Juno observations of magnetotail dynamics at Jupiter

The goal of the proposed work is to establish the role of magnetotail reconnection in the overall transport of mass and magnetic flux in Jupiter's magnetosphere and to determine the drivers of magnetotail dynamics at Jupiter. In order to achieve this goal, we will survey Juno magnetic field and plasma measurements to establish the properties of magnetotail dynamics at Jupiter, including the size, recurrence time, and location of tail reconnection signatures. The results of this work will improve our understanding of plasma loss mechanisms at Jupiter, which has implications for other rotation-dominated planetary systems.

1. Introduction

Jupiter's magnetosphere, illustrated in Figure 1, is the largest in the solar system on both absolute and relative (to the planetary radius) terms, with a typical magnetopause standoff distance of ~60-90 R_J (Jovian radii, 1 R_J = 71492 km) depending on the solar wind dynamic pressure. The large size is due in part to the strong planetary magnetic field and the presence of hot plasma, largely confined to the magnetodisk or current sheet, which primarily comes from the volcanically active moon Io rather than from the solar wind as at Earth. Material is released from Io's SO_2 atmosphere at a rate of ~0.4 to ~1.3 ton/s and forms a neutral cloud near Io's orbit; this material is later ionized through charge exchange and electron impact ionization, adding ~500–1,000 kg/s of plasma, in the form of sulfur and oxygen ions, to the magnetosphere (e.g. Thomas et al., 2004).

Magnetic reconnection is an important physical process that allows for the release of built-up of mass and energy from a magnetosphere. The mechanism by which magnetic reconnection occurs is a critical diagnostic of the overall behavior of a magnetosphere. In the Earth's magnetosphere, the solar wind is the primary plasma source, and magnetotail reconnection is driven by the solar wind, in a process called the Dungey cycle (Dungey, 1961). By comparison, at

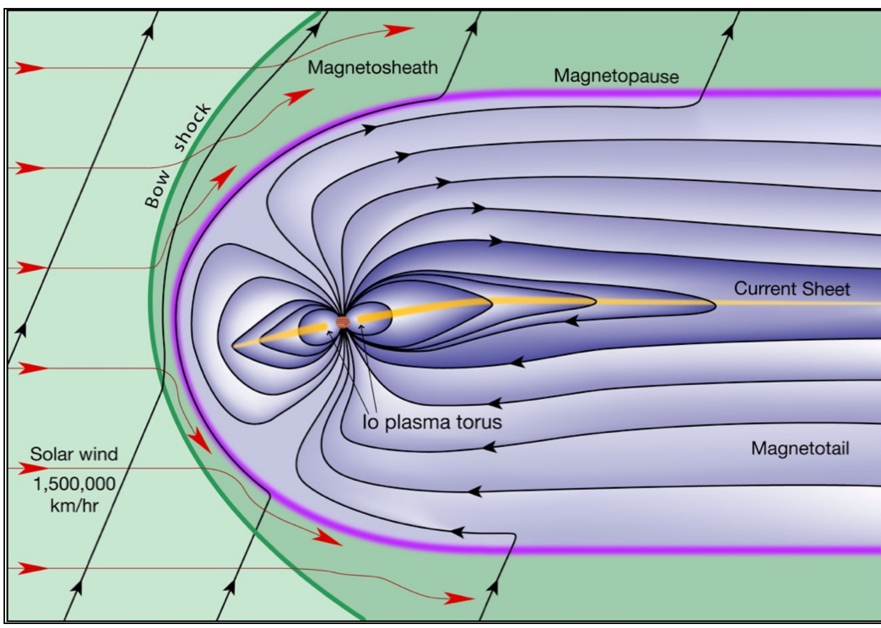

Figure 1. The main features of Jupiter's magnetosphere, shown here in a meridional plane, including the Io plasma torus, current sheet, and magnetotail. Arrows indicate the magnetic field direction. Courtesy: Fran Bagenal and Steve Bartlett, LASP MOP website.

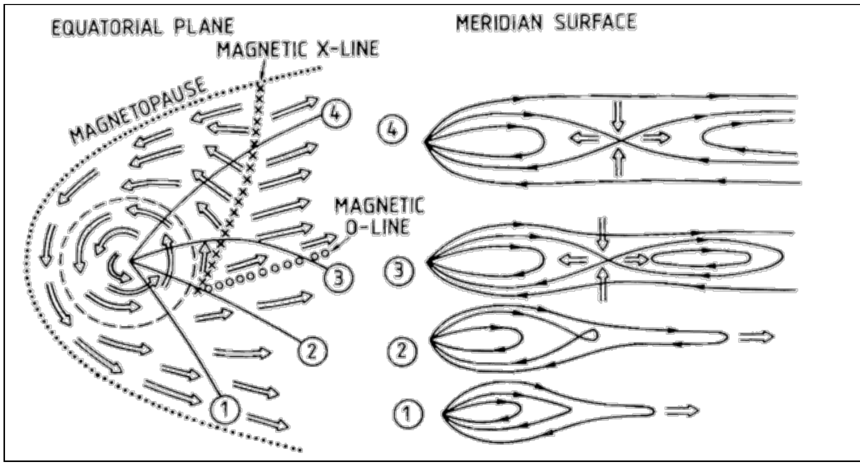

Figure 2. Schematic of the internally driven reconnection of the Vasyliunas cycle. Mass-loaded flux tubes (1) rotate to the night side, (2) are stretched due to centrifugal acceleration of rotating particles, and (3-4) pinch off, releasing a plasmoid. From Vasyliūnas (1983).

Jupiter, it is commonly assumed that centrifugal stresses, rather than the solar wind, are the dominant factor driving magnetospheric dynamics (e.g. Krupp et al., 2004). For example, one can consider the ratio of the potential energy from corotation to the solar wind induced potential across the polar cap (the latter being an indicator of the amount of energy available from the solar wind). This ratio is about 5 for the Earth and about 50 for Jupiter, suggesting that rotational stresses are much more significant than the solar wind in driving dynamics at Jupiter (Khurana et al., 2004). The proposed internally-driven tail reconnection process is known as the Vasyliunas cycle (Vasyliūnas, 1983). It occurs as mass-loaded flux tubes rotate into the night side, are stretched radially by the centrifugal force, break off, and release a plasmoid, as illustrated in Figure 2. Plasmoids are structures which form during reconnection when part of the plasma sheet breaks off, releasing a plasma bubble on closed loops of disconnected field lines that can be ejected down the tail. While the Vasyliunas cycle is generally thought to drive tail reconnection at Jupiter, several important questions about this process remain unanswered by the available observations.

Figure 3 shows reconnection signatures observed in multiple magnetospheric datasets collected by the Galileo spacecraft, which orbited Jupiter from late 1995 to 2003. The reconnection signatures include flow bursts measured by the Galileo Energetic Particle Detector (EPD) (Woch et al., 1998; Kronberg et al., 2005, 2008) and magnetic field dipolarizations and reversals measured by the magnetometer (Vogt et al., 2010). The reconnection signatures in the magnetic field (red highlighted intervals in B_θ, the north-south magnetic field component, in the top panel) and radial flow bursts (increased radial anisotropy, second panel) in Figure 3 show good agreement. Surveys of the Galileo EPD and magnetometer data have identified hundreds of reconnection events throughout the magnetotail.

The reconnection events observed in the magnetic field and EPD data have been associated with increases in the hectometric (HOM) auroral radio emissions measured by Galileo's Plasma Wave Subsystem (PWS) (Louarn et al., 1998, 2000, 2007), as shown in the bottom panel of Figure 3. Jupiter's auroral radio emissions are generated by the cyclotron maser instability and extend in frequency from the kilometer to decimeter range; the HOM emissions have frequencies between a few hundred kHz and a few MHz and originate in the high-latitude auroral zones (Zarka, 1998). The correlation between the reconnection signatures and increases in the auroral radio emissions has been interpreted as evidence for global-scale magnetodisk reconfigurations that include tail reconnection and energetic particle injections in the inner magnetosphere (Louarn et al., 2014).

The data shown in Figure 3 come from Galileo orbit G2 and display quasi-periodic variations on a ~2-3 day time scale. This ~2-3 day time scale is similar to the expected characteristic time scale of an internally-driven mass loading and release process associated with the Vasyliunas cycle (Kronberg et al., 2007). However, it is noteworthy that throughout the Galileo dataset the quasi-periodic behavior occurs only intermittently, particularly in the magnetic field data, and in other orbits the characteristic period can vary from 1 to 7 days (Kronberg et al., 2009). Orbit G2, which took the spacecraft through the deep pre-dawn magnetotail in fall 1996, was an exceptionally dynamic interval, featuring 70 of the 249 reconnection events reported by Vogt et al. (2010). Unfortunately, with the exception of the G2 orbit and the Pioneer and Voyager flybys, essentially no data is available in the deep pre-dawn region (beyond ~60 R_J, local times 02:00 and later), as shown in Figure 4. **Therefore, an important unanswered question is whether the Galileo spacecraft flew through an especially dynamic region of the magnetosphere during orbit G2 or whether other (temporal) factors during that interval, such as extreme plasma mass loading by Io or disturbed external solar wind conditions, were responsible for the unusually dynamic tail conditions.** Understanding whether the dynamic behavior of orbit G2 is temporal or spatial in nature provides important insight into what factors drive tail reconnection at Jupiter, since at Jupiter the Dungey cycle is expected to be restricted to pre-dawn local times (e.g. figure 1 of Cowley et al., 2003) whereas the Vasyliunas cycle is expected to operate across the tail.

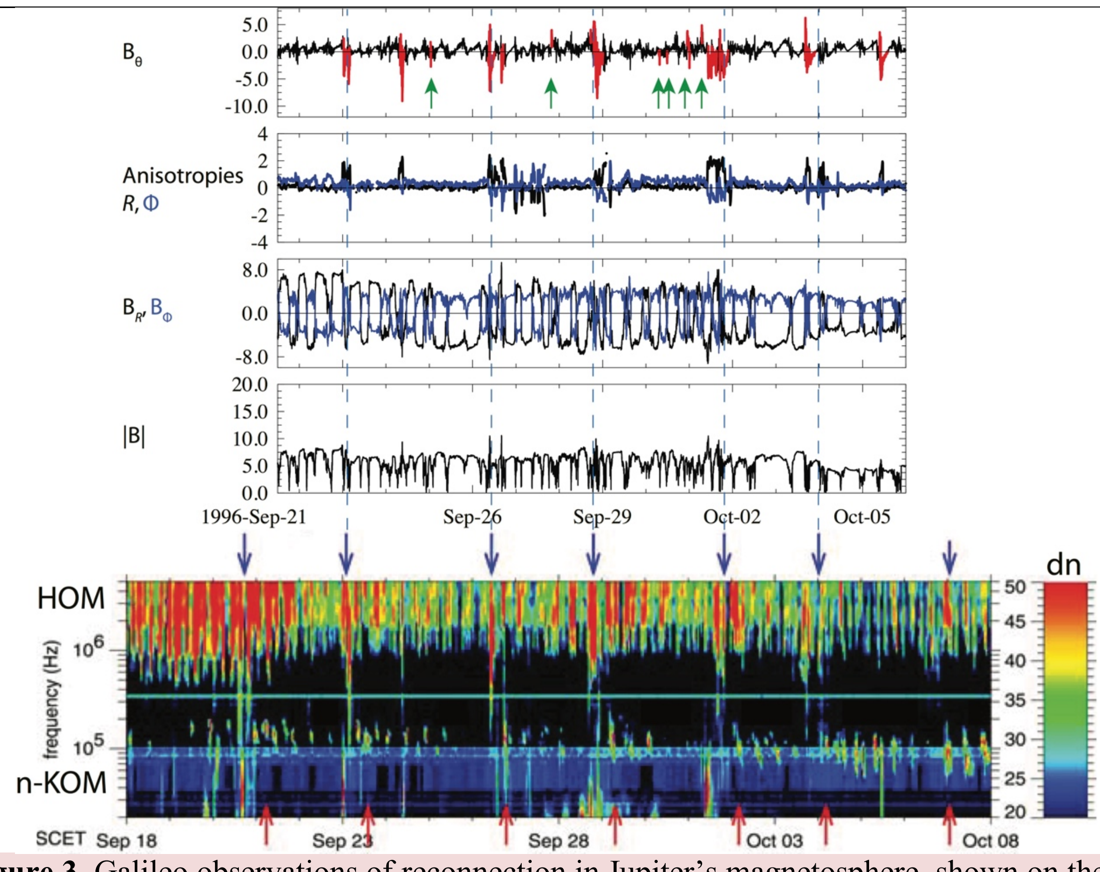

Figure 3. Galileo observations of reconnection in Jupiter's magnetosphere, shown on the same time scale for an interval during orbit G2 in Sept.-Oct. 1996. (Top) Magnetic field in spherical coordinates and EPD flow anisotropies as a function of time. Modified from Vogt et al. (2010). (Bottom) Frequency-time spectrogram of Jupiter's radio emissions in the hectometric and kilometric frequency ranges, measured by Galileo's Plasma Wave Subsystem. The HOM intensity increases every 2-3 days (blue arrows and vertical dashed lines), in good agreement with the EPD and MAG reconnection signatures. Modified from Louarn et al. (2007).

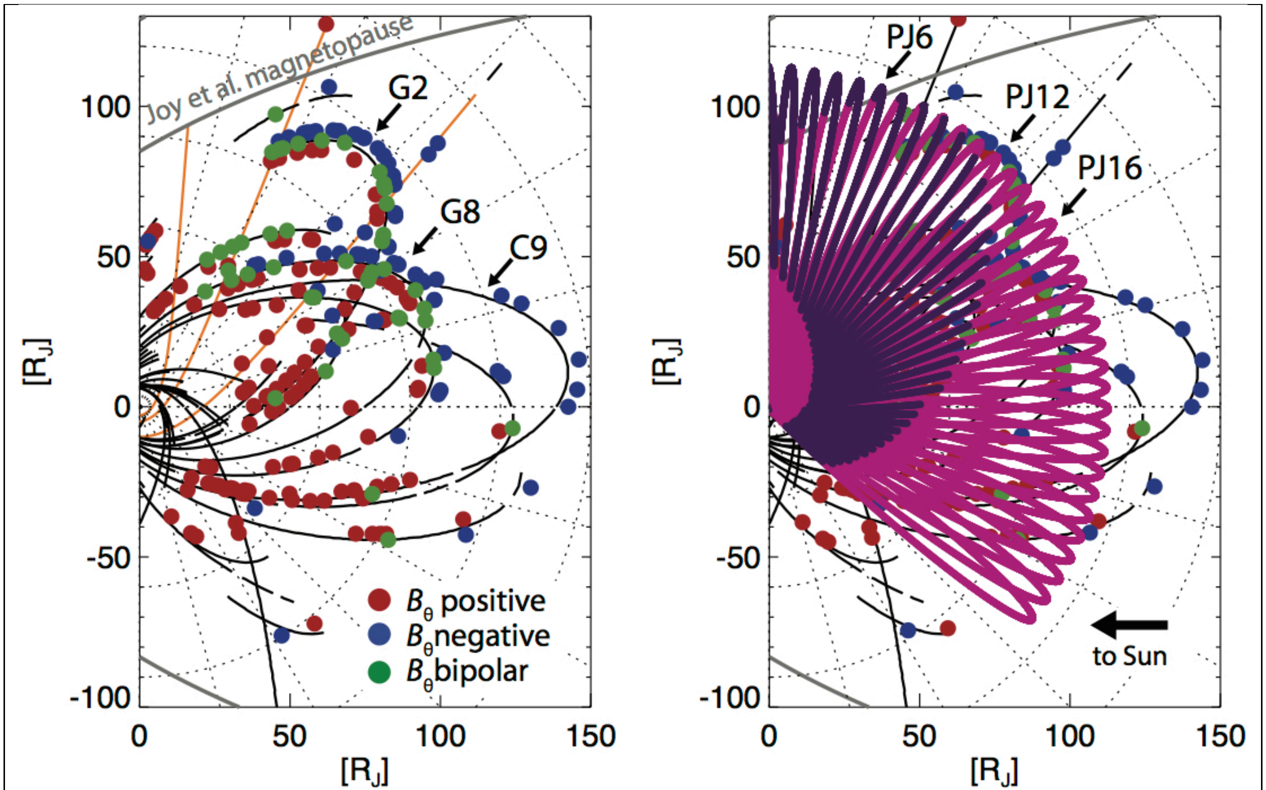

Figure 4. Locations of the Vogt et al. (2010) Jovian reconnection events identified in magnetometer data. Colors indicate the sign of the B_θ deflection during the event, which is a proxy for radial flow and suggestive of location inside (red) or outside (blue) of an x-line. Galileo orbits are shown in black; Pioneer and Voyager flyby orbits are shown in orange in the left panel. The Juno orbits (pink) have been overplotted in the right panel, with purple indicating intervals when the spacecraft is within 10 degrees of the equator (10 degrees is significant because the magnetic dipole is tilted ~10º with respect to Jupiter's rotation axis).

It is also important to understand whether or not the level of activity observed during orbit G2 is typical of the deep pre-dawn magnetotail because the plasmoid occurrence rate is a key quantity in estimating the mass loss rate. The plasmoid mass loss rate can then be compared to the rate at which plasma from Io is added to the magnetosphere, which gives insight into the role that reconnection plays in the overall transport of mass and energy throughout the magnetosphere. Previous studies have attempted to estimate the plasmoid mass loss rate in Jupiter's magnetotail and most have concluded that it is small (~1-120 kg/s) compared to the mass loading rate from Io (~500-1000 kg/s), suggesting that tail reconnection is not the dominant source of mass loss (e.g. Bagenal, 2007; Vogt et al., 2014a). However, it is difficult to constrain the size and mass of Jovian plasmoids with measurements from a single spacecraft, so **the role of plasmoids in mass transport at Jupiter remains a topic of debate** (e.g. Cowley et al., 2015). This difficulty was compounded for the Galileo plasmoids by the limited availability of the necessary plasma measurements because of the failure of Galileo's high-gain antenna and other issues with the plasma science instrument (e.g. Bagenal et al., 2016). The plasma velocity is needed to constrain the plasmoid size, and density is needed to constrain the plasmoid mass. Vogt et al. (2014a) assumed average velocity and density values and concluded that a plasmoid mass loss rate of ~1-

120 kg/s was consistent with the Galileo observations, but this estimate could be refined with more accurate plasma measurements. Proposed loss mechanisms other than plasmoids include interchange motion (Southwood and Kivelson, 1987, 1989) across centrifugally unstable, highly stretched field lines in the dusk local time sector (Kivelson and Southwood, 2005), a planetary wind, and a ubiquitous but small-scale reconnection and plasmoid release ("drizzle") occurring across the tail (e.g., Delamere and Bagenal, 2010). Finally, we note that the plasmoid occurrence rate is also an important quantity for estimating how much open flux can be closed via tail reconnection, which is crucial for understand the solar wind-magnetosphere interaction.

Juno is currently measuring the magnetic field and plasma properties of Jupiter's magnetosphere out to radial distances of ~110 R_J during its 53-day orbits. We propose to analyze Juno data to answer two key questions about reconnection in Jupiter's magnetotail:

- **Where and how often does reconnection occur in Jupiter's magnetosphere?**
- **What are the properties of Jovian plasmoids, including their mass, size, and flux closure rates?**

Taken together, the answers to these questions establish the role of magnetotail reconnection in the overall transport of mass and magnetic flux in Jupiter's magnetosphere and determine the drivers of magnetotail dynamics at Jupiter. Though these questions were addressed in initial studies of the Galileo data, there are many outstanding issues as discussed above. **Juno represents an unrivaled opportunity to resolve these outstanding issues because it extends or complements the Galileo data in two key ways.** The first is that the Juno orbit takes the spacecraft through the deep pre-dawn magnetotail, overlapping with the exceptionally dynamic Galileo orbit G2, as shown in Figure 4. Juno will provide crucial coverage in the region beyond ~60 R_J at local times 02:00-06:00, which will help determine whether the dynamic nature of Galileo orbit G2 was temporal or spatial. In this way, Juno observations will establish the occurrence frequency and spatial distribution of reconnection at Jupiter, which has important implications for understanding the factors that drive magnetotail dynamics at Jupiter as discussed above. The second way in which the Juno observations complement the Galileo data is that Juno provides a more complete picture of the plasma properties at Jupiter, providing high time resolution measurements of the energy, pitch angle, and composition distributions for both ions and electrons. In this way, Juno observations provide key information (plasma density and velocity) needed to calculate the plasmoid mass loss and flux closure rates, which yield insight into the importance of magnetotail reconnection in the overall mass and flux transport at Jupiter. The results of our work will improve our understanding of plasma loss mechanisms at Jupiter, which has implications for other rotation-dominated planetary systems.

2. Juno data to be used in this work

Juno is carrying a suite of instruments that measure the magnetic field and plasma properties in Jupiter's magnetotail. Together, data from several of these instruments can provide a complete picture of the conditions in Jupiter's magnetotail. In our work we will use data from the following instruments:

- MAG (Magnetometer; Connerney et al., 2017) – Vector fluxgate magnetometer measuring the magnetic field components; data available on the PDS have a time resolution of 1 second per vector
- JEDI (Juno Energetic particle Detector Instrument; Mauk et al., 2017) – Measures energy and pitch angle distributions for electrons from 40 to 500 keV and energy, pitch angle, and

ion composition distributions for ions at ~20-50 keV to more than 1 MeV. Time resolution as high as 0.5 seconds in the auroral region.

- JADE (Jovian Auroral Distributions Experiment; McComas et al., 2017) – Provides energy spectra and pitch angle distributions for electrons at 0.1-100 keV and ions 5 eV - 50 keV, also measures ion composition from 1 to 50 amu. Time resolution ranges from 30 seconds to 10 minutes in low rate science mode depending on bandwidth.
- Waves (Juno WAVES Investigation; Kurth et al., 2017) – Provides electric spectra at frequencies 50 Hz to 40 MHz and magnetic spectra at frequencies 50 Hz to 20 kHz, with a time resolution of 30 seconds per spectra (in apoapsis mode)

Both JEDI and JADE provide ion plasma moments (e.g. density and velocity) as higher-order data products. These data are not yet available in the PDS but they have been included in some Juno science team publications (e.g. Ebert et al., 2017), demonstrating that they will be available.

A similar suite of instruments was included in the Galileo spacecraft, and though the Galileo data rates were limited due to the failure of the high-gain antenna, the Galileo instruments provide a dataset that is highly complementary to the Juno measurements. Specifically, data from Juno's magnetometer can be compared to the magnetometer measurements from Galileo (Kivelson et al., 1992), which were typically available at a time resolution of 24 seconds per vector; JEDI data can be compared to data from Galileo's Energetic Particle Detector (EPD) (Williams et al., 1992); JADE data can be compared to data from Galileo's plasma science instrument (PLS) (Frank et al., 1992); and Waves data can be compared to data from Galileo's Plasma Wave Subsystem (PWS) (Gurnett et al., 1992).

Juno is in a 53-day polar orbit with an apojove of 113 R_J and inclination up to 105.5º (Bolton et al., 2017). The right panel of Figure 4 shows its orbit projected into the equatorial plane, with labels indicating the apojove for orbits (which are referred to as perijove passes, or PJ) 6, 12, and 16. The orbital tilt increases during each orbit so that with each successive orbit Juno spends less time near the equatorial plane (purple highlighted regions in Figure 4) and the equatorial crossing point of its orbit moves radially inward. By comparison, Galileo's orbit was largely confined to the equatorial plane. Therefore, Juno's orbit is not as favorable as Galileo's for observing the plasma sheet, which is located roughly at the magnetic equator and passes over the equator every ~5 hours due to Jupiter's 10º dipole tilt. Fortunately, Juno's trajectory places it within 10º of the equatorial plane during most of the inbound portion of the first ~16 orbits (see purple highlighted regions in Figure 4). Juno will observe the near-equatorial magnetosphere out to distances of at least ~90 R_J at local times ~02:00-06:00, which provides crucial measurements for comparison to the dynamic Galileo orbit G2.

Finally, we note that data from Juno's first 6 orbits were made publicly available in the PDS more than 30 days before the proposal step-2 deadline, and by the proposal deadline Juno was scheduled to have completed PJ12.

3. Outline of proposed research

The proposed research consists of three tasks. **Task A** is a survey of the Juno magnetic field data from Jupiter's magnetotail to identify signatures of tail reconnection and determine their statistical properties. Initially we will focus only on the magnetometer data to facilitate comparisons to the Galileo-era studies which relied primarily on magnetic field data (e.g. Vogt et al., 2010, 2014a). In **Task B** we will expand our analysis from Task A to include other Juno datasets, including JEDI, JADE, and Waves. We will use these additional datasets to validate the events that were identified using only the magnetic field in Task A. The results of Tasks A and B together will establish where and how often Juno observes reconnection in Jupiter's magnetotail. Finally, in **Task C** we will estimate the size and mass of Jovian plasmoids to determine the importance of tail reconnection to mass transport in Jupiter's magnetosphere. We will also calculate the rate at which Jovian plasmoids close magnetic flux.

3.1 Task A: Survey of reconnection events in Juno magnetometer data

The goal of the first task is to identify reconnection events in the Juno magnetic field data and determine their statistical properties. We will survey the magnetic field data alone, and in Task B extend our analysis to other Juno datasets, so that our results can be more directly compared to Galileo-era studies that relied only on magnetometer data. Reconnection events can be inferred from magnetometer data alone by the occurrence of a field dipolarization or field reversal, and the direction of flow can be inferred by the sign of B_θ, as illustrated in Figure 5. However, plasma measurements are still useful for placing the magnetic field observations into context and for confirmation of features, like plasma heating and fast radial flows, associated with tail reconnection.

Separate surveys of flow bursts in the Galileo EPD data (Kronberg et al., 2005) and reconnection signatures in the magnetometer data (Vogt et al., 2010) revealed overall good agreement between the two datasets, with most EPD events accompanied by a magnetometer event. However, the magnetometer data revealed many additional events compared to the EPD data, particularly in the pre-midnight local time sector where the plasma sheet is thick. One possible explanation for the additional events is that the Galileo magnetometer data have a higher time resolution (typically 24 seconds per vector) than the EPD data (~3-11 minutes), which makes it easier to identify shorter events; of the 249 Vogt et al. (2010) events, 104 have a duration less than 30 minutes, and the average duration is 59 minutes. Another possible explanation is that the pre-midnight magnetic field events are not actually reconnection signatures and that they are produced by a different process than the post-midnight events, since the EPD data suggested that the post-midnight magnetic field events are accompanied by faster radial flows and larger density changes than the pre-midnight events (Kasahara et al., 2013). In that case, the field dipolarizations could be the result of radially stretched field lines being pulled back in by magnetic tension rather than reconnection (e.g. Ogino et al., 1998; Walker et al., 2001). By first identifying tail reconnection signatures in Juno magnetic field data alone and then confirming (or refuting) the events with other Juno datasets we will gain insight into whether the Galileo magnetic field reconnection events may be over- or underestimating the occurrence frequency of tail reconnection at Jupiter.

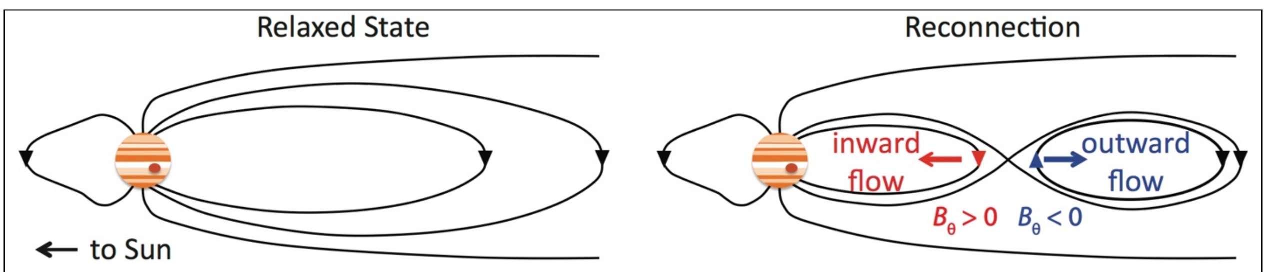

Figure 5. Cartoon illustrating reconnection in Jupiter's magnetotail. A field dipolarization (increased positive B_θ) or reversal (negative B_θ) can indicate reconnection, and the sign of B_θ can be used to infer the flow direction and position with respect to the reconnection x-line.

We will search for tail reconnection events, identified by magnetic field dipolarizations and reversals, in all of the available Juno magnetometer data. We will follow the approach used in our previous analysis of the Galileo magnetometer data (Vogt et al., 2010) by identifying events using an automated routine that selects for times when $|B_\theta|$ is larger than background values; a similar approach has also been applied to Saturn (e.g. Smith et al., 2016). In our previous work we searched for, among other requirements, intervals when $|B_\theta|$ was larger than the background (a 1-day running average) by at least a factor of 2. Examples of events identified by these criteria are shown by the red highlighted intervals in the B_θ panel in Figure 3. We will first inspect the Juno data by eye and will adjust the Vogt et al. (2010) event detection algorithm as necessary to ensure that it faithfully identifies reconnection signatures in the Juno data. Some adjustments may be needed to the algorithm to account for the fact that Juno's orbit is inclined out of the equatorial plane; relative to Galileo, which was in an equatorial orbit, Juno will spend less time in the equatorial plasma sheet where it is easier to observe plasmoids. Therefore, we may need to adjust our algorithm to increase its sensitivity for the identification of traveling compression regions (TCRs). TCRs are the remote signature of a plasmoid that are observed when a spacecraft does not pass directly through the plasmoid but observes the draping, and subsequent compression of, the lobe field around the plasmoid (Slavin et al., 1993).

An example reconnection event that we have identified by eye in the Juno magnetometer data is shown in Figure 6. The top four panels show Juno magnetometer data as a function of time and the bottom panel shows a JADE electron energy-time spectrogram. Juno was located in the deep pre-dawn magnetotail at this time, at ~85 R_J and ~05:00 LT. Juno observed this event as it was entering the plasma sheet; these plasma sheet crossings occur because of Jupiter's ~10º dipole tilt and are evidenced in the magnetic field data as reversals in the radial field (top panel). In the day interval before the event Juno observes small increases in B_θ and increased electron fluxes occurring every ~5 hours as the spacecraft crosses through Jupiter's plasma sheet. During the event B_θ increases and there is evidence of electron energization. This is a significant event: the maximum B_θ value, ~7 nT, is larger than the maximum $|B_\theta|$ signature observed in roughly 75 percent of the Vogt et al. (2010) Galileo-era events.

After identifying reconnection signatures in Juno magnetometer data with an automated routine, we will compile statistics on their location, recurrence time, duration, and other properties, following a similar approach to Vogt et al. (2010, 2014a). This information will be used together with the results of Tasks B and C to answer our two motivating science questions, as we discuss in more detail below. We will compare these statistics to those derived from the Galileo-era list of reconnection events identified from magnetometer data alone (Vogt et al., 2010). This comparison will establish the degree to which the results of Tasks B and C, which will take advantage of the availability of Juno plasma measurements, could alter our interpretation of the Galileo-era data. For example, if we find that a significant fraction of the Juno magnetic field events does not show evidence of reconnection in the plasma measurements (e.g. fast flows) then we would conclude that identifying tail reconnection on the basis of magnetic field measurements alone likely overestimates the occurrence rate, and we would revisit our previous Galileo-era estimates for the plasmoid mass loss and flux closure rates.

The example event shown in Figure 6 demonstrates the ability of the Juno spacecraft to observe reconnection signatures even in Juno's non-equatorial orbit. We expect to find scores of additional events, especially in the data from PJ6 through PJ16, an interval during which Juno still spends a significant amount of time in or near the plasma sheet and also passes through the deep pre-dawn magnetotail (near orbit G2). However, even if we identify very few reconnection signatures in the Juno data the lack of detection would be a significant result because it will have important consequences for our estimates of the occurrence frequency of reconnection at Jupiter. For example, if we identify only a few reconnection signatures in the Juno data that would likely mean that the Galileo-era studies provide an upper bound on the occurrence frequency estimates, which would mean that the Galileo-era estimates of plasmoid mass loss could also be upper limits.

Finally, we note that the data shown in Figure 6 were downloaded from the PDS. This figure demonstrates our ability to work with the Juno data files that are available on PDS, which is significant because the Juno Participating Scientists Proposal Information Package states that "it is the intention of the Juno Science Team to utilize the same files for science as are archived with the PDS".

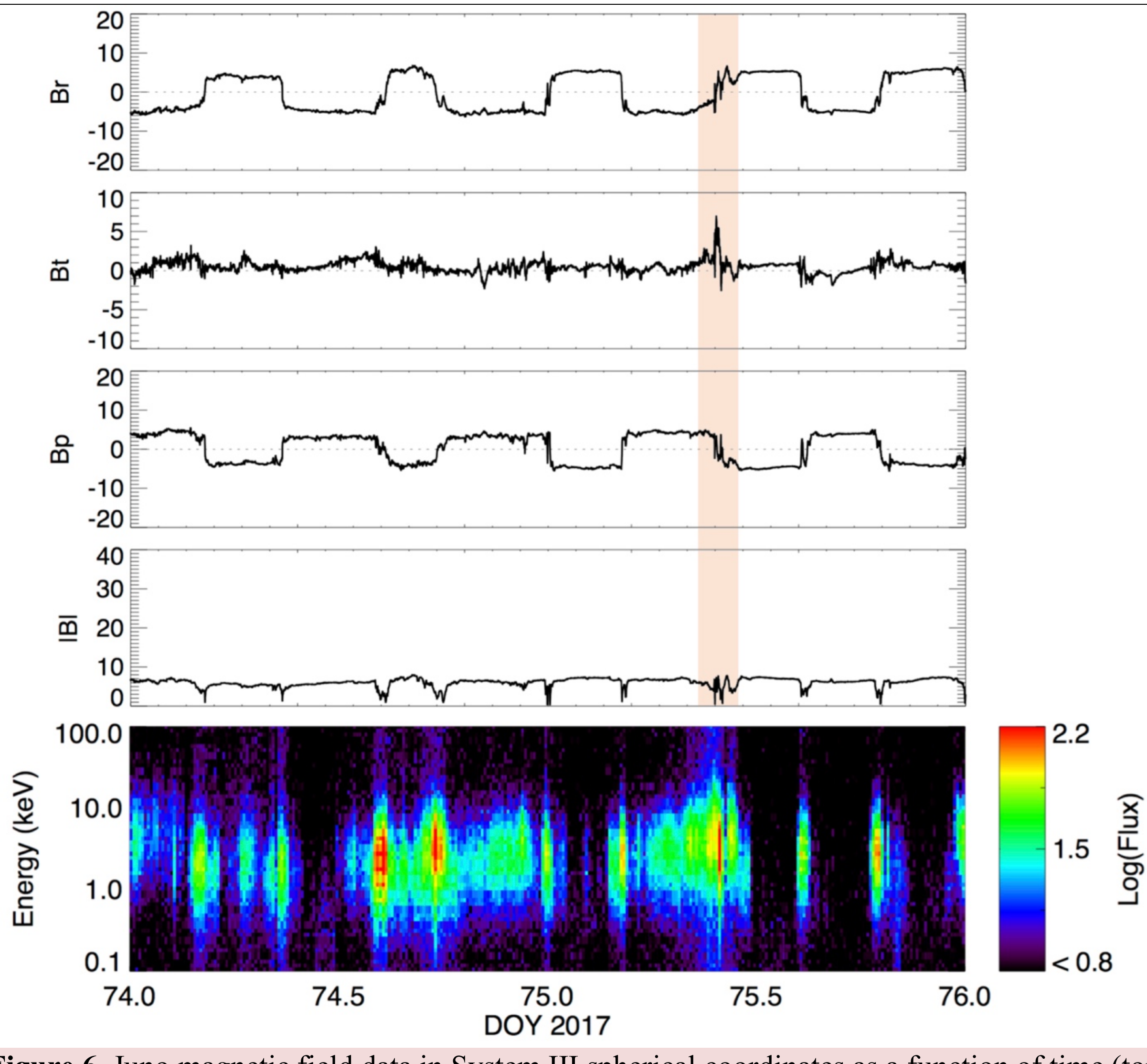

Figure 6. Juno magnetic field data in System III spherical coordinates as a function of time (top four panels) and JADE electron spectrogram (bottom panel) from PJ5. A reconnection event candidate, which features a strong field dipolarization (increase in B_θ) is highlighted by the orange vertical area in the top four panels. Juno was located at ~85 R_J and just before 05:00 LT.

3.2 Task B: Expansion to other Juno datasets

The goal of the second task is to expand our analysis to use other Juno datasets so that we can definitively establish the spatial distribution, occurrence frequency, and other properties of tail reconnection at Jupiter. From Task A we will have identified a list of events that we interpret as being due to reconnection based on the magnetic field signature alone. We will begin by testing the validity of this interpretation. We will examine the plasma velocity measured by JADE and JEDI for each magnetic field event to determine whether or not the magnetic field signature was accompanied by a strong plasma flow which would further indicate reconnection. There are multiple approaches we could use to validate the magnetometer events, depending on the number of events and the availability of the JADE and JEDI velocity measurements. Where possible we will use quantitative criteria (e.g. requiring that plasma velocities reach some threshold value, or increase by some amount, to confirm a reconnection event) and statistical analyses like a superposed epoch analysis. As part of the event validation we will also examine the electron and ion energy spectra, like that shown in Figure 6, for evidence of plasma energization as is expected during reconnection. On the basis of the JADE and JEDI data analysis we will classify each magnetic field event as a "confirmed" or "unconfirmed" reconnection signature. For example, in Figure 3 there are 6 Galileo reconnection events, indicated by the green arrows in the B_θ panel, that are not accompanied by an increase in radial anisotropy (second panel) which would indicate flow. We would classify these 6 events as "unconfirmed reconnection" and would classify the remaining events as "confirmed reconnection".

After dividing the magnetic field events into "confirmed" and "unconfirmed" reconnection classifications we will compile statistics on the occurrence frequency, spatial distribution, duration, and other properties of the "confirmed reconnection" events, following the analysis of Vogt et al. (2010, 2014a). In Task A we will have done this for all magnetic field events. As discussed in section 3.1, it is important to consider how the properties of all magnetic field events compare to the properties of the "confirmed reconnection" events so that the results of our analysis with the Juno data can be viewed in context to the Galileo-era results that relied primarily on magnetic field measurements. We will compare the spatial distribution of the Juno reconnection events (all events and "confirmed" events) to the spatial distribution of the Galileo events, with particular attention to the region near Galileo orbit G2 in the deep pre-dawn magnetotail. Our results will establish whether the G2 orbit was so dynamic in nature because that region of the magnetotail is very active or whether it was the G2 time interval that was so dynamic. We will also examine the local time distribution of the Juno events and will compare the occurrence frequency of the Galileo-era events (~2-3 day quasi-periodicity) to the Juno events (again, separately considering all events and "confirmed" events). These properties are relevant to the question of what factors drive reconnection. Finally, we will attempt to derive a statistical x-line separating inward and outward flow events and compare the location of this x-line to that derived from Galileo data (Woch et al., 2002; Vogt et al., 2010). However, we acknowledge that our ability to do so may be limited in local time because Juno (see purple orbit segments in Figure 1).

Finally, we will analyze Juno Waves data and qualitatively correlate the observed reconnection events with increases in the HOM auroral radio emissions in a manner similar to Figure 3. These findings will provide insight into the global significance of the observed reconnection events, since the reconnection events and HOM increases together have been interpreted as evidence for global-scale magnetodisk reconfigurations (Louarn et al., 2014).

Understanding the degree to which the observed reconnection events may be part of global-scale dynamics also provides insight into their role in the global mass transport and flux closure, which is a goal of Task C.

3.3 Task C: Quantifying the mass loss and flux closure rates due to plasmoids

Once we have established the occurrence frequency and duration of magnetotail reconnection at Jupiter we can use that information, along with the plasma measurements provided by JADE and JEDI, to calculate the mass lost and flux closed by Jovian plasmoids. Plasmoids form during reconnection when part of the plasma sheet breaks off, releasing a plasma bubble on closed field lines that can be ejected down the tail, and are an important mass loss mechanism in the Earth's magnetosphere (Slavin et al., 1993). Plasmoids are identified by a characteristic bipolar signature in the north-south component of the magnetic field (Hones, 1976; 1977), or B_θ, as illustrated in Figure 7.

Vogt et al. (2014a) analyzed the properties of plasmoids observed in the Galileo magnetometer data and used this information to calculate the plasmoid mass loss rate. The calculations required estimates for some quantities, such as the plasmoid occurrence frequency, which were relatively under-constrained by the Galileo observations but will be better constrained by the Juno measurements. Additionally, the mass calculation requires information about the plasmoid length, which can be estimated by multiplying the plasmoid duration by its velocity, and density. Ideally the plasmoid length and density would be calculated individually for each event; however, because of the poor time resolution of the Galileo plasma measurements, Vogt et al. (2014a) used average values (velocity 450 km/s following Kronberg et al. (2008a); density 0.01 particles/cm^3 with particle mass 20 m_p following Kasahara et al. (2013)). Because so many required quantities were unconstrained in their calculation, Vogt et al. (2014a) arrived at a plasmoid mass loss rate spanning two orders of magnitude, concluding that the Galileo observations supported a mass loss rate ranging from ~0.7 to ~120 kg/s.

We will calculate the typical mass loss rate of plasmoids observed by Juno, following the analysis approach of Vogt et al. (2014a); however, quantities such as the plasmoid occurrence frequency, velocity, and density will be better constrained by Juno data than they were by Galileo, so our calculation will produce a mass loss rate that is both more precise and accurate than the previous study. Specifically, the plasmoid occurrence frequency will be better constrained by the

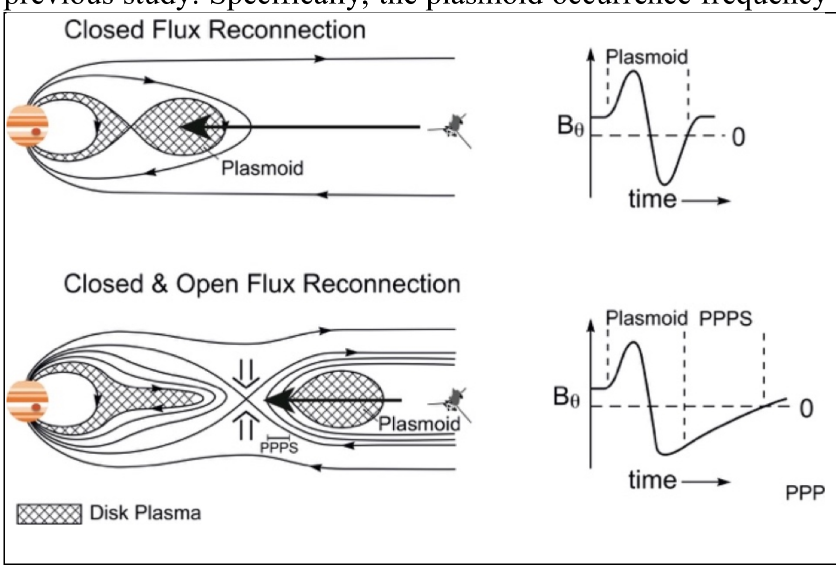

Figure 7. Cartoon illustrating the field line configuration (left) and observed B_θ signature in a plasmoid during closed flux reconnection (top right), and open flux reconnection (bottom right), assuming the plasmoid moves tailward with respect to the spacecraft. Modified from Vogt et al. (2014a).

statistical analysis of reconnection event properties described in Tasks A and B above, and the plasma velocity and density will be provided by JADE and JEDI measurements.

We will also analyze the structure of plasmoids observed by Juno to determine the flux closed by Jovian plasmoids and provide insight into the drivers of tail reconnection at Jupiter. The bipolar B_θ magnetic field signature of a plasmoid is followed by a return to background levels, and the nature of this recovery can indicate whether the observed tail reconnection is occurring on open or closed field lines, as illustrated in Figure 7. If the recovery is on the same time scale as the field dipolarization and reversal signatures, so that the spacecraft records only the symmetric B_θ signature of the plasmoid, then the reconnection likely proceeded on closed field lines (top panel). By comparison, if reconnection proceeds onto open lobe field lines, the spacecraft will record an extended interval of negative B_θ following the main plasmoid signature (bottom panel). This region of open lobe field lines draped over the tailward-moving plasmoid is called the post-plasmoid plasma sheet, or PPPS (Richardson et al., 1987). At Jupiter, the PPPS signature may be expected for Dungey cycle reconnection, which would involve closure of open flux in the tail lobes, but not for the centrifugally-driven reconnection of the Vasyliunas cycle.

The magnetic field in the PPPS consists of newly reconnected field lines with both ends in the IMF, so information about the PPPS duration and flow speed can be used to estimate the amount of open flux that is closed through reconnection of open lobe field lines. The amount of open flux Φ closed in the post-plasmoid plasma sheet is given by

$$\Phi = L_\varphi \int V_R B_\theta \, dt, \quad (1)$$

where L_φ is the plasmoid's azimuthal width, V_R is the outward radial velocity, and the integral is taken over the duration of the PPPS (c.f., Jackman et al., 2011). Vogt et al. (2014a) calculated that plasmoids observed by Galileo close an average of ~4-8 GWb of open flux via the PPPS, or roughly 1 percent of the ~720 GWb of open flux in the polar cap and tail lobes (Vogt et al., 2011). They calculated a flux closure rate of ~7-70 GWb/day, which shows relatively good agreement with the average rate of flux removal on the day side through reconnection, which is an estimated ~18 GWb/day according to Nichols et al. (2006). They therefore concluded that tail reconnection and plasmoids play an important role in flux transport at Jupiter.

We will examine the Jovian plasmoid signatures observed with Juno to establish how often a PPPS signature is observed and how much open flux is closed in the PPPS. We will follow the general approach of Vogt et al. (2014a). However, these flux calculations, like the mass loss rate estimates, relied on average values for the plasma radial velocity. Using more accurate velocity measurements, as will be available from Juno, to analyze the PPPS is therefore important for constraining the PPPS flux closure estimates. <u>More importantly, though, using Juno velocity measurements addresses some important assumptions about the plasmoid velocity that may be an oversimplification.</u> If the radial velocity slows significantly as a plasmoid moves tailward, a spacecraft may record an extended interval of negative B_θ (from the planetward edge of the plasmoid) even without encountering IMF field lines in the PPPS. Observations from the Earth show that terrestrial plasmoids accelerate as they are pulled tailward by IMF field lines which are draped around the plasmoid (Ieda et al., 1998), so the magnetic signature of a PPPS likely does indicate closure of open flux at the Earth. However, at Jupiter, Vasyliunas cycle plasmoids would be enveloped within closed field lines which could slow the tailward plasmoid motion. Therefore the relatively high time resolution velocity measurements that Juno will are crucial for distinguishing whether the PPPS signature in Jovian plasmoids truly indicates closure of open lobe field lines or whether the plasmoid velocity slows as it moves tailward. Similarly, the relatively high time resolution density measurements provided by Juno will further confirm whether reconnection during the PPPS interval is proceeding on low density lobe field lines or high density plasma sheet field lines. Therefore, the Juno measurements will greatly improve our understanding of flux closure rates by plasmoids at Jupiter.

4. Expected results and their significance

We will survey Juno magnetic field and plasma measurements to identify signatures of tail reconnection, with the ultimate goal of understanding what processes drive magnetospheric dynamics in Jupiter's magnetosphere and how reconnection contributes to the transport of mass and energy throughout the system. We will produce a database of candidate reconnection signatures observed in Juno magnetic field data and will analyze JEDI and JADE data to classify these events as "confirmed reconnection" or "unconfirmed reconnection". We will perform a statistical analysis of the spatial distribution, occurrence frequency, and duration of the reconnection event candidates and confirmed reconnection events, and will compare these properties to previous results obtained using Galileo data. This information will provide insight into the drivers of reconnection at Jupiter, for example by determining whether or not the deep pre-dawn magnetotail is always very dynamic and whether or not an internally-driven quasi-periodicity is always observed, since at Jupiter the Dungey cycle is expected to be restricted to pre-dawn local times whereas the Vasyliunas cycle is expected to operate across the tail. We will use Juno observations to calculate plasmoid mass loss and flux closure rates that will be more precise and accurate than estimates based on Galileo data. This will make the comparison between the plasmoid mass loss rate and the ~500-1000 kg/s input rate from Io more meaningful and will further constrain our understanding of the importance of magnetotail reconnection in the overall mass and flux transport at Jupiter. Additionally, we will determine whether or not reconnection at Jupiter proceeds on open field lines, which directly answers the question of whether reconnection is internally (Vasyliunas cycle) or solar wind (Dungey cycle) driven.

5. Research Team and Work Plan

PI Marissa Vogt will perform the data analysis work described in Tasks A, B, and C above. PI Vogt will be responsible for the management of this investigation and compliance with all reporting requirements. PI Vogt will also be responsible for preparing manuscripts for publication, and implementation of the data management plan. PI Vogt's research is focused on Jupiter's magnetosphere and aurora (Vogt et al., 2011, 2014b, 2015, 2017). Her past work has included a survey of reconnection signatures in the Galileo magnetometer data (Vogt et al., 2010) and analyzing the structure and statistical properties of Jovian plasmoids, including estimating the mass loss rate (Vogt et al., 2014a).

Our work plan is as follows:

Task A: Survey reconnection signatures in the Juno magnetometer data

- Develop an algorithm, based roughly on the Vogt et al. (2010) criteria, to identify magnetic field dipolarizations and reversals in the Juno magnetometer data
- Compile statistics on the location, recurrence time, and duration of reconnection events identified in Juno magnetometer data and compare these properties to Galileo-era results
- Effort: 1.5 weeks/year

Task B: Expand analysis to additional Juno datasets

- Test the validity of the reconnection events identified in task A using the JADE and JEDI data to confirm plasma flows (or absence thereof) and examine plasma energy and density
- Compile statistics on the properties of the "confirmed reconnection" events and compare these properties to Galileo-era results
- Analyze Waves data to examine any correlation between tail reconnection events and inner magnetosphere dynamics
- Effort: 2 weeks/year

Task C: Calculate plasmoid mass loss and flux closure rates

- Calculate size and mass loss rate of plasmoids following the approach of Vogt et al. (2014a) but with additional plasma measurements
- Calculate the flux closure rate following the approach of Vogt et al. (2014a) but with additional plasma measurements
- Effort: 2 weeks/year

The three tasks will be executed in each of Years 1, 2, and 3 as new data become available. We will publish two manuscripts summarizing our initial (early in Year 2) and full (in Year 3) results. Total effort requested (0.15 FTE, or 8 weeks/year) includes the 5.5 weeks/year of effort listed in Tasks above, plus 12 days per year (2.5 weeks/year) for attending Juno Science Team Meetings as required by the Juno Participating Scientist call for proposals. (PI Vogt has submitted two Juno Participating Scientist proposals and in the event that both proposals are selected, the 2.5 weeks/year of effort for attending the Juno Science Team Meetings would be requested in only one project.)

6. Relevance

Our work will use Juno magnetic field and plasma measurements to study the properties and drivers of magnetotail dynamics at Jupiter. These topics are related to the science objective "Global magnetosphere: Explore Jupiter's three-dimensional magnetosphere away from the polar regions," which was not originally planned but is now feasible because of Juno's 53-day orbit, with apoapsis beyond 100 Jovian radii. Therefore this investigation is relevant to the Juno Participating Scientist program because it will "enhance the scientific return during the science phase of the Juno mission … through new investigations that broaden and/or complement existing mission investigations." This work is not relevant to other programs, such as the New Frontiers Data Analysis Program, because it requires use of Juno data that are not in the public domain, including future Juno data. In particular, our work requires higher order data products from JEDI and JADE – plasma moments (density and velocity) – that are not yet archived on the PDS. Additionally, our work requires data through at least PJ16, covering the deep pre-dawn magnetotail region sampled by Galileo orbit G2, so that our findings can be compared to Galileo-era results.

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