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Key Points:
- Magnetic structures on the ion inertial scales are identified in Juno's high temporal resolution data measured in Jupiter's magnetotail
- These structures are shown to be quasi-force-free flux ropes using minimum variance analysis and force-free model fitting
- Multiple reversals in the north-south component are observed during a 30-min interval, possibly due to sequential plasmoid release

Supporting Information:
- Supporting Information S1

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Juno Observations of Ion-Inertial Scale Flux Ropes in the Jovian Magnetotail

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Abstract Two ion-inertial scale magnetic flux ropes are identified in the Juno magnetic field measurements in the dawnside Jovian magnetotail. Previously reported plasmoids in this region had typical diameters of several Jovian radii (R_J). However, events reported here are only ∼0.15–0.19 R_J in diameter, assuming that they move at the local Alfven speed. Using the plasma density determined by the Juno Waves instrument, the diameters are calculated to be on the order of the local ion inertial length (∼0.6–1.6 d_i). Multiple reversals in the north-south component are observed ∼30 min before one of these events, which suggests that plasmoid ejection in the dawnside magnetotail may proceed via multiple X-line reconnection in a highly thinned cross-tail current sheet in a manner similar to that observed at Mercury and Earth. Further studies will be required to determine the contribution of these small flux ropes to mass loss through plasmoid ejection.

Plain Language Summary Magnetized planets such as Earth, Mercury, and Jupiter interact with the solar wind and create magnetospheres. Within these magnetospheres, magnetic reconnection periodically reconfigures the magnetic field and in the process releases mass and energy. Frequently observed as part of magnetic reconnection are loop-like or helical magnetic structures called magnetic flux ropes. At Earth and Mercury, these vary in diameter from hundreds to thousands of km. At Jupiter, however, magnetic reconnection operates differently than Earth or Mercury, primarily because of the Galilean moons which add significant plasma to the magnetosphere. Previously reported magnetic flux ropes at Jupiter were much larger when compared to their terrestrial counterparts. Using data from the Juno spacecraft, which has the capability to detect small structures, we found magnetic flux ropes which were much smaller than those previously observed. The presence of small-scale flux ropes in Jupiter's magnetosphere could have far-reaching implications for its magnetospheric dynamics, specifically on how mass is lost from the magnetosphere.

1. Introduction

Magnetic reconnection in the magnetotail results in the formation of helical or loop-like magnetic structures called plasmoids, which contain strong plasma pressure gradients that maximize along the central axis and balance the magnetic forces directed inward (Hones et al., 1984; Kivelson & Khurana, 1995; Slavin et al., 1989). However, a subset of plasmoids, called "flux-ropes," lack strong pressure gradients in their interior, and the magnetic force of the outer wraps is balanced by the strong axial core field present at their center (Moldwin & Hughes, 1991; Sibeck et al., 1984). Flux ropes in which magnetic stresses are completely self-balancing are referred to as "force-free" as $\vec{J} \times \vec{B} = \nabla p = 0$. These force-free flux ropes correspond to the minimum energy state for a plasmoid that all such structures will evolve toward with increasing time (Priest, 2013; Taylor, 1974). Plasmoids which lack a core field and possess weak magnetic fields at their center compared to their surroundings are termed "O-lines."

Decades of in situ observations in the terrestrial magnetosphere, together with kinetic simulations (Drake et al., 2006a; Drake et al., 2006b), have revealed that magnetic flux ropes in the night-side plasma sheet can range in size from order 1 to 10 Earth radii (Ieda et al., 1998; Slavin et al., 1995) to below the local ion inertial length, which is typically on the order of hundreds of km (Eastwood et al., 2016; Sun et al., 2019).

The latter are produced due to simultaneous magnetic reconnection occurring at multiple X-lines due to the tearing instability acting on a current sheet that has thinned to between the ion- and electron-inertial length scales (Daughton et al., 2011; Drake et al., 2006b; Lapenta et al., 2015). A similar dichotomy in flux rope size is seen at Mercury (DiBraccio et al., 2015; Slavin et al., 2009; J. Zhong et al., 2019), whose magnetosphere is closest to that of Earth with tail reconnection being driven by a Dungey-type (Dungey, 1961) magnetic flux transfer cycles, but also possesses differences related to its proximity to the Sun and its lack of an ionosphere. Small-scale flux ropes play an important role in energizing electrons and ions, which can undergo both, adiabatic acceleration due to the evolving flux rope structure (Drake et al., 2006a; Le et al., 2012; Z. H. Zhong et al., 2020) and nonadiabatic acceleration due to electromagnetic turbulence (Kronberg et al., 2019).

Plasmoids and flux ropes have also been observed at Jupiter (Kronberg et al., 2007, 2008; Russell et al., 2000; Vogt et al., 2010, 2014; Woch et al., 2002), Saturn (Jackman et al., 2011), and Uranus (DiBraccio & Gershman, 2019). Especially for Jupiter, Dungey-cycle reconnection is considered to play a minor role (Cowley et al., 2008; McComas & Bagenal, 2007) and plasmoid release is facilitated primarily by the centrifugal force associated with mass loading and the energization of fresh plasma. Closed field lines on the Jovian nightside stretch freely, thinning the equatorial current sheet and in the process initiating reconnection and the release of plasmoids down the magnetotail (Cowley et al., 2015; Kivelson & Southwood, 2005; Vasyliūnas, 1983). However, single-spacecraft measurements cannot provide reliable estimates on the three-dimensional structures of the Jovian plasmoids. Despite the limitations, it was estimated that plasmoids with diameters between 2 and 20 R_J and cross-tail width between 40 and 70 R_J (Vogt et al., 2014) could only account for a loss of ∼30–210 kg/s, which is significantly less than the production at Io, estimated to be between 250 and 1,000 kg/s. This discrepancy could be a result of the underestimation of the size of the event (Cowley et al., 2015) or indicate a different loss mechanism altogether—either a diffusive "drizzle" across weak magnetotail field lines or recurring release of small plasmoids (Bagenal, 2007; Kivelson & Southwood, 2005).

Plasmoids and flux ropes observed so far in the Jovian magnetosphere have been fairly large. The mean duration of the observed plasmoids and flux ropes observed by the Galileo spacecraft at Jupiter was determined by Vogt et al. (2014) to be 6.8 min and by Kronberg et al. (2008) to be between 10 and 20 min (The two studies use different definitions for the duration of a plasmoid event). Vogt et al. (2014) estimated the average diameter of the plasmoid to be ∼2.6 R_J (where 1 R_J = 71,492 km) or 1.85×10^5 km, though they note that because of single-point measurement limitations, these plasmoid sizes could be larger. Assuming that the equatorial plasma density at a distance of 90 R_J downtail is ∼0.01 cm^{-3} (Bagenal & Delamere, 2011) and that the plasma is made up of mostly S^+, S^{++}, O^+, and H^+ ions (Kim et al., 2020), we can approximate a mass of 16 amu for the average singly charged ion and estimate an ion inertial length ($d_i = c / \omega_{pi}$, where $\omega_{pi} = \sqrt{e^2 Z^2 n_i / \epsilon_0 m_i}$ is the ion plasma frequency) of ∼10^4 km, which is at least an order of magnitude smaller than the diameter of the plasmoids seen by Galileo. Considering that the Galileo magnetometer had a cadence of a few seconds per vector, it would have been difficult to detect subion scale flux ropes or O-lines, whose in situ signatures would last only a few seconds.

The dichotomy seen at the other planets and in simulations of reconnecting fields leads to a natural question of whether ion-scale flux ropes exist in the Jovian magnetotail and if they can be identified using the high-resolution capabilities of the Juno instrument suite. Recent plasmoid observations by the Juno spacecraft reported by Vogt et al. (2020) have corroborated the Galileo observations, in that large plasmoids lasting several minutes on average were observed. In this work, we extend upon previous Galileo and Juno investigations and present two ion-inertial scale flux ropes observed by Juno in the dawn-side Jovian magnetotail, which lasted roughly 22 and 62 s. The local plasma density surrounding these flux ropes is estimated using the low-frequency cutoff for the continuum radiation as observed by the Juno Waves instrument (e.g., Barnhart et al., 2009), which shows that these durations correspond to plasmoid diameters comparable to the ion-inertial length. This study is the first reported observation of magnetic flux ropes on the ion scale in Jupiter's magnetosphere and shows that while reconnection on the global scale at Jupiter's magnetosphere is influenced by the Vasyliunas cycle, as evidenced by the large plasmoids seen by both Galileo and Juno; small-scale reconnection also occurs and secondary magnetic islands are generated in the Jovian magnetotail, similar to observations at Earth and Mercury.

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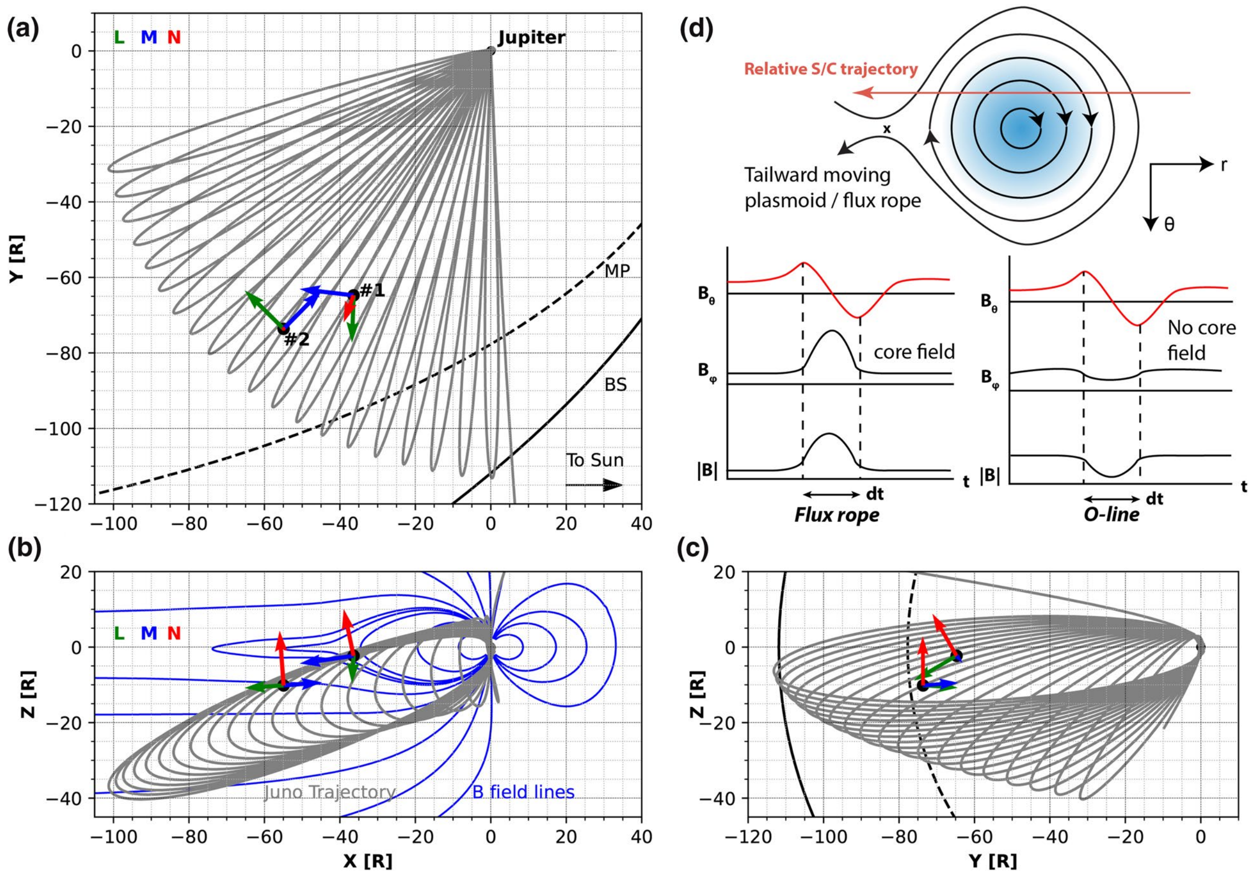

Figure 1. Juno's trajectory in the Jupiter Sun State (JSS) coordinate system in gray. The location of the two events discussed in this study are marked. The arrows indicate the directions of minimum (green), intermediate (blue), and maximum (red) variance obtained using MVA. The solid blue lines in (b) are magnetic field lines from Sarkango et al. (2019) global MHD model. Note that in reality the magnetic field is not axisymmetric, and the current sheet oscillates with respect to the rotational equator with a period of roughly 10 h. In subset (d), the expected magnetic signature of a tailward moving plasmoid is illustrated.

2. Data and Methods

We use high-resolution magnetometer data in the Jupiter De-Spun Sun (JSS) coordinate system. The Z axis for the JSS system is aligned with Jupiter's north pole, X points toward the sun and Y completes the right-handed coordinate system. Also used are the corresponding magnetic field components in the spherical polar JSS system (B_r, B_θ, B_ϕ) referring to the radial, co-latitudinal and azimuthal directions. The Juno Magnetometer investigation measures the magnetic field strength and direction ambient to the spacecraft using boom-mounted fluxgate magnetometers (Connerney et al., 2017) and measures at rates of 16–64 vectors/second. These high cadence rates are significantly greater than what was returned by the Galileo magnetometer (between 24 and 60 s per vector, e.g., Vogt et al., 2010, 2020) and they allow us to study smaller scale structures durations down to ∼100 ms. We also use data from the Juno Waves instrument (Kurth et al., 2017), which measures the fluctuations in the electric field between 50 and 40 MHz and in the magnetic field from 50 and 20 kHz. We use the low frequency cutoff for the continuum radiation to infer the electron density (Barnhart et al., 2009).

Juno orbits Jupiter in a highly elliptical trajectory, with each perijove pass separated by ∼53 days. However, Juno spent a reasonable amount of time in the equatorial region (Figure 1), which enabled it to capture multiple current sheet crossings on every inbound pass.

In this study, as in Vogt et al. (2010, 2014), positive values of B_θ indicate a field pointing in the negative Z_{JSS} direction at the equator. In the quiet state with Jupiter's magnetic moment pointing north, the equatorial magnetic field is primarily in the positive θ (negative Z_{JSS}, assuming no current sheet tilt) direction. The

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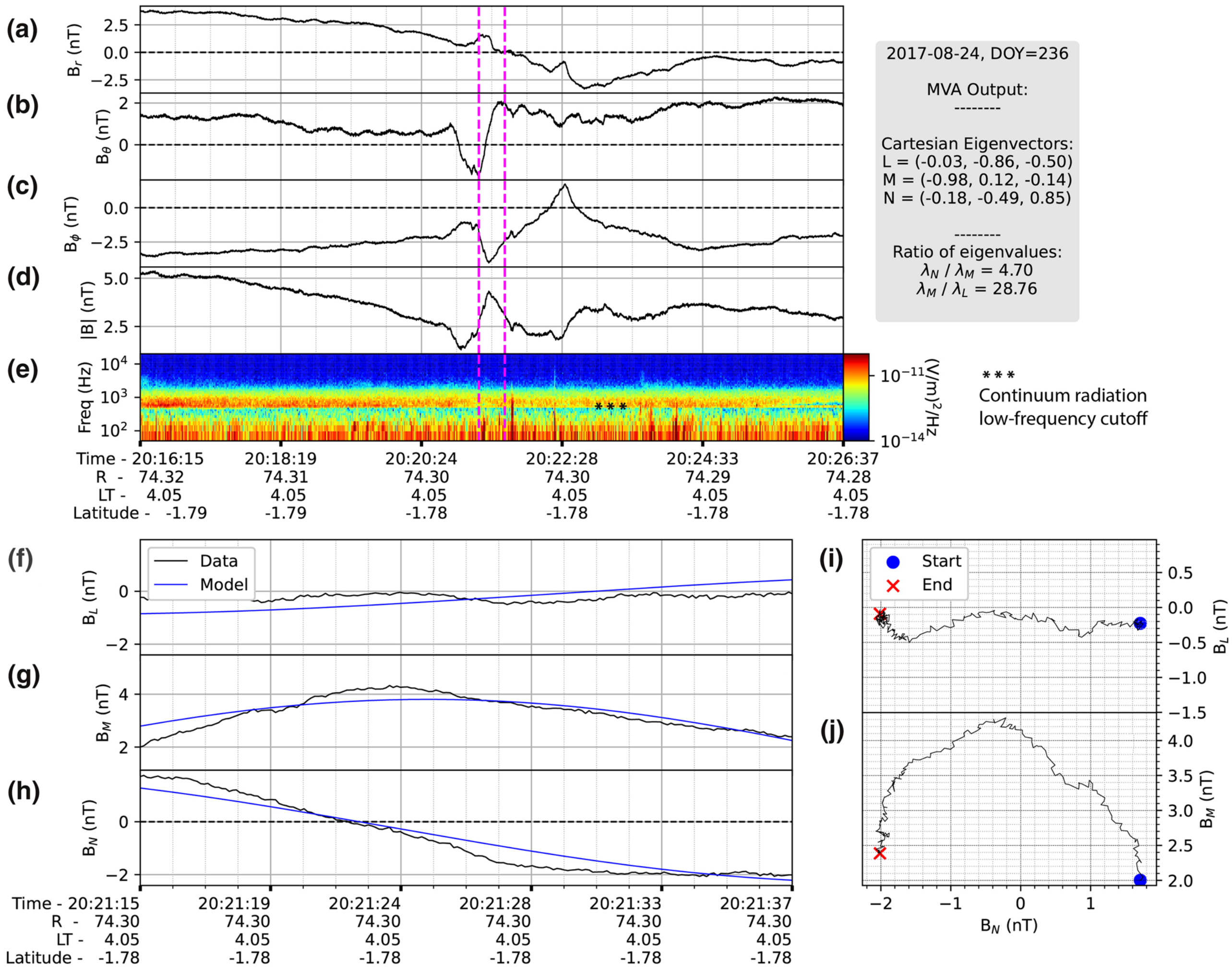

Figure 2. Flux rope event on DOY 236, 2017 observed by Juno. The first four rows (a–d) show the magnetic field components in spherical JSS coordinates (B_r, B_θ, B_ϕ) along with the field magnitude. Row (e) shows the electric field spectra as obtained by the Waves instrument. The bottom figures (f–h) show the results of the minimum variance analysis performed in the magenta-delimited region, with the magnetic field components in the direction of minimum, intermediate, and maximum variance. The associated hodograms are shown in (i) and (j). The blue solid line is a force-free flux rope model that has been fit to the Juno magnetic field measurements. Note the close agreement between the measurements and the model.

magnetic signature of a tailward-moving plasmoid passing over a spacecraft near the equatorial plane is primarily observed in the B_θ component as a slight increase and subsequent reversal to negative values (e.g., Figure 1d for the signature of a tailward moving plasmoid). As the plasmoid passes over the spacecraft, the return to positive values can either be symmetric, hinting at reconnection occurring in closed field lines, or gradual, indicative of a postplasmoid plasma sheet that is formed when reconnection has progressed to the tail lobes (Jackman et al., 2011; Jia et al., 2012). Conversely, planetward moving plasmoids would exhibit the opposite signature, that is, an increase of B_θ in the negative direction and a reversal to positive values. If the plasmoid possesses a core field, it should typically be identified by a peak in the cross-tail component, either B_y or B_ϕ as well as a corresponding peak in the magnetic field strength which roughly matches the time where the reversal in B_θ is observed. Most plasmoids observed in Jupiter's plasma sheet (e.g., Vogt et al., 2014, 2020) lack an axial core field and are identified as O-lines. This result is similar to what has been observed at Saturn (Jackman et al., 2011) and could be due to large plasma pressure in a high β plasma and their primary role of carrying plasma away from these planets and balancing the plasma derived from their moons (Cowley et al., 2015; Kivelson & Khurana, 1995).

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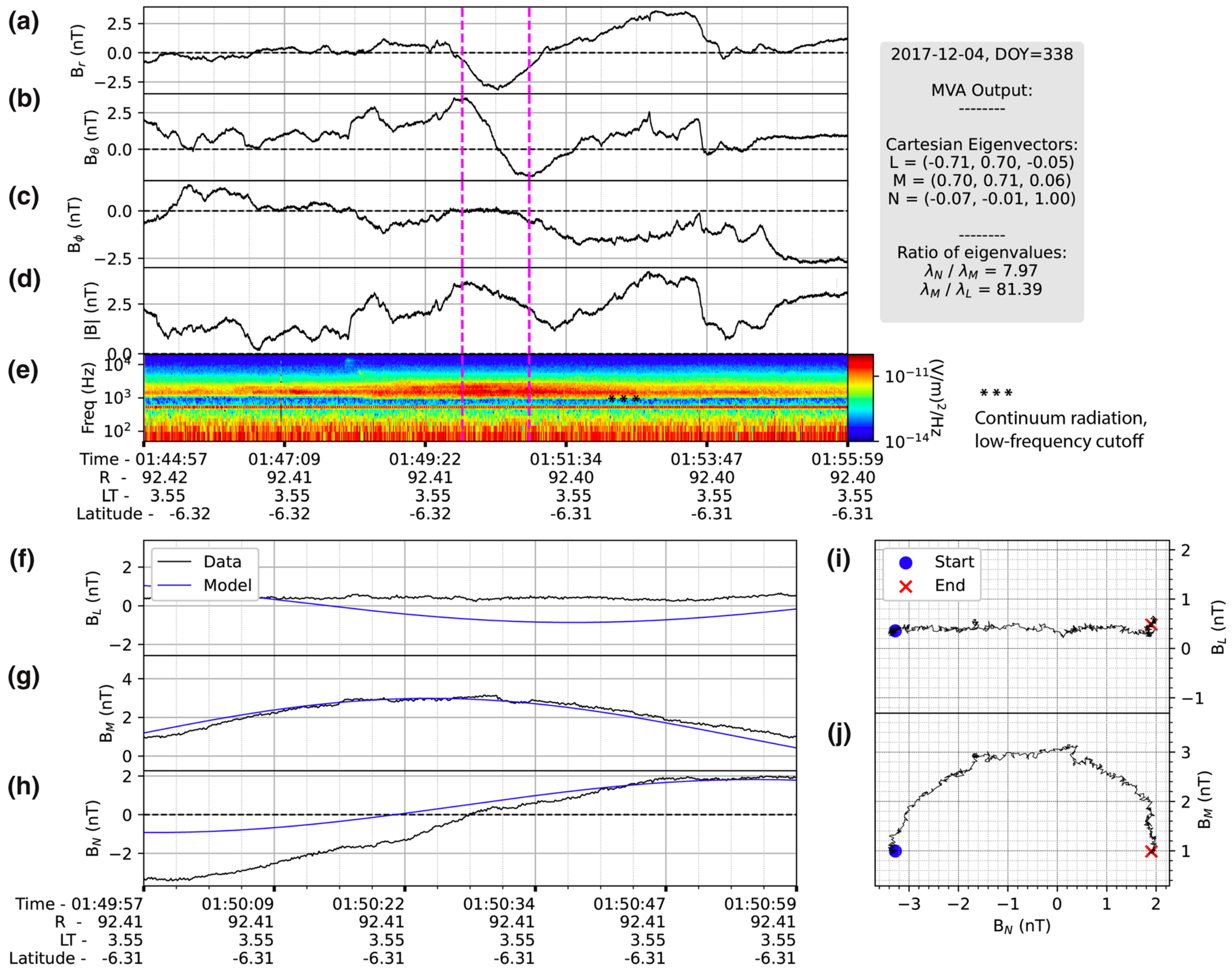

Figure 3. Flux rope event on DOY 338, 2017. Juno was present at ~92.4 R_J in the magnetotail between 03 and 04 LT. (Same format as Figure 2).

Using the high-resolution Juno data, we searched (by eye) for bipolar variations in the B_θ component in proximity to current sheet crossings to identify flux rope signatures which are roughly 1 min or less in duration. Current sheet crossings (identified by a reversal in B_r) are observed only during the planet bound phase of Juno's trajectory with a periodicity of roughly 10 h, which reduces the search duration. As reported by Vogt et al. (2020), Juno frequently observed bipolar variations close to current sheet crossings. This is more evident in the high-resolution data and we show two promising examples in this study (Figures 2–4).

The minimum variance analysis (MVA) can be used to identify the orientation of a flux rope with respect to the magnetotail (e.g., Sonnerup & Cahill, 1967). The eigenvectors of the covariance matrix, M- $\overrightarrow{x_L}$, $\overrightarrow{x_M}$, and $\overrightarrow{x_N}$ corresponding to the three eigenvalues (in increasing magnitude) λ_L, λ_M, and λ_N, represent the directions of minimum, intermediate and maximum variance, respectively. For magnetic flux ropes, which possess a helical field on the outside and a unidirectional axial field on the inside, the axial direction can be inferred using the eigenvector of intermediate variance ($\overrightarrow{x_M}$). There are additional criteria required to identify a flux rope using MVA: A bipolar signature in the maximum (B_N) varying component should be present and the eigenvector of the maximum variance should be predominantly in the direction normal to the current sheet. The ratio of maximum to intermediate (λ_N / λ_M) and intermediate to minimum (λ_M / λ_L) eigenvalues must be relatively large (ideally larger than 3 or 4, e.g., Lepping et al., 1990) for the orthogonal coordinate system to be well-defined. A rotation should be observed in the $B_M - B_N$ hodogram. An almost zero B_L indicates that the spacecraft passed close to the center of the flux rope or O-line. For a flux rope, the core field should be

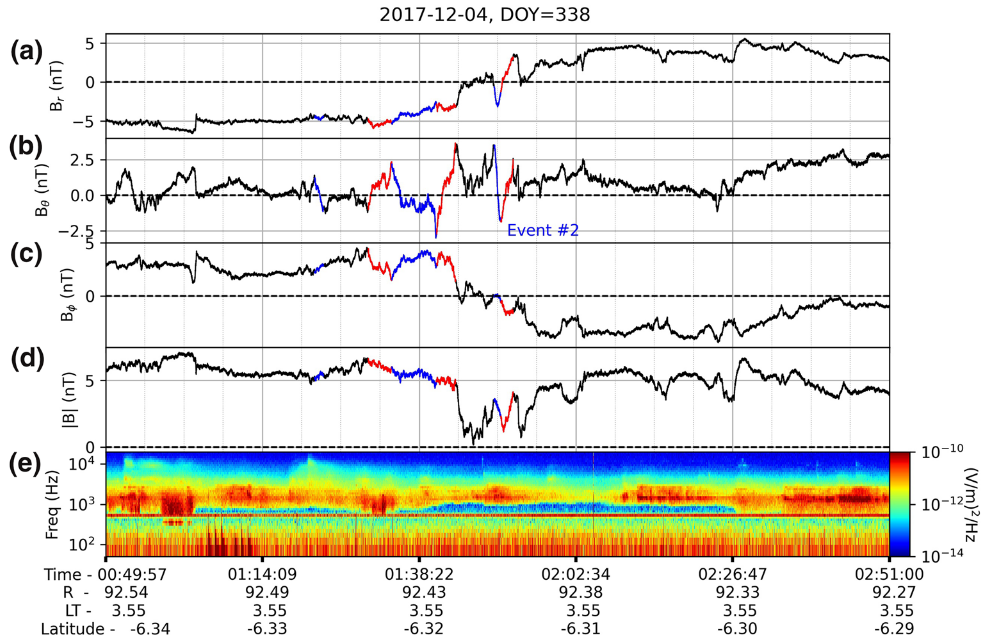

Figure 4. Consecutive bipolar variations in B_θ observed <30 min before Event #2 (the final B_θ reversal shown in blue). Panels (a–d) show the magnetic field components in the spherical JSS coordinate system and panel (e) shows the spectra for the electric field as measured using the Juno Waves instrument. Highlighted in red and blue are North-to-South and South-to-North turn pairs of the magnetic field respectively, each pair corresponding to potential plasmoid signatures.

seen as an enhancement in the B_M component, whereas for an O-line, a local minimum in the B_M component would be seen. Following the procedure of Lepping et al. (1990), we also fit a constant alpha force-free flux rope to the selected events (see Text S1, supporting information).

3. Observations

3.1. Event 1—Flux Rope

On DOY 236, 2017 Juno was located 74.3 R_J away from Jupiter at ~04 LT (dawnside magnetotail) when it encountered a flux rope between 20:21:15 and 20:21:37 UTC. The sign of B_θ was positive before and after this event, but briefly reversed to negative values during the interval (Figures 2a–2d). The positive B_θ before and after the bipolar signature is consistent with Juno being in the near-Jupiter plasma sheet where the inward magnetic stress exerted by the stretched, closed magnetic field is balanced by the inward gradient in the plasma pressure. B_r is less than 1 nT during the encounter and B_ϕ increases (in the negative) by ~2 nT, which is the core field of the flux rope. The difference between the extrema in B_θ is about 4 nT. The sharp peak in the magnetic field strength, closely aligned with the center of the B_θ reversal, is a characteristic signature of a flux rope. The flux rope is close to the current sheet, as evidenced by the reversal of B_r from positive-to-negative values before and after the event. Although there is both a positive-to-negative and negative-to-positive polarity reversal of B_θ, the core field peak is seen during the negative-to-positive reversal, which hints that the flux rope was traveling planetward.

After performing the MVA, we find a bipolar variation in the B_N (maximum) component and a peak in the B_M (Figures 2f–2h), which is expected for a flux rope with a core field. The ratio between the intermediate and minimum eigenvalues of the variance matrix is 4.7, whereas the ratio between the maximum and intermediate values is 28.76. Looking at the $B_M - B_N$ hodograms shown in Figure 2i and 2j, we can observe a rotation of the magnetic field. Figure 2 also shows the magnetic field components of the modeled force-free flux rope (in blue) in the MVA coordinate system which best fits the data (minimum $\chi_r^2 = 0.13$). The modeled flux rope has a core field strength of 3.86 nT and an impact parameter of 0.0, which indicates that the spacecraft passed very close to the center of the flux rope structure. This is also supported by the extremely low magnitude of B_L (less than 0.4 nT).

The eigenvectors of the variance matrix in the direction of minimum, intermediate, and maximum variance are (in the Cartesian JSS coordinate system), $\overrightarrow{x_L} = (-0.03, 0.86, -0.5)$, $\overrightarrow{x_M} = (-0.98, 0.12, -0.14)$, $\overrightarrow{x_N} = (-0.18, -0.49, 0.85)$. Although flux ropes in the terrestrial magnetotail typically have a core field in the Y_{JSS} direction (as provided by $\overrightarrow{x_M}$), we find that for this event the direction of intermediate variance is in the X_{JSS} direction, which is close to azimuthal direction at the given spacecraft location (Figure 1).

3.2. Event 2—Flux Rope

On DOY 338, 2017 between 01:49:57 and 01:50:59 UTC Juno was located at ∼92 R_J between 03 and 04 LT and observed a reversal in B_θ from positive-to-negative values, indicating a tailward moving flux rope (Figures 3a–3d). Unlike the previous example, the magnetic field magnitude did not peak inside the event interval, despite the presence of an axial core field. The azimuthal field component remained close to zero.

Performing the MVA provides us with additional information (Figures 3f–3h)—the maximum variance is in the Z direction $\left(\overrightarrow{x_N} = (-0.07, 0.01, 1.00)\right)$, as expected, whereas the intermediate and minimum variance directions lie in the XZ plane close to the local radial and tangential directions. The component of the magnetic field in the minimum variance direction is close to zero. The intermediate component (B_M) peaks in the middle of the event interval. The $B_M - B_N$ hodograms show a clear rotation of the magnetic field.

The spectra for the electric field as observed by the Waves instrument for Event #2 is shown in Figure 3e. A broadband intensification can be seen between 1 and 3 kHz for the duration of this event. Enhanced fluctuations in the electromagnetic field have been seen inside plasmoid intervals in the past in the terrestrial magnetosphere (e.g., Kennel et al., 1986). Although the continuum radiation is observed during the first event as well, no transient intensification was observed due to the flux rope.

Although Event #1 is an isolated flux rope event during the associated current sheet crossing, that is not true for Event #2. Figure 4 shows the magnetic field observations ∼2 h before and after Event #2. Multiple, alternating B_θ reversals, with peak-to-peak durations of roughly 2–3 min or more were observed prior to the event, and the continuum radiation can be seen throughout the ∼2-h current sheet crossing interval. For context, during the same day (DOY 338, 2017), Vogt et al. (2020) also report two large events observed at times 4:15 and 17:47 UTC.

4. Discussion

The duration of the two events discussed in this study, as defined by the time between extrema in B_θ, is roughly 22 and 62 s, respectively. Using the low-frequency cutoff for the continuum radiation, which is roughly between 500 and 600 Hz for Event #1 and ∼1 kHz for Event #2, we estimate the plasma densities (e.g., Barnhart et al., 2009) during the intervals in question to be 0.003 and 0.012 cm^{-3}, respectively, which correspond to ion inertial lengths of roughly 16,356 (0.23 R_J) and 8,178 km (0.11 R_J), assuming an ion mass of 16 amu. Assuming that the plasmoid travel speed is limited by the Alfven speed in the surrounding lobes (Cowley et al., 2015) which are 489 and 220 km/s (which is calculated based on the observed magnetic field strength of 5 and 4.5 nT, respectively and electron density obtained from Waves), the 22 and 62 s duration of the event would correspond to diameters of roughly 10,771 km (0.15 R_J or 0.65 d_i) and 13,360 km (0.19 R_J or 1.67 d_i), respectively. Kronberg et al. (2008) found that most energetic particle bursts corresponding to plasmoid events have speeds of roughly 450 km/s, which would provide diameters of 9,900 km (0.6 d_i) and 27,900 km (3.4 d_i) for the two events respectively, comparable to the local ion inertial length.

After Event #1, when the flux rope has passed over the spacecraft, a reversal in the guide field (B_ϕ) is observed from −4 to 2 nT. This reversal of the out-of-plane component of the magnetic field in close proximity to the reconnection *x*-line could be due to the quadrupolar Hall magnetic field (Eastwood et al., 2007; Sonnerup, 1978), which is formed due to the decoupling of ions and electrons in the ion diffusion region and has been identified by multiple spacecraft in the terrestrial magnetotail (e.g., Nagai et al., 2001). We caution however that single-spacecraft measurements are unreliable to conclusively determine whether or not the reversal in B_ϕ is due to the Hall field. Another possible explanation for the reversal could be related to the bend-back of the magnetic field, which has been seen as a correlation between the sign of B_r and B_ϕ. In the present situation, the latter theory is less likely since B_ϕ returns to negative values despite multiple current sheet crossings as seen in B_r.

For Event #2, the MVA analysis shows that Juno is sampling the portion of the flux rope where its axis is almost radial, as determined by the direction of intermediate variance. The ratio of the maximum to intermediate and intermediate to minimum eigenvalues are quite large $\left(\lambda_N / \lambda_M = 7.97, \lambda_M / \lambda_N = 81.39\right)$, indicating that the coordinate system is well-defined. Note that observations of flux ropes in the terrestrial magnetotail have shown that many flux ropes are tilted in the plane of the current sheet (Slavin et al., 2003). However, $\left|\vec{B}\right|$ does not peak at the center of the interval and the best fit force-free flux rope does not fit the data well ($\chi_r^2 = 5.9$), although the modeled field in the B_M component looks reasonable, and a bipolar signature is observed in the B_N component. While conventionally flux ropes in the terrestrial magnetotail are seen to possess a strong core field, this has not been the case for the giant planet magnetospheres. Plasmoids observed at Jupiter and Saturn usually possess a weak magnetic field at their core, which is likely due to large plasma β. The force-free model is based on the assumption that pressure gradients inside and surrounding the flux rope are negligible, which may not be the case for this event. Another possible explanation is that this is a flux rope in the early stages of formation and has not yet reached the minimum energy force-free state.

Multiple alternating B_θ reversals, with peak-to-peak durations of roughly 2–3 min or more were observed prior to Event #2 (Figure 4, shown in red and blue). There is no clear increase in the axial magnetic field strength inside these events, which indicates that these north-south reversals correspond to magnetic O-lines. These observations of recurring north-south reversals are similar to those expected for sequentially released plasmoids from a reconnection X-line due to current sheet instabilities, though single-point measurements are not definitive.

Both events are observed in the dawnside magnetotail, where plasma density is relatively low and the Dungey-cycle flux closure is expected to occur (Cowley et al., 2003). However, without context of the global magnetosphere, it is not possible to determine whether the reconnection events discussed here were a product of the Dungey or Vasyliunas cycles. Note that both Dungey and Vasyliunas cycle plasmoid release can be initiated by reconnection initially within closed field lines, as proposed by theoretical models (Cowley et al., 2008) and seen in global simulations (Sarkango et al., 2019).

5. Conclusions

Despite differences in magnetospheric dynamics, reconnection occurs in the Jovian magnetotail and releases plasmoids, much like at Earth and Mercury. However, unlike at the terrestrial-like planets, where plasmoids (or O-lines) and flux ropes are observed in various sizes, with some at or below the ion inertial length, Jovian plasmoids and flux ropes were observed to be fairly large, with diameters of several R_J (or an order of magnitude larger than the local ion inertial length) or an in situ magnetic signature that is seen to last 6 min on average (Vogt et al., 2014). Potential ion-scale structures, however, could not have been detected by the Galileo magnetometer, owing to its low temporal resolution of several seconds per vector.

In this letter, we report on observations made by the Juno spacecraft of two magnetic flux ropes in the Jovian magnetotail, whose diameters are comparable to the local ion inertial length. Similar to previous studies, the two events were selected based on a bipolar variation in B_θ, the component of the magnetic field normal to the current sheet. Each event was further analyzed using the MVA to infer the orientation of the flux rope and modeled using a constant α force-free model. Also seen preceding one of the events are multiple reversals in the north-south component of the magnetic field, which could be a result of sequential plasmoid release from multiple X-line reconnection.

While the large-scale dynamics of the Jovian magnetosphere may be determined by the relatively large plasmoids reported by earlier investigations, the observations reported in this letter show that ion-scale flux ropes also exist in the Jovian magnetotail, much like at Earth and Mercury. How these flux ropes influence the mass and energy budget of the magnetosphere remains an open question, for which additional surveys are needed to understand their distribution, size, mass, and frequency of occurrence. Moreover, the dusk-side magnetotail has not been explored in detail, either by Galileo or Juno. An understanding of reconnection, or lack thereof, in this region is crucial to understand how Iogenic plasma ultimately escapes the Jovian magnetosphere.

Data Availability Statement

The Juno magnetometer (MAG) used in this study is publicly available from the Planetary Plasma Interactions node of the Planetary Data System at https://pds-ppi.igpp.ucla.edu/and the Waves data can be obtained from the das server hosted at the University of Iowa (http://jupiter.physics.uiowa.edu/das/server?dataset=Jun).

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