensity (B_t , in nT); magnetic elevation angle (θ), $\theta = \arctan(B_z / \sqrt{B_x^2 + B_y^2})$. Beneath the bottom panel, the ticks are labeled with UT, X'_{MSM} , Y'_{MSM} , and Z'_{MSM} . Vertical dashed lines mark the boundary of plasma sheet as determined from the energy spectra.

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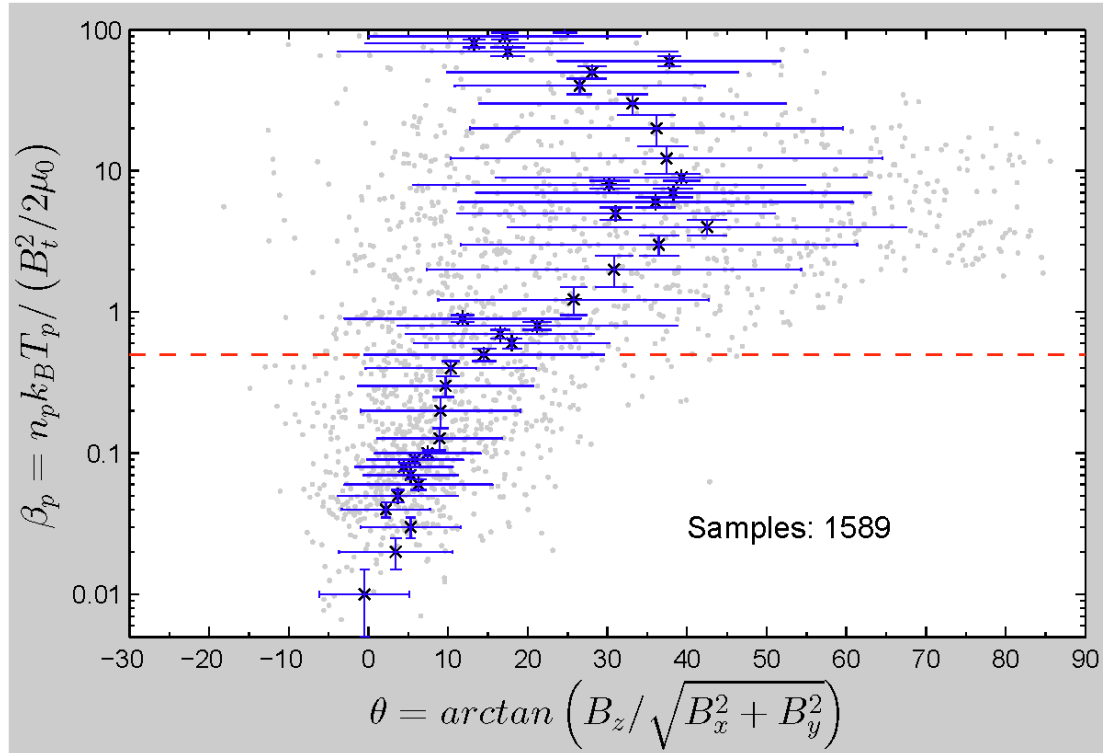


Figure 3. Scatterplot of the magnetic elevation angle (θ) and plasma β_p when MESSENGER was in the magnetotail during the three hot seasons. Both θ and β_p are in one minute resolution. Gray dots represent data points. The averaged value of θ and the corresponded standard deviation in each β_p bin are shown as the asterisk and blue lines. Red dashed line marks the bin of $\beta_p = 0.5$.

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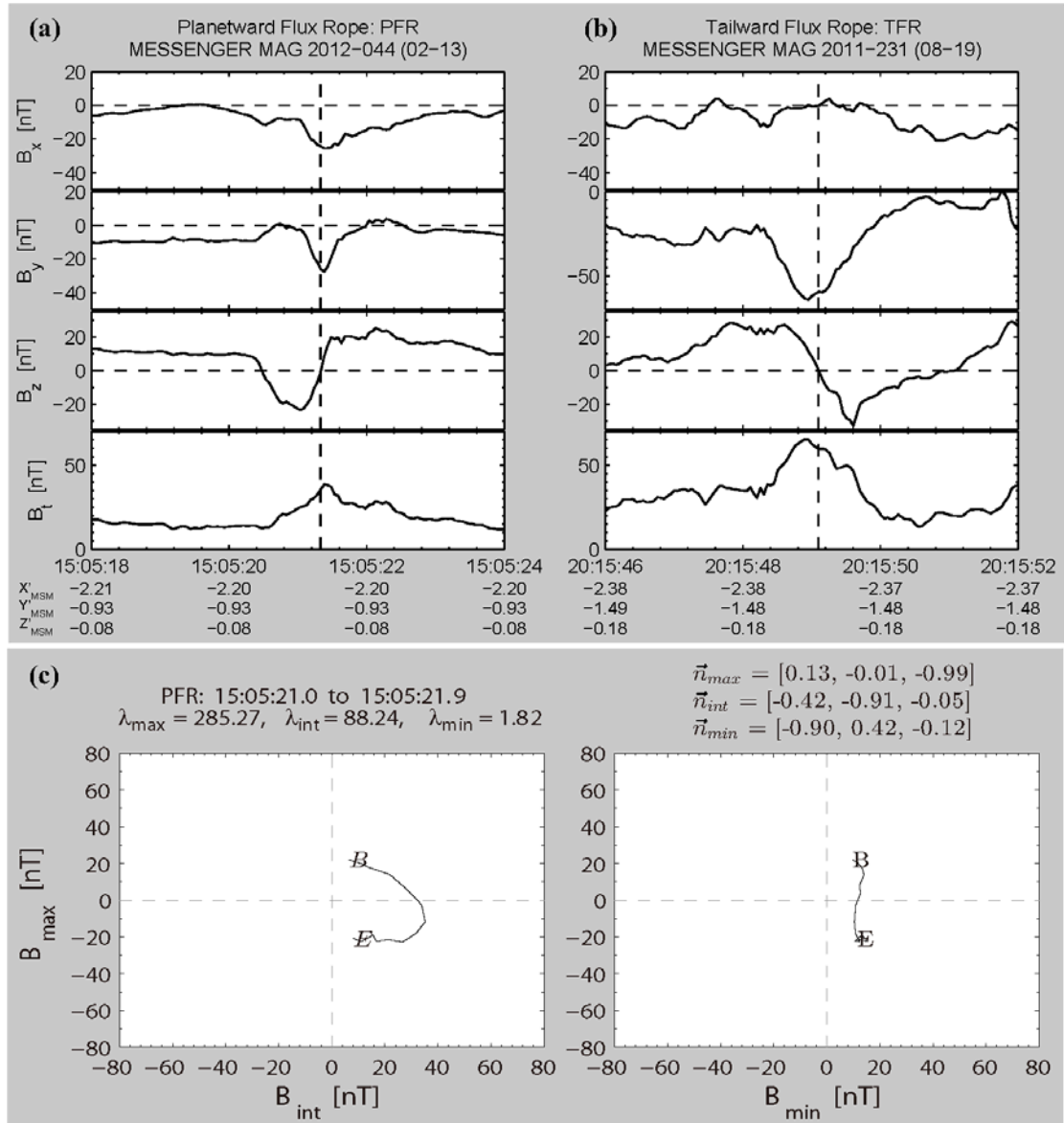


Figure 4. MESSENGER observations of a planetward traveling flux rope (a. PFR) and a tailward traveling flux rope (b. TFR). The vertical dashed line marks the inflection point of the B_z bipolar in each column. (c) Hodograms of the magnetic field measurements in MVA coordinates for the PFR.

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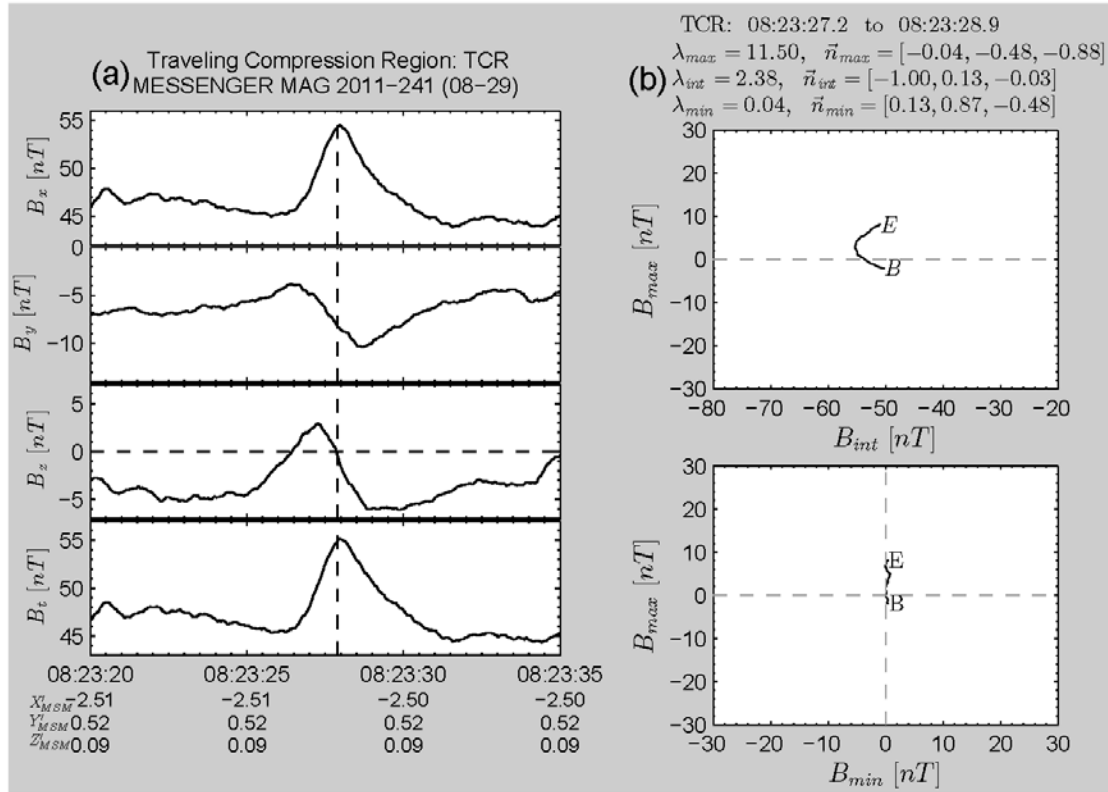


Figure 5. (a) Magnetic field measurement of a tailward traveling compression region (TCR), the vertical dashed line marks the inflection point of B_z bipolar. (b) Hodograms of the magnetic field data in MVA coordinates for the TCR.

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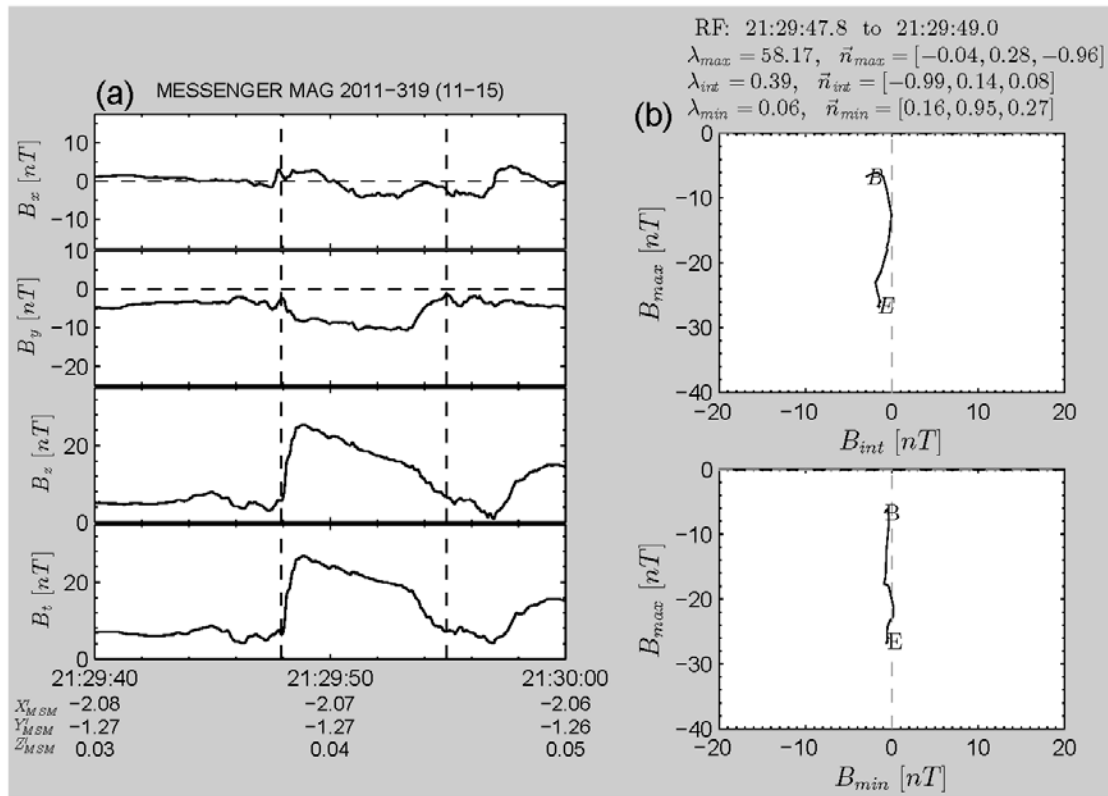


Figure 6 (a) The magnetic field measurements of a dipolarizing flux bundle (DFB, also called plasma bubble) with the leading and trailing edges marked by the two vertical dashed lines. The leading edge is defined as reconnection front (RF, also called dipolarization front). (b) Hodograms of the magnetic field data in MVA coordinates for the reconnection front.

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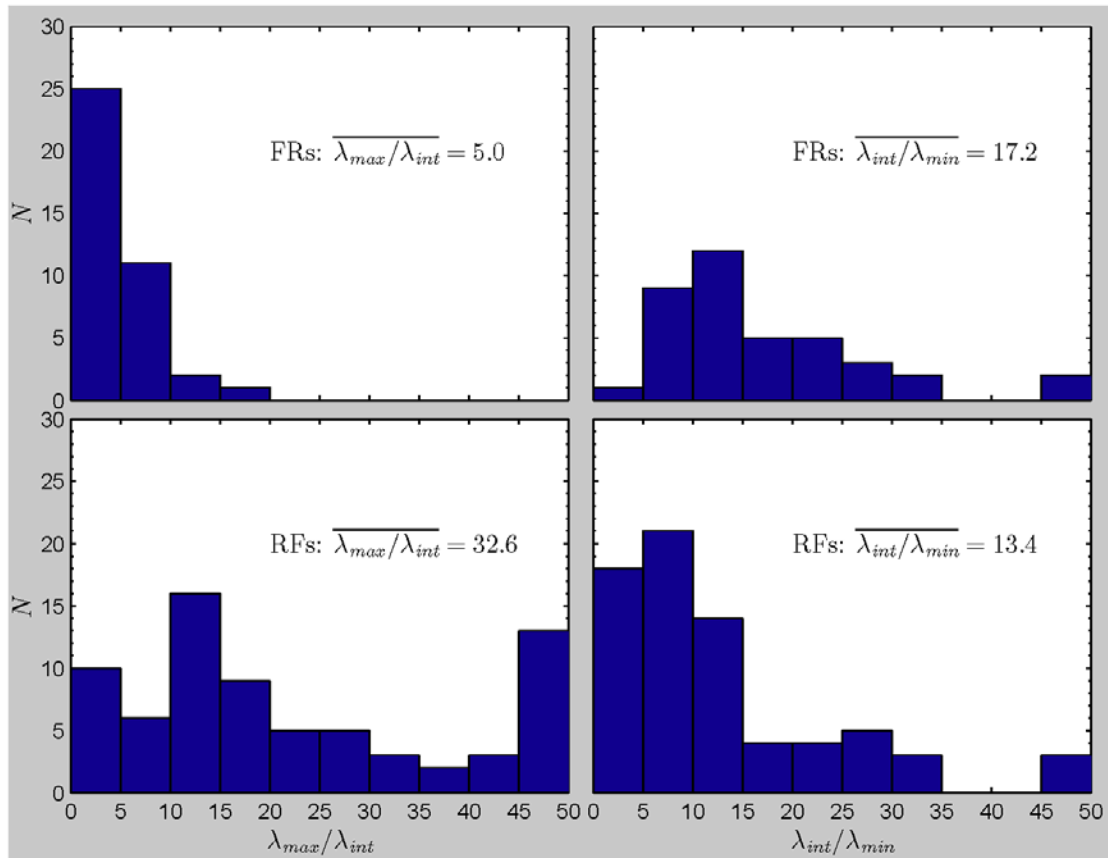


Figure 7 Histograms of the ratio distributions for FRs (upper panel) and RFs (bottom panel). The ratios of maximum to intermediate eigenvalues are shown in the left column. And the ratios of intermediate to minimum eigenvalues are shown in the right column. The average values of each figure are shown in the middle.

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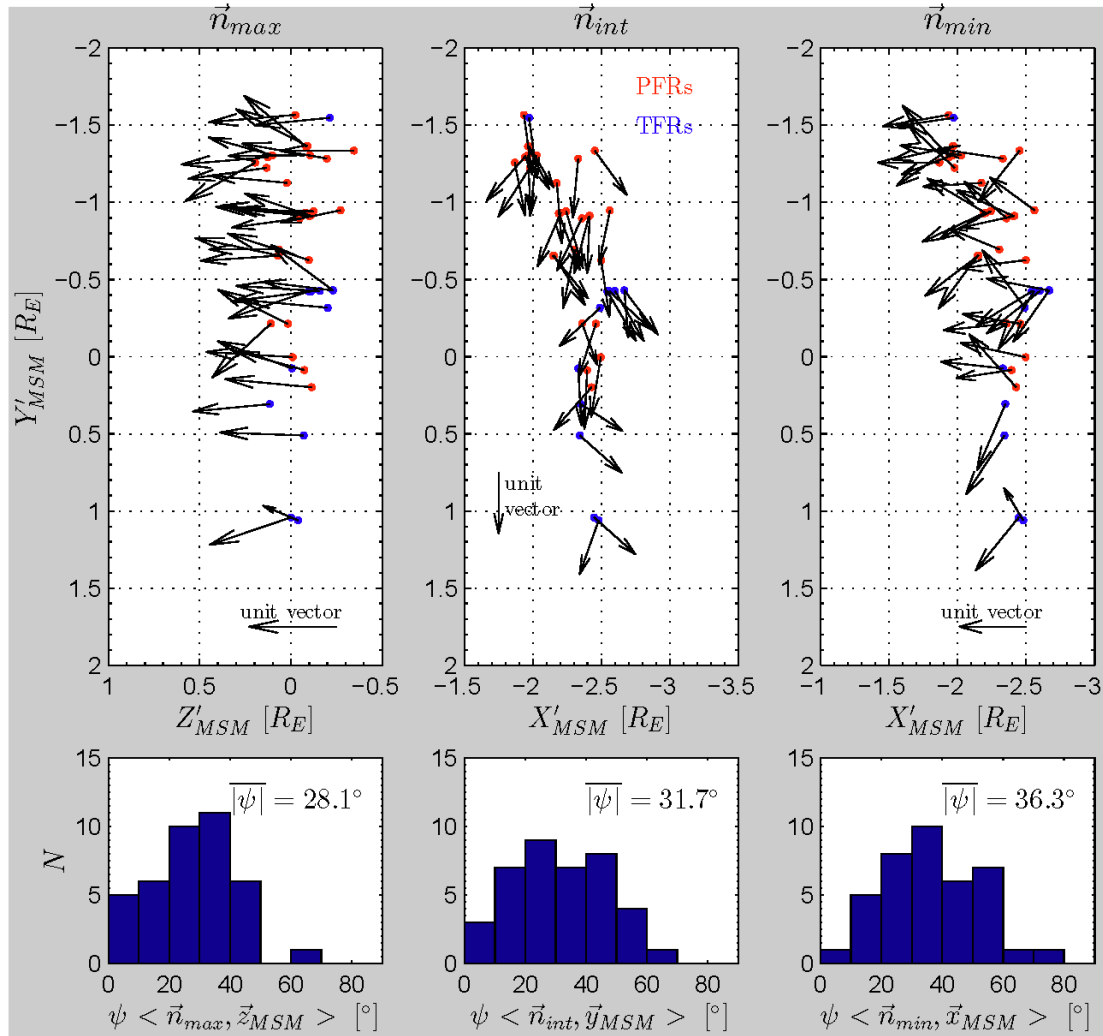


Figure 8. The above three columns from left to right show the projections of \vec{n}_{max} onto the X'_{MSM} - Z'_{MSM} plane, \vec{n}_{int} onto the X'_{MSM} - Y'_{MSM} plane, and \vec{n}_{min} onto the X'_{MSM} - Y'_{MSM} plane, respectively. Red and blue dots represent the locations of PFRs and TFRs. Below three histograms from left to right show the separation angles between \vec{n}_{max} and Z'_{MSM} axis, \vec{n}_{int} and Y'_{MSM} axis, and \vec{n}_{min} and X'_{MSM} axis, respectively. The average values for each separation angle are shown in the middle of each figure.

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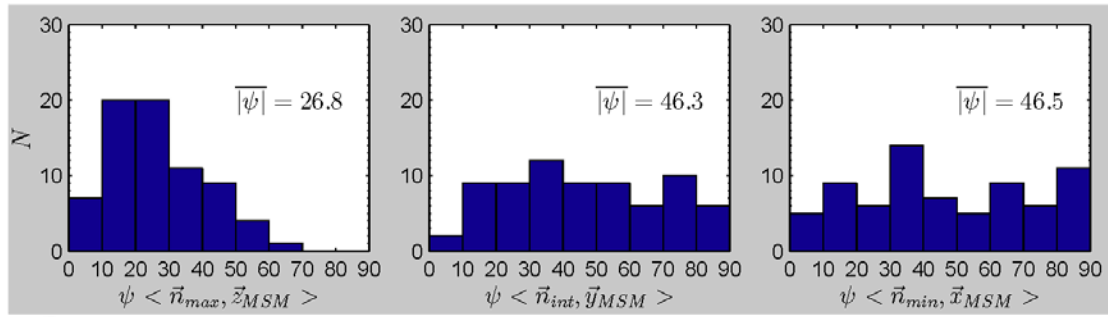


Figure 9. Three histograms from left to right show the separation angles between \vec{n}_{max} and Z'_{MSM} axis, \vec{n}_{int} and Y'_{MSM} axis, and \vec{n}_{min} and X'_{MSM} axis, respectively. The average values for each separation angle are shown in the middle of each figure.

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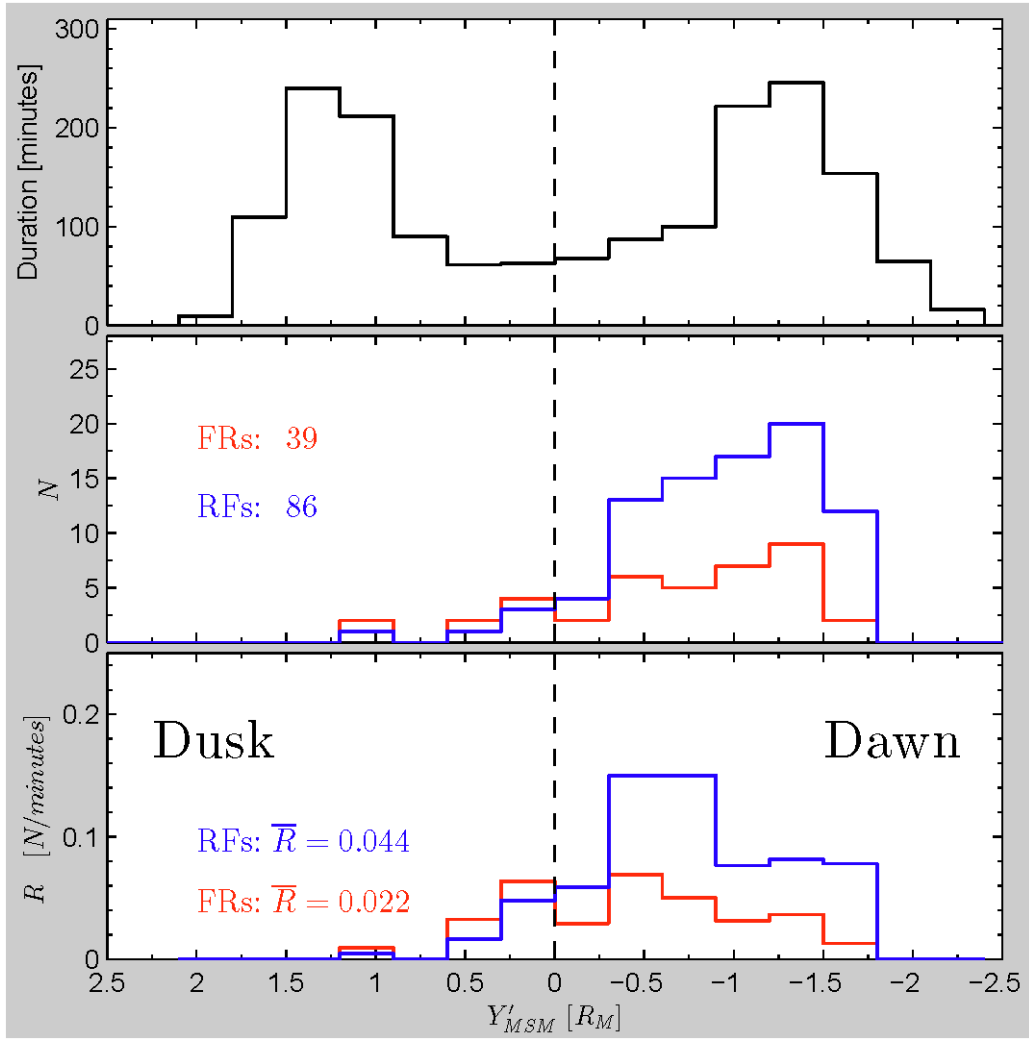


Figure 10. From top to bottom: the distribution of durations MESSENGER spent in the plasma sheet along Y'_{MSM} ; the distribution of number of flux ropes (red line) and reconnection fronts (blue line) along Y'_{MSM} ; the occurrence rates of flux ropes (red line) and reconnection fronts (blue line) along Y'_{MSM} . A dashed line is plotted through $Y'_{MSM} = 0$. The total number of flux ropes and reconnection fronts are shown in the middle panel. The average occurrence rates of flux ropes and reconnection fronts are shown in the bottom panel.

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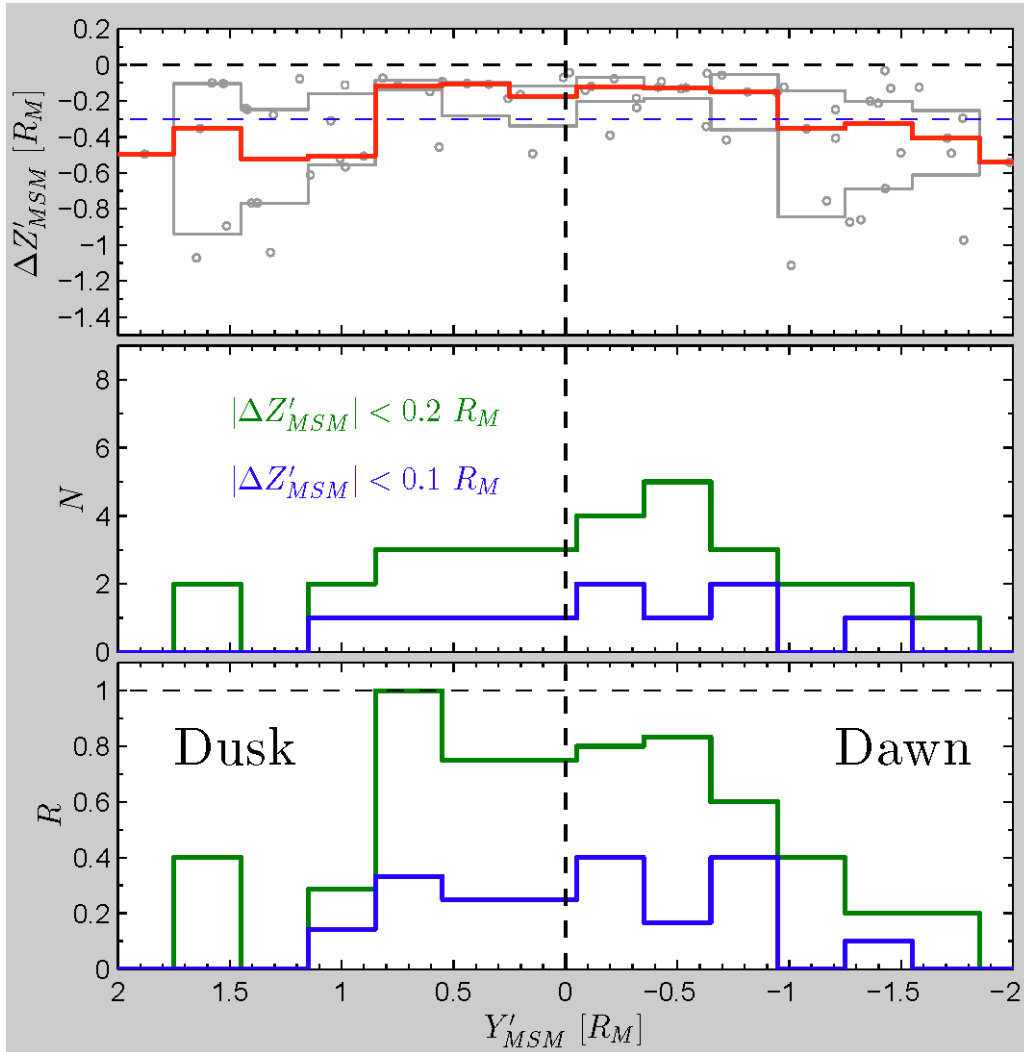


Figure 11. Upper panel: the distribution of plasma sheet thickness. Red line represents the mean value of plasma sheet thickness in each bin, and gray lines represent the upper and lower quartile. Middle panel: the distribution of the event number along dawn-dusk direction. Green line represents the events with $|\Delta Z'_{MSM}| < 0.2 R_M$, and blue line for the events with $|\Delta Z'_{MSM}| < 0.1 R_M$. Bottom panel: the occurrence rate for the thin plasma sheet events.

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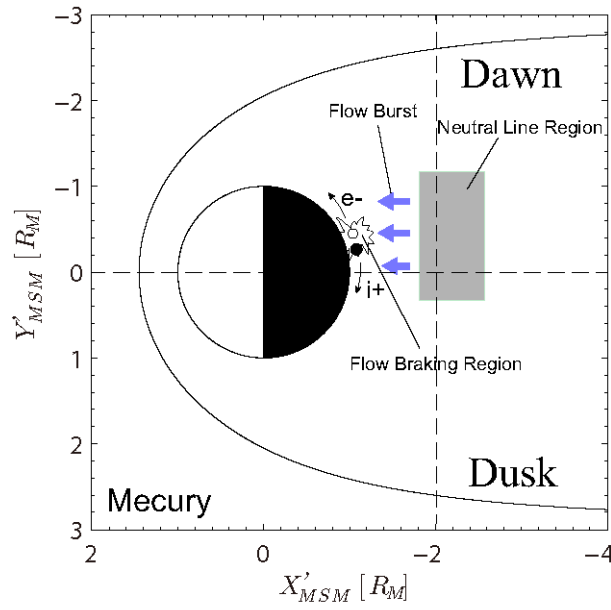
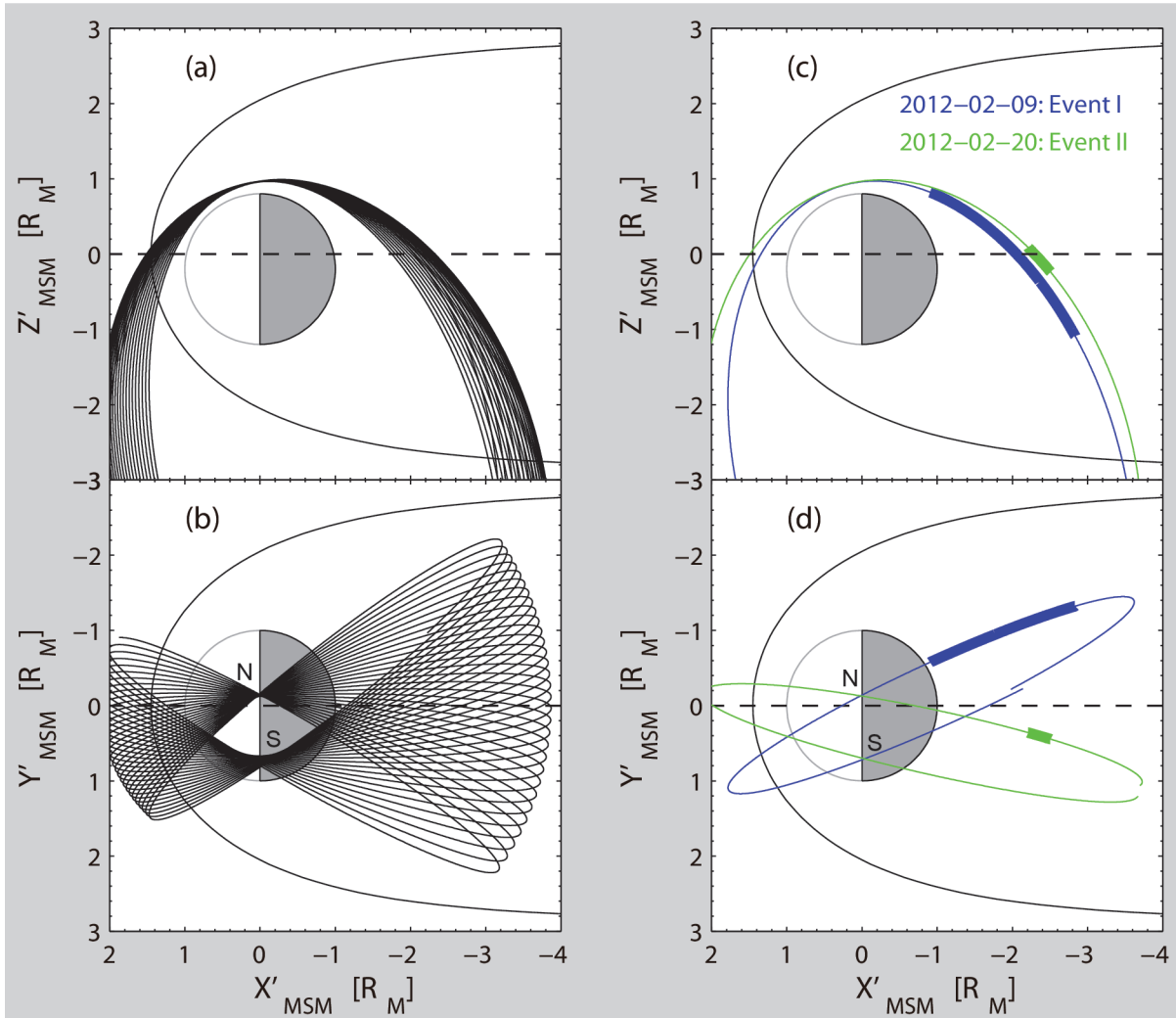


Figure 12. Schematic view of reconnection locations and flow braking region at Mercury. Gray region indicate the detected near tail neutral line regions for both planets. Blue arrows represent reconnection generated planetward propagating flow bursts.

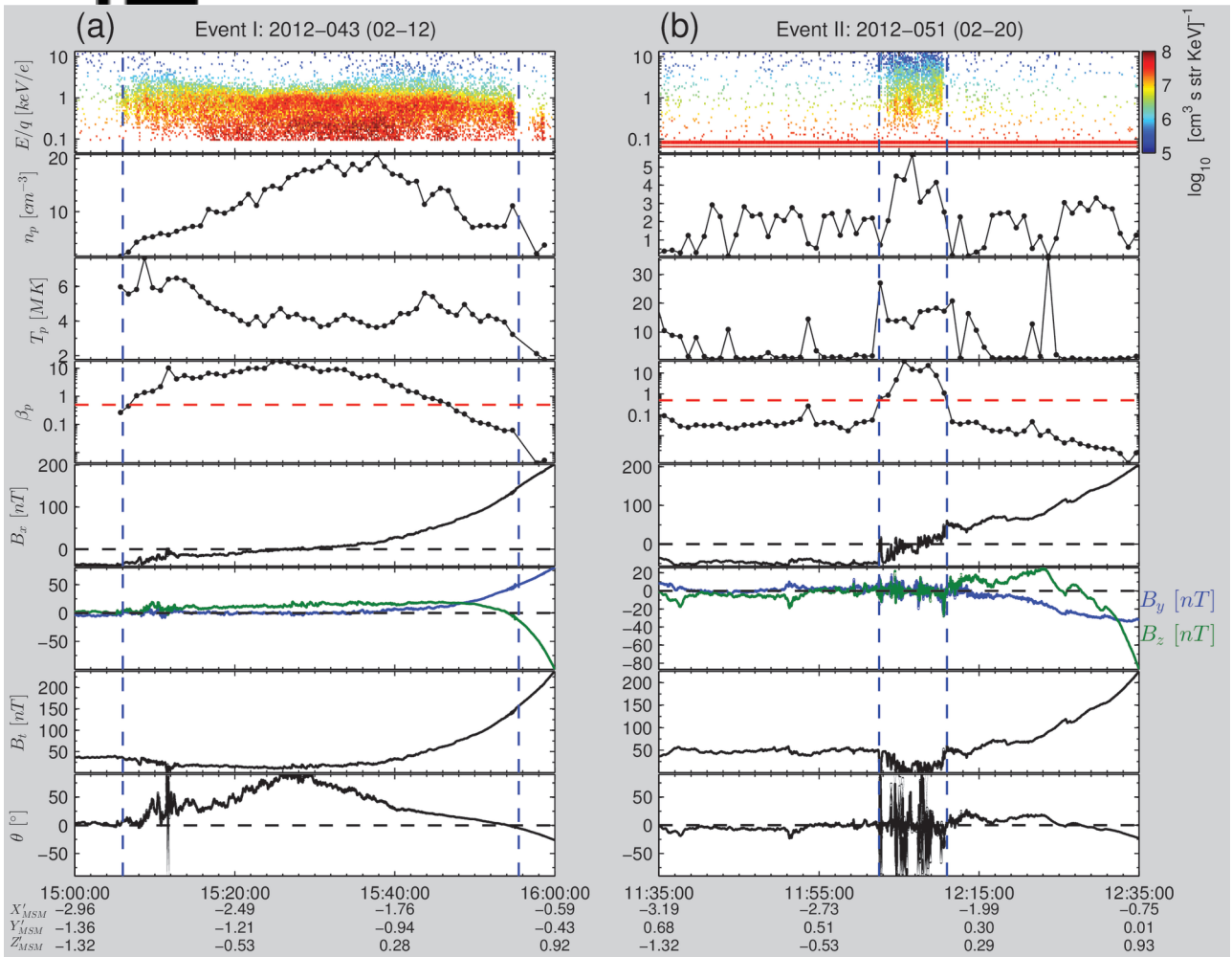
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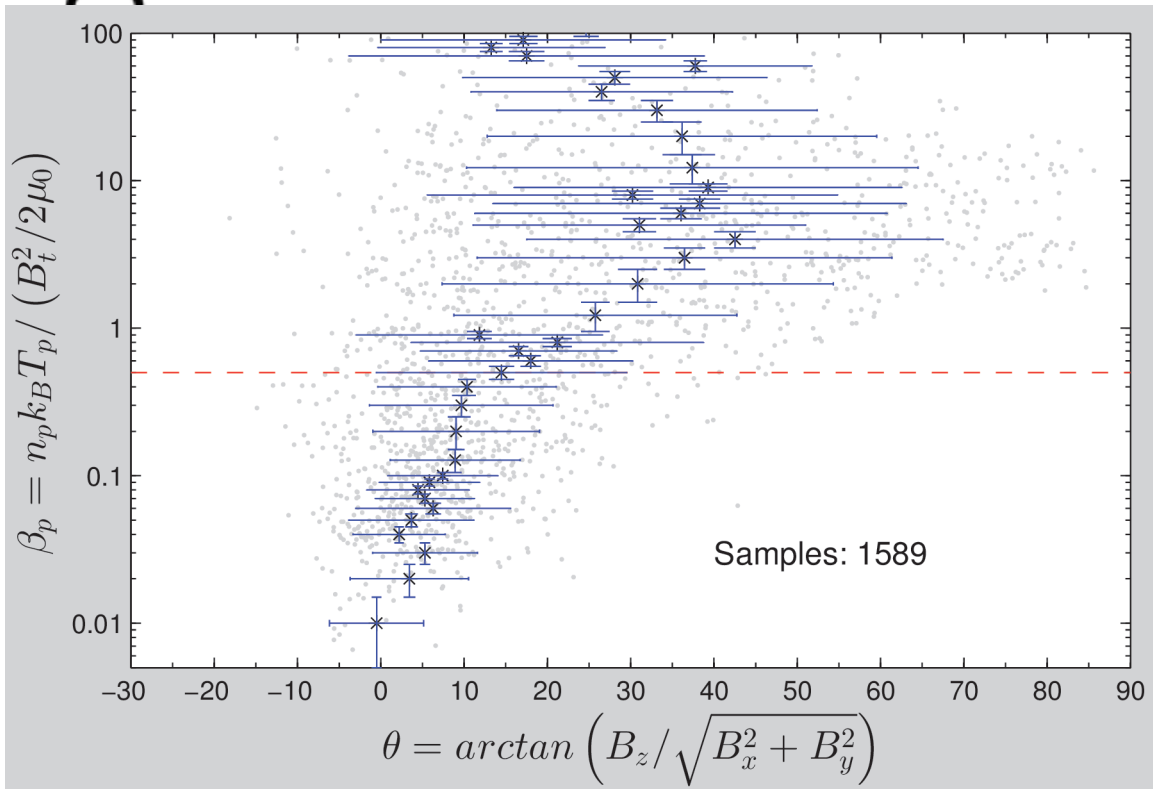
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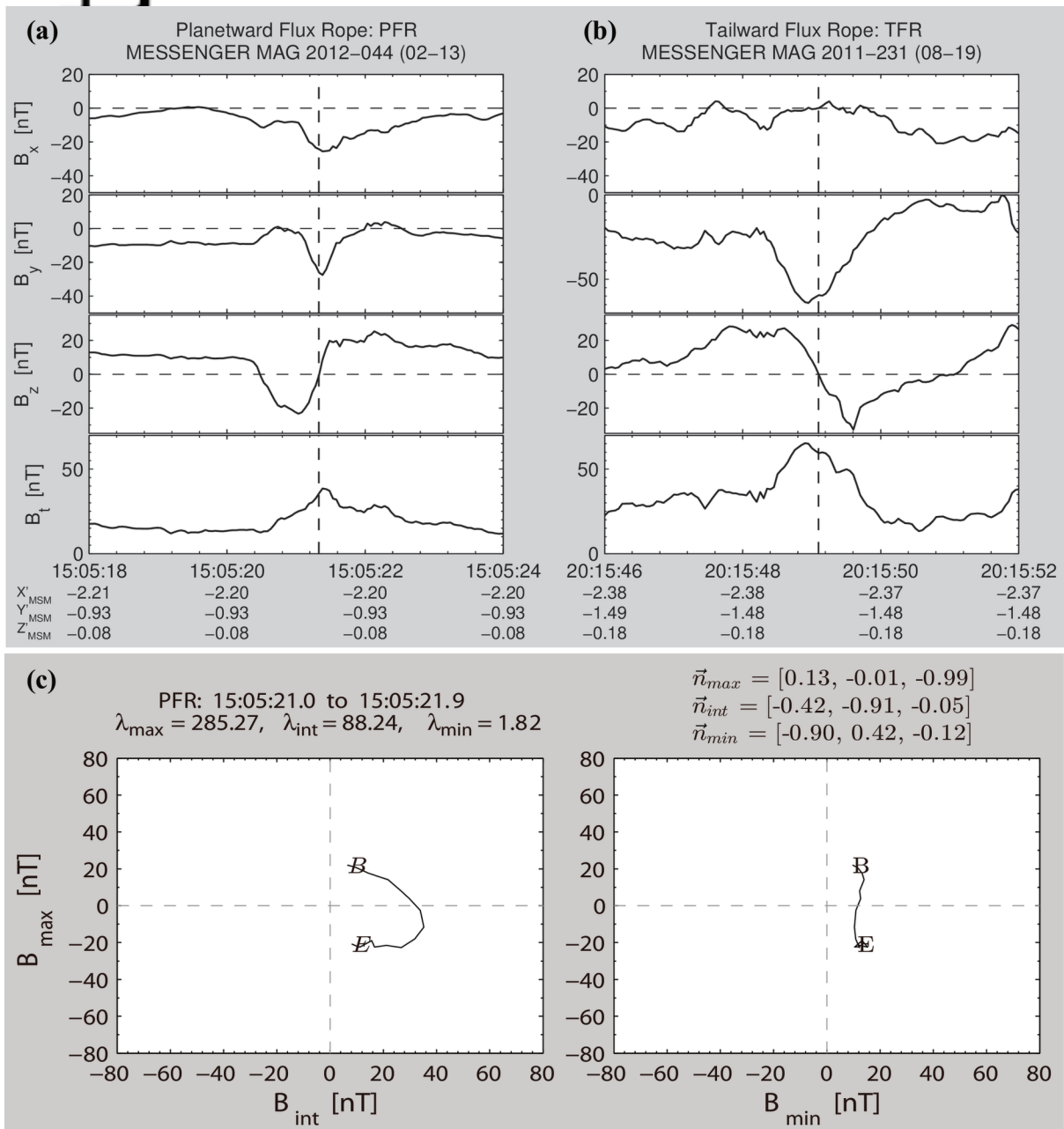


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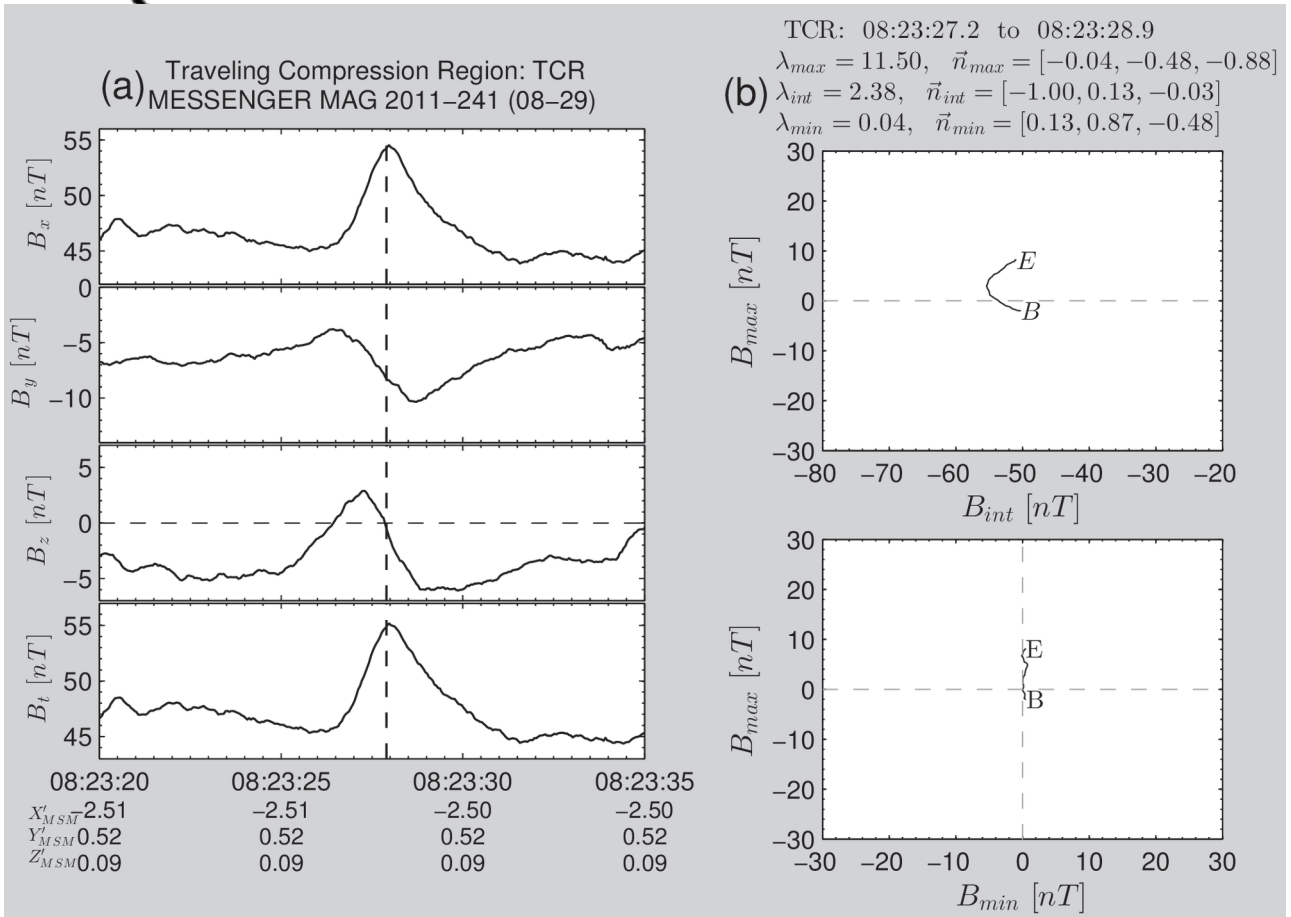
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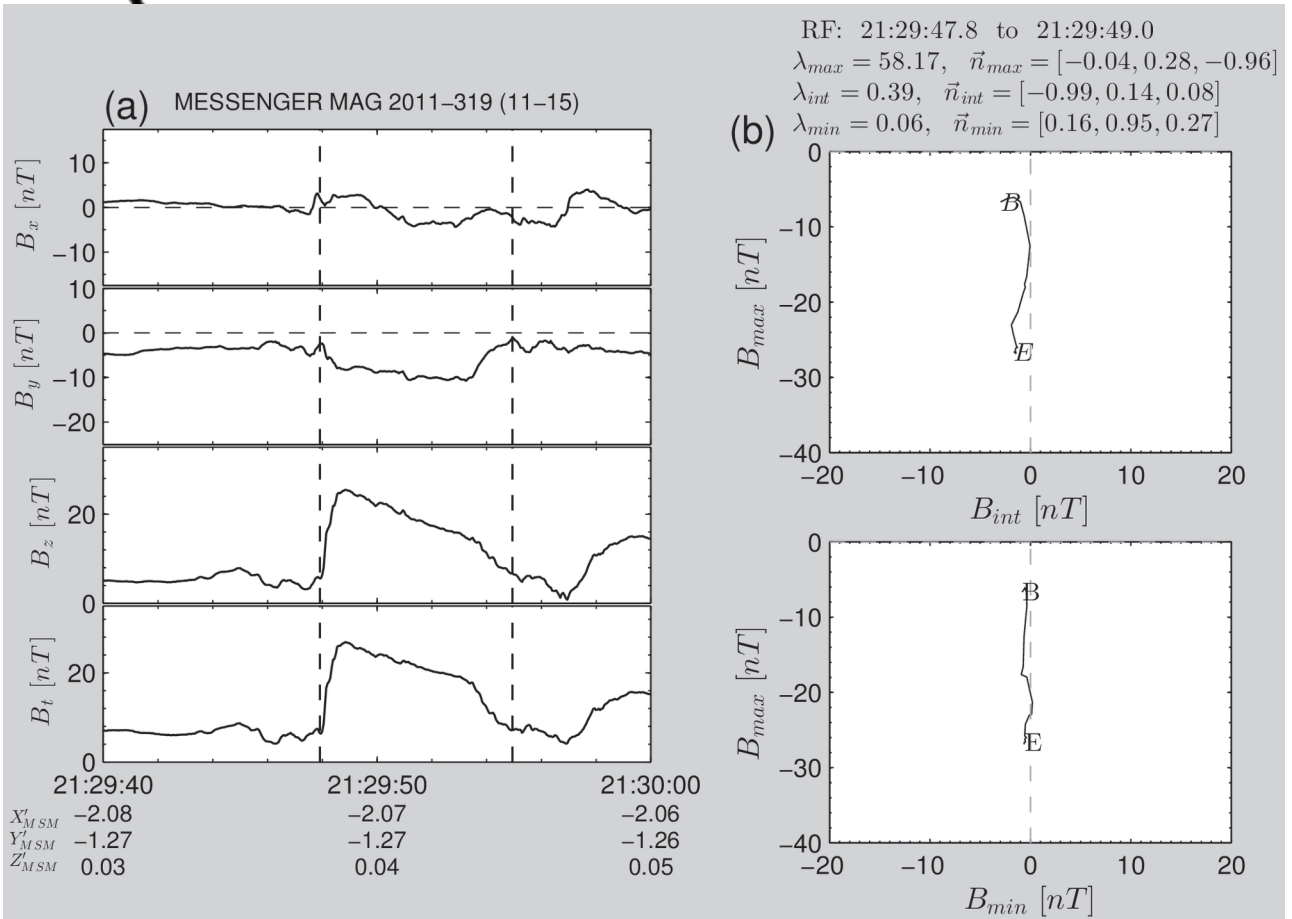


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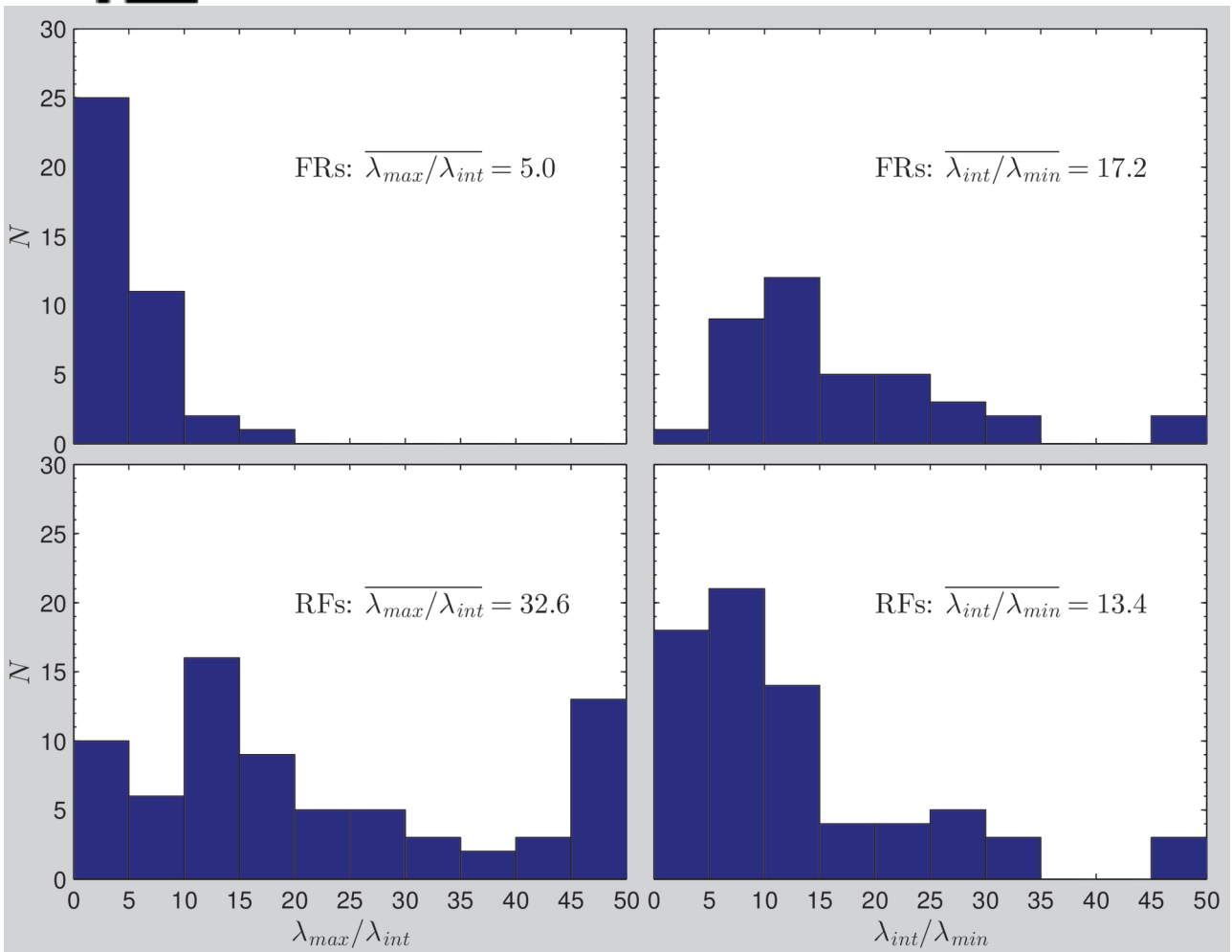


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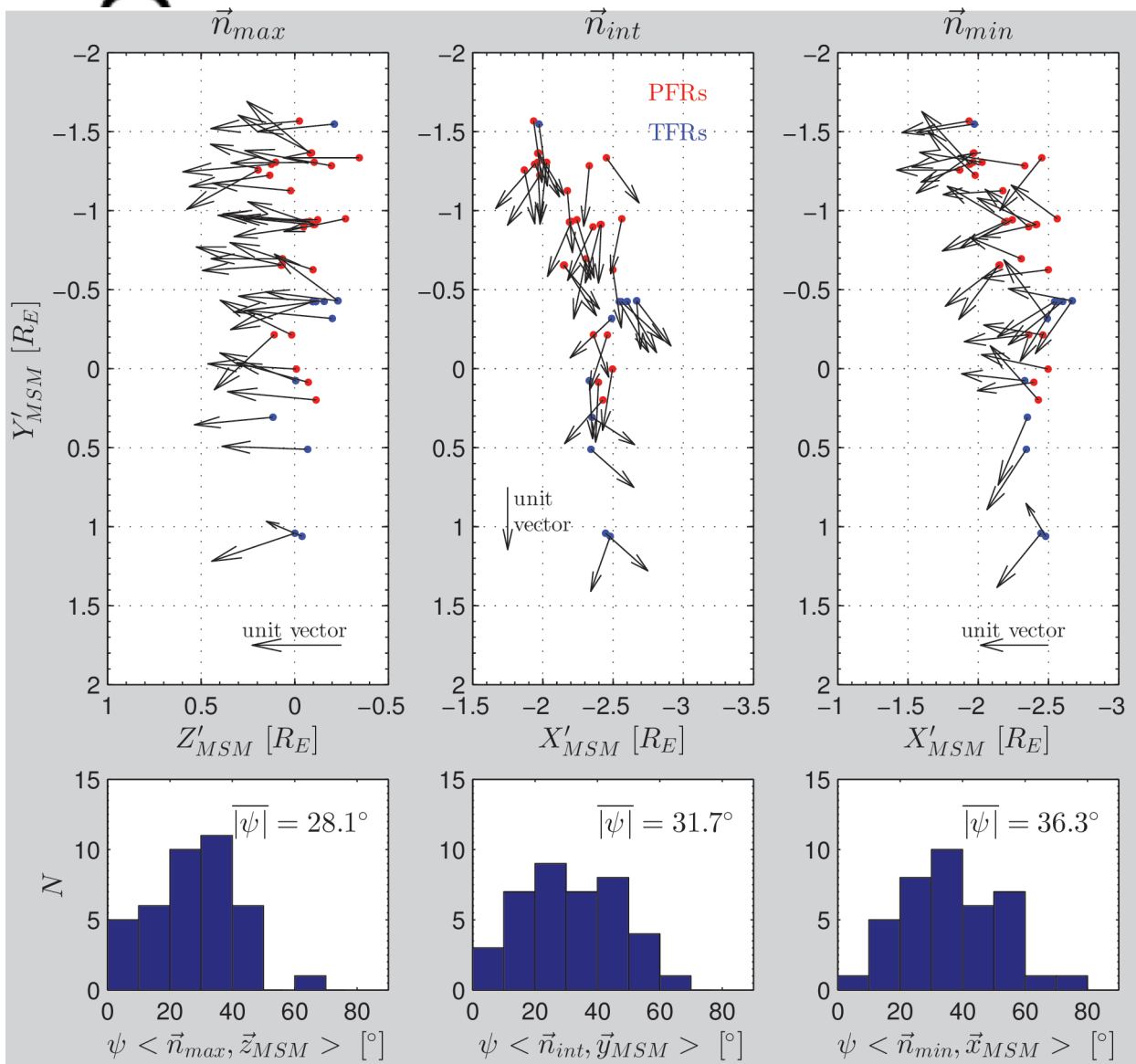


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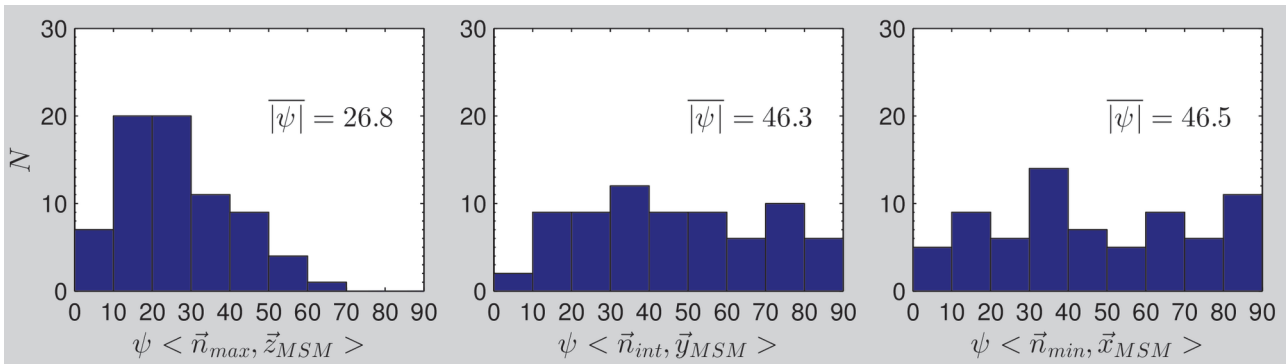


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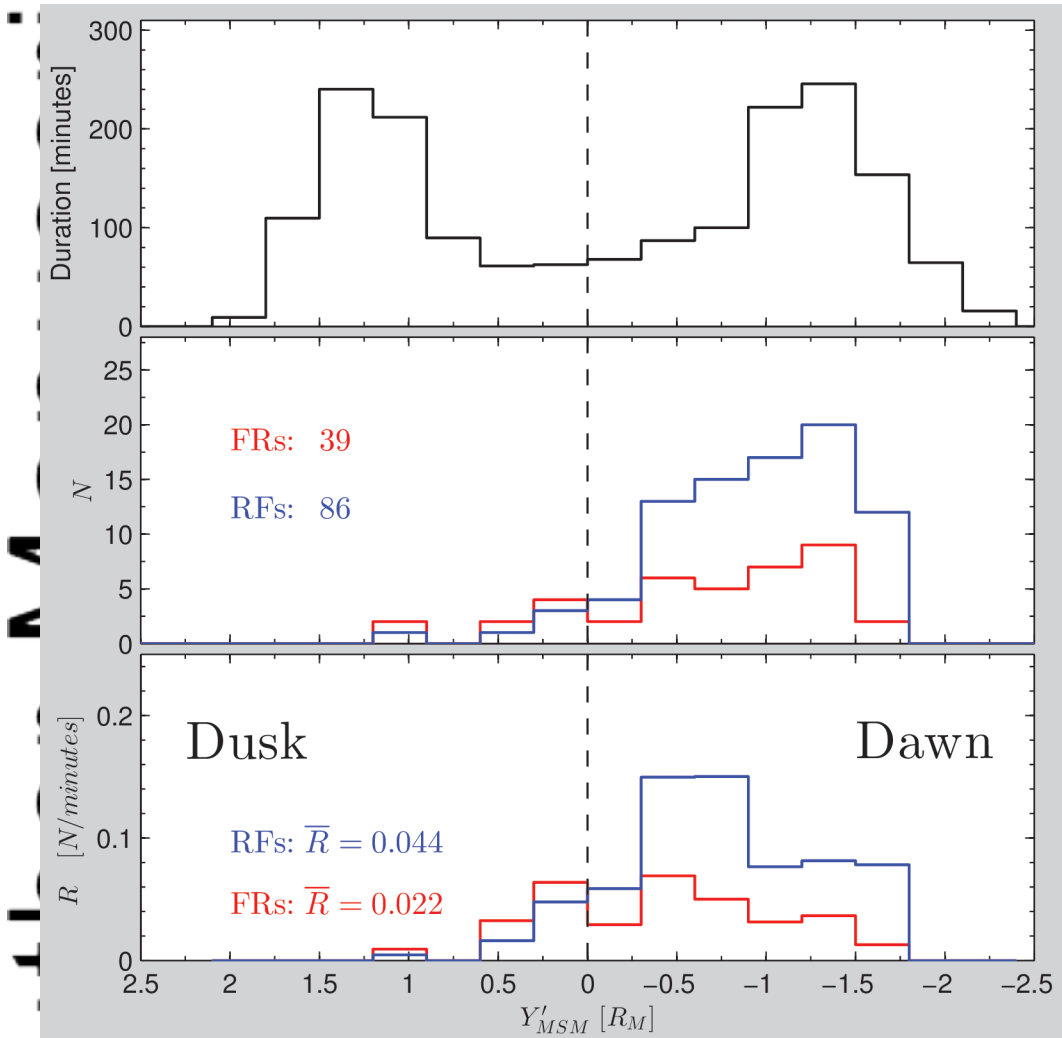


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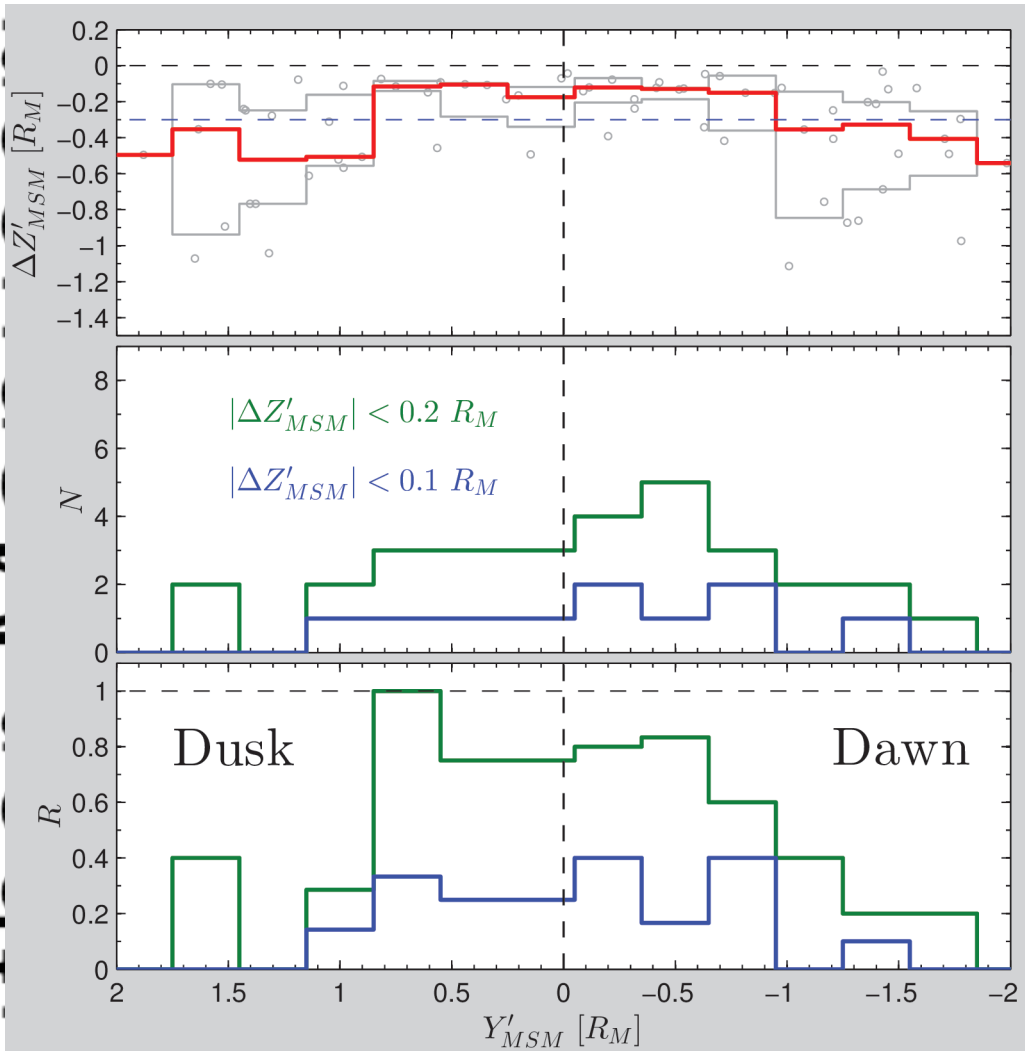
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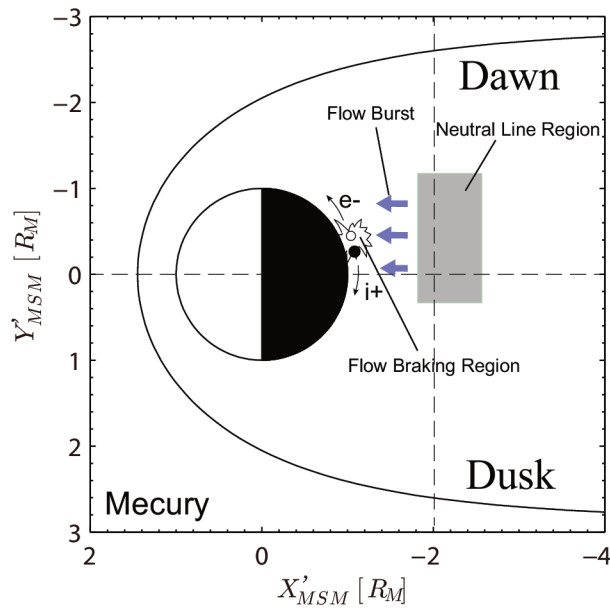


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