**Abstract**  Routine spacecraft encounters with the Saturn current sheet due to the passage of aperiodic waves provide the opportunity to analyze the current sheet structure. The current density is expected to peak where the field strength reaches a minimum if approximated as a Harris current sheet. However, in Earth’s magnetotail this is not always the case as the sheet is sometimes bifurcated (having two or more maxima in the current density). We utilize measurements of Saturn’s magnetic field to estimate the current density during crossings of the current sheet by time differentiating the $B_B$ component of the field in a current sheet coordinate system, where $B_B$ is perpendicular to both the current and current sheet normal. This is then averaged and organized by the magnitude of $B_B$. Using this method, we can identify a classical Harris-style or bifurcated current sheet as a peak at the center or two distinct maxima on either side of $B_B = 0$, respectively. We find that around 10% of current sheet profiles exhibit a bifurcated current sheet signature, which is substantially lower than an ~25% occurrence rate at Earth.

1. Introduction

The equatorial current sheet at Saturn is a result of a rotationally dominated system (Southwood & Kivelson, 2001) with internal plasma sources such as Enceladus and the other moons, the rings, and even the planet itself (e.g., Felici et al., 2016; Jurac et al., 2002; Pontius & Hill, 2006; Tokar et al., 2005). The internal plasma and fast rotation result in centrifugal stresses (Arridge et al., 2007) that cause the planet’s magnetic field to stretch outward at the equator. This ballooning forms a washer-shaped current sheet (much like Earth’s cross-tail current sheet). Unlike Earth, however, Saturn’s current sheet can be found in all local time sectors, except near noon during compressions due to solar wind dynamic pressure (Arridge, Russell, et al., 2008). The thin current sheet extends outward from $\sim 15R_S$ (Saturn radii $= 58,232$ km) where pressure gradients and the magnetic tension force become dominated by centrifugal stresses (Arridge et al., 2007).

Sergis et al. (2017) mapped the equatorial current density in Saturn’s inner magnetosphere from 5–16 $R_S$, showing that the particle pressure is dominated by hot plasma pressure (hot ions) outside of 12 $R_S$ with a number of local time effects. Kellett et al. (2011) detailed the local time and temporal variability of the current density using Cassini’s equatorial orbits between 2005 and 2006. The current is strongest from dusk to midnight and can vary temporally by a factor of 2–3. In the middle to outer magnetosphere, the current density increases from premidnight to prenoon and forms a region-2-like current system (Martin & Arridge, 2018).

A number of studies have shown that the current sheet exhibits predictable quasi-static features, such as flapping at the rotation rate of the planet (e.g., Arridge et al., 2011; Provan et al., 2012). The current sheet also forms a seasonal bowl shape (Arridge, Khurana, et al., 2008) and also displays random movements associated with single waveforms traveling along the sheet (Martin & Arridge, 2017). These waves are solitary movements which kink the sheet as they travel. Some local time dependence of the thickness of the current sheet can be attributed to the magnetic field being more dipolar through noon or due to ambipolar magnetic fields (e.g., Arridge et al., 2015; Kellett et al., 2009; Krupp et al., 1999; Martin & Arridge, 2017).

The current sheet is also thought to vary in thickness due to oscillations near the planetary rotation rate (Thomsen et al., 2016). However, it is commonly assumed that the current density peaks at the center of the current sheet and that the current sheet magnetic field exhibits Harris-like behavior where the magnetic field increases as a hyperbolic tangent function away from the center, and the current density decreases exponentially away from the center. While this assumption is necessary for a number of analysis techniques, it might fail. In this study we will test whether the assumption of a Harris-like current sheet at Saturn is a
discriminative or restrictive assumption to make. Throughout, we refer to “Harris-like” current sheets; this refers to a current sheet in which the current density peaks where the magnetic field passes through one minimum and is not necessarily a strictly Harris current profile (Harris, 1962).

Bifurcation, or splitting of the current into two maxima of current that do not lie at the expected current sheet center, is a common occurrence in Earth’s magnetotail first observed by Hoshino et al. (1996) using single-spacecraft measurements and by Runov, Nakamura, Baumjohann, Zhang, et al. (2003) using the Cluster mission. Around 25% of all current sheets encounters exhibit bifurcated behavior (Thompson et al., 2006). A dependence on the magnitude of $V_x$ (velocity along Earth-Sun line) in the tail is found by Asano et al. (2005), where up to 50% of “fast” events and around 10% of “not-fast” events show bifurcations. A number of authors show, with spacecraft data and models of the current sheet, that bifurcation in the tail current sheet is a precursor to or a result of reconnection occurring (e.g., Birn & Hesse, 2014; Hoshino et al., 1996; Nakamura et al., 2002; Thompson et al., 2006). More recently, bifurcation of the current sheet has been linked to substorm onset and an increase in current density in the tail current sheet (Saito, 2015).

Models have shown that a bifurcated current sheet can be caused by a number of instabilities (Camporeale & Lapenta, 2005; Delcourt et al., 2006; Génot et al., 2005; Matsu & Daughton, 2008; Ricci et al., 2004; Zelenyi et al., 2002, 2003) such as the lower hybrid drift instability and Kelvin-Helmholtz instabilities. These instabilities may be related to increased reconnection (Mok et al., 2006; Runov, Nakamura, Baumjohann, Treumann, et al., 2003) and flapping motions of the current sheet (Runov, Nakamura, Baumjohann, Zhang et al., 2003; Sitnov et al., 2004).

Perpendicular anisotropies in the ion temperature have been shown to form bifurcated current sheets in models and in Cluster observations of the terrestrial magnetic field and plasma (Israelevich & Ershkovich, 2008; Sitnov et al., 2003, 2004). Dalena et al. (2010) specifically focused on the role of oxygen ions in these anisotropies that may also cause instabilities and, hence, bifurcation. Simulations have shown that bifurcations can be formed by perturbations in the dipole field (Sitnov & Merkin, 2016). Altogether, we can assume that the bifurcation of the current sheet at Earth is linked to an unstable current sheet caused by a number of the above described processes.

At Earth, most studies make use of Cluster four-point measurements to determine current density; however, at Jupiter and Saturn single-spacecraft measurements and other methods must be used. Bifurcated current sheets at Jupiter have previously been investigated using the full time derivative of the magnetic field component perpendicular to both the direction of current flow and the current sheet normal (Hoshino et al., 1996; Israelevich & Ershkovich, 2006). Several examples of bifurcated sheets were found using Voyager 2 and Galileo magnetometer data (Israelevich & Ershkovich, 2008, Israelevich et al. 2007). The authors concluded that the bifurcation is due to an ion pressure anisotropy perpendicular to the magnetic field. The total number of bifurcated sheets detected is very small compared to the total number of current sheet crossings, suggesting that this is a very rare phenomenon at Jupiter. The difference in the bifurcated and nonbifurcated ratio between Earth’s tail current sheet and Jupiter’s current sheet is likely caused by the different ion distribution functions, initially due to the differing processes of plasma transport that create the plasma sheet (Israelevich & Ershkovich, 2008).

To investigate the proportion of bifurcated sheets at Saturn, we utilize the aperiodic wave structures (Martin & Arridge, 2017) that cause Cassini to encounter the current sheet. The overall flapping motion of Jupiter’s magnetosphere, due to the offset of the magnetic axis from the rotational axis, allows for periodic sampling of the current sheet at Jupiter. This process does not occur at Saturn due to a near alignment of the magnetic and rotational axes (Acuña & Ness, 1980; Dougherty et al., 2018; Smith et al., 1980), and so we do not get constant periodic sampling of the current sheet. We note that the planetary period oscillations allow for current sheet flapping (Arridge et al., 2011; Provan et al., 2012); however, this does not frequently result in the sampling of both lobes but acts instead to move the current sheet toward and away from Cassini without a direct encounter.

The aperiodic waves are detected using Cassini magnetometer data (Dougherty et al., 2004) and appear as a traversal from one lobe to the other and back again to the original lobe. We consider waves that have a period of less than the global flapping waves (most waves have time periods of from 1 to 30 min), are nonrepeating (solitary), and have a deflection in the radial magnetic field of over 1 nT. The waves kink the
field as they travel in a predominantly outward radial direction. All events occur planetward inside of the magnetopause boundary, which is found by manual examination of the magnetic field data. The magnetic field magnitude and direction describe the regime in which Cassini resides, and hence a boundary between two regimes can be established by examining the changes in these parameters; that is, the magnetosheath generally has a smaller magnitude than the current sheet and lobes. The direction of lobe magnetic field is mainly radial, whereas the current sheet has a predominantly north-south component. Between January 2005 to December 2012, 1,461 events fit these criteria from the equatorial revolutions of Cassini. For further analysis of aperiodic wave properties and applications, the authors direct the reader to Martin and Arridge (2017, 2018).

2. Method

First, we must rotate the magnetic field into a current sheet coordinate system (A, B, C) where \( \hat{a} \) is positive in the direction of largest change in magnetic field (roughly in the positive radial direction), \( \hat{c} \) is normal to the current sheet, and \( \hat{b} \) completes the right-handed system and is in the direction of the current density vector. A representation of the two coordinate systems can be found in Figure 1. To rotate the original coordinates, we must first find the normal to the current sheet which is done using a number of methods. We first find a normal using minimum variance analysis (MVA), where we can use single-spacecraft data to estimate the direction of minimum variance which is the normal to an approximately one-dimensional current layer (Sonnerup & Cahill, 1967).

However, if the variance ellipsoid (a three-dimensional representation of the variance of the data in space) is degenerate such that we cannot separate the minimum and intermediate eigenvectors, then the uncertainty of the normal placement is high. In such cases, we then use a second method of finding the normal to reduce the uncertainty in the normal direction. This second method, the coplanarity method, calculates the difference in northern and southern lobe fields (\( \Delta B \)) and the cross product of the northern lobe magnetic field and the southern lobe magnetic field (\( B_N \times B_S \)). As both of these vector products are in the plane of the current sheet, the cross product \( \Delta B \times (B_N \times B_S) \) will be in the normal direction of the current sheet.

We initially use MVA to determine the normal direction as the uncertainties ascertained using a bootstrapping method are on average much smaller than the uncertainties found when using the coplanarity method, under the assumption that the minimum and intermediate variance directions are not degenerate. Uncertainties in the coplanarity method are determined using the standard deviation of the mean values of \( B_N \) and \( B_S \), which are then propagated to give an uncertainty on the variance directions. In the computational algorithm, we use coplanarity when we find that the MVA uncertainties are larger than the coplanarity uncertainties and/or the MVA analysis is degenerate. An additional feature of MVA is that the maximum variance direction is equivalent to the direction of \( \Delta B \), which can be used as a check for both methods as the maximum variance is often the least degenerate and most accurately calculated variance direction. In examples where both methods of finding the coordinate system give acceptable uncertainties, the results are in agreement.
Once we have the normal direction, we can establish the angles needed to rotate the magnetic field into the new (A,B,C) coordinate system described above. These angles ($\alpha$, $\beta$, $\gamma$) give the angles in three planes of the normal from the radial direction for $\alpha$ and $\beta$ and from the $\phi$ direction for $\gamma$. Hence, we now have our new coordinate system ordered by the current sheet of Saturn.

We focus now on the magnetic field in $\hat{a}$, or $B_a$. $B_a$ is not only time dependent but also dependent on the position of the current sheet $B_s(t) \approx B_s(c(t))$, and hence the full derivative is

$$\frac{dB_a}{dt} = \frac{\partial B_a}{\partial c} \frac{dc}{dt}. \quad (1)$$

For an aperiodic wave we find that $\langle \frac{dB_a}{dt} \rangle$ will equal 0 over the course of one wave, assuming the current sheet returns to its original position and the spacecraft does not move during this time. Hence, $\langle \frac{dB_a}{dt} \rangle \approx 0$. Through Ampère’s law, we know that $\frac{\partial B_a}{\partial c}$ is proportional to the current density in the sheet and so organizing $\langle | \frac{dB_a}{dt} | \rangle$ versus $B_a$ will show the peak in current density as Cassini measures the center of the current sheet (assuming a Harris-like current sheet). A Harris-like current sheet will show a peak in $\langle | \frac{dB_a}{dt} | \rangle$ at $B_a = 0$, whereas a bifurcated current sheet will show two peaks either side of $B_a = 0$. Additionally, we note that these may be shifted from the zero line due to global motion of the current sheet that cannot be accounted for in this analysis, that is, $\langle \frac{dB_a}{dt} \rangle \neq 0$. Most aperiodic waves occur on small timescales, and thus we can neglect global motion effect on a zero shift.

At Jupiter, Israelevich and Ershkovich (2006) calculated the differential value using a number of crossings and the assumption $\langle \frac{dB_a}{dt} \rangle = 0$ is held for regular flapping motion since Galileo was an equatorial orbiter. However, at Saturn, Cassini covers a large range of latitudes and we cannot assume that the periodic oscillations will result in $\langle \frac{dB_a}{dt} \rangle = 0$. Using aperiodic waves allows for this assumption to be satisfied as the aperiodic waves sample both lobes, and the time series of magnetometer data for a single aperiodic wave can be restricted so that there is equivalent sampling of both magnetic lobes of Saturn.

$\frac{dB_a}{dt}$ is calculated numerically by $[B_a(t + \Delta t) - B_a(t - \Delta t)]/2\Delta t$, where in this study $\Delta t = 1$ s. We bin the differential into $B_a$ bins of size 0.1–0.25 nT to allow for at least reasonable number of data points ($N > 10$) in each bin for each aperiodic wave. Hence, we can now relate a proxy for current density with a proxy for the distance from the center of the current sheet ($B_a$).

To test whether we find a bifurcated, Harris-like, or unclassified current density profile, we used a model made up of three Gaussian distributions. The first Gaussian is centered on a “center” value ($C$) or close to $B_a = 0$; the second and third Gaussians are centered on an “offset” from the center ($\omega$), on either side ($C - \omega$ and $C + \omega$). All distributions share the same “spread” ($\sigma$); the central Gaussian has an independent amplitude ($A_{Harris}$) to the peripheral Gaussians ($A_{Bifurcated}$). Hence, if we find a Harris-like current sheet, we expect the central Gaussian to have a considerably larger amplitude than the peripheral Gaussians, and vice versa for a bifurcated signature.

This model is fitted to $\langle | \frac{dB_a}{dt} | \rangle$ versus $B_a$ as described above using Bayesian regression analysis, where prior knowledge of the probable outcome is used to give a probability distribution of the final result. We find that the use of Bayesian regression analysis allows for a much more in-depth analysis of the uncertainties of the fitting of the model; this method of fitting easily shows any covariance between the variables. Each unknown ($C, \omega, \sigma, A_{Harris}, A_{Bifurcated}$) is given a prior distribution, which for $C_{prior}$ is a normal distribution around $B_a = 0$, $\sigma_{prior}$, and $\sigma_{prior}$ are positive only distributions with decreasing probability with larger offsets and spreads. Both amplitude priors are given as a positive only normal distribution around the median value of $\langle | \frac{dB_a}{dt} | \rangle$. These prior distributions are then multiplied by a likelihood distribution based on finding the lowest $\chi^2$ value when comparing the data to 100,000 randomly distributed samples taken from the prior distributions. The output for this method is hence a “posterior” distribution of each fitted parameter which peaks at the most likely value and shows a spread (and hence uncertainty) in that value.

To algorithmically determine whether the profile is Harris-like or bifurcated, we implement a number of criteria. To be bifurcated, the distribution must have an $A_{Bifurcated}$ of at least 1.5 times an $A_{Harris}$. Additionally, the offset ($\omega$) must be more than twice the spread ($\sigma$), and the absolute center value ($C$) must be less than the offset ($\omega$) value. To be considered a Harris-like sheet, the criteria are as follows: the $A_{Harris}$ must be at least 1.5 times the $A_{Bifurcated}$; $\sigma$ must be less than twice the offset ($\omega$); and the absolute center value ($C$) must be less than the offset ($\omega$). Distributions that do not comply with either criteria are considered unclassified and...
are visually inspected. Distributions that are borderline on either classification are also visually inspected as a secondary check.

This method of fitting variables is useful to find the interconnectivity of the variable themselves. We may find a dependence of one variable on another, and if this is found then the model must be updated or revised to remove this dependence. In this study, the majority of events lead to the conclusion that the variables fitted are independent of each other, and any case of strong dependence is removed from further analysis.

3. Results

The normal vector can be found using either MVA or coplanarity in 1,018 out of 1,461 aperiodic wave events, of these events 807 sample an adequate amount of both lobes to build up an acceptable picture of the current density profile. We find 79 bifurcated signatures and 632 Harris-like signatures. From the total, 96 events give a striated, unclassified, or ambiguous signature. Thus, we find that 10% of current sheet profiles at Saturn are bifurcated, 78% of profiles show a Harris-like current sheet, and 12% of current sheets show an unclassified signature.

Figure 2 shows an example of a Harris-like current sheet signature for Saturn’s equatorial current sheet. The dotted line shows the mean value of $\langle |dB/dt| \rangle$, and the error bars give the standard deviation in each $B_\parallel$ bin. An orange solid line shows the most likely fitted distribution from the Bayesian inference algorithm.
Figure 4. Proxies for the distance from the current sheet versus current sheet density for an unclassified/ambiguous profile. The dotted line shows the mean of current density as a function of distance from the center of the current sheet, with standard deviation shown by the error bars. The solid orange line is the fitted model of three Gaussians, where the peripheral Gaussians are dominant, and hence the example is a bifurcated current sheet. This example is found at 29.2 \( R_S \) and 1.6 SLT.

described in the previous section. Figure 3 shows an example of a bifurcated current sheet. Figure 4 shows an example of an unclassified/ambiguous profile.

Figure 5 shows the distribution of bifurcated and Harris-like current sheets around Saturn, with nominal magnetopause positions, Titan’s orbit at 20 \( R_S \), and Rhea’s orbit at 9 \( R_S \). Figure 5 a shows the total number of aperiodic wave events in the magnetosphere; we see an asymmetry in dawn and dusk where a larger number are found along the dusk flank. Overall, we can assume that the number of events in each area of the magnetosphere scale with the time spent there by Cassini. Figure 5b shows the number of bifurcated current sheets normalized by the total number of aperiodic wave events (and hence takes into account Cassini’s trajectory bias). We see a large asymmetry between dawn and dusk where no bifurcated signatures are seen in the dawn sector outside of Titan’s orbit.

In comparison, Figure 5c shows the number of Harris-like current sheets normalized to the total number of aperiodic waves. To compare, we divide the number of bifurcated sheets by the number of Harris-like current sheets to find the ratio of bifurcated and Harris-like sheets (Figure 5d) where 1 is Harris-like dominated.
Figure 5. Distribution of total number of aperiodic wave events (a), number of bifurcated sheets normalized by total number of events (b), and number of Harris-like normalized by total number of events (c). (d) The ratio of bifurcated to Harris-like current sheets. (e) The number of unclassified or striated current sheets normalized by total number of events, and (f) the number of NaN and NED events normalized by total number of events. Nominal magnetopause positions guide the eye in black, along with Titan’s orbit at 20 $R_S$ and Rhea’s orbit at 9 $R_S$.

and −1 is bifurcated dominated. As Harris-like sheets are dominant, the plot shows mainly red values (+1). However, we also see the asymmetry shown in Figure 5a with no bifurcation in the dawn section and around double the number of Harris-like sheets than bifurcated sheets in the dusk sector. We show the number of striated and NaN (undefined number) and NED (not enough data) current sheets for completeness in Figures 5e and 5f; both are normalized to the total number of events.

Spatially, we find no strong correlation with radial distance or Saturn local time when normalized to the distributions of the entire catalogue of events for the Harris-like or unclassified. The only deviation from the distribution of all events is a lack of any bifurcated signatures outside of 20 $R_S$ in the dawn flank, which may be linked to a more stable and on average thinner current sheet in this area (e.g., Kellett et al., 2009; Kidder et al., 2009; Giampieri & Dougherty, 2004).

4. Discussion

The vertical structure of current density in Saturn’s equatorial current sheet is explored using Cassini magnetometer measurements during aperiodic wave events. The structure is inferred from calculating the full time derivative of the magnetic field in the $a$ direction in a current sheet coordinate system. Harris-like, bifurcated, and unclassified sheets are found to be in proportions of 78%, 10%, and 12%, respectively. These proportions are insensitive to changes in the criteria of classification.

At Earth, approximately 25% of current sheets examined are bifurcated (Thompson et al., 2006); however, Asano et al. (2005) showed that a dependence on velocity along the Earth-Sun line was a factor in the number of bifurcated current sheets found. At high velocities (>500 km/s), bifurcated and Harris-like were proportioned at 50%/50%, whereas at lower velocities (<300 km/s) the distribution of Harris-like sheets to bifurcated sheets is much lower at 90%/10%—a ratio nearer to the values found in this study.

A general consensus on bifurcated current sheets at Earth is that they are caused by a perturbation or instability of the current sheet. One example is tail reconnection occurring during substorms at Earth, where the reconnection is constrained in local time to near midnight. At Saturn, the equatorial current sheet is present in all local times (given solar wind conditions) and hence reconnection can occur in all local times (Guo et al., 2018). As bifurcation happens at Saturn in most local time sectors, reconnection and associated phenomena could be the causes of the splitting of the current density. We find a small increase in bifurcation occurrence in the postmidnight sector, where we expect the x line from reconnection in the Vasyliunas cycle to be situated, hence giving additional credence to this theory.

Delamere et al. (2015) suggest that a “patchy network of reconnection sites” along the magnetopause may be responsible for small-scale losses of plasma in the noon sector through to the dusk sector of Saturn’s magnetosphere. This area is also where an increased number of bifurcated current sheets are found, and
as such plasma instabilities caused by the patchy reconnection may be attributed to the larger number of bifurcated current sheet detected. Pressure anisotropies are also found in the nightside current sheet at Jupiter, showing that the pressure parallel to the field was greater than the pressure perpendicular during the Voyager 1 and 2 flybys (Paranicas et al., 1991). However, at present, the plasma instabilities and anisotropies are not fully understood at the outer planets, and as such, a definitive conclusion for the sources for the bifurcation cannot be made.

5. Summary

In this study the vertical structure of Saturn’s equatorial current sheet is explored using the single-spacecraft method from Israelevich and Ershkovich (2006) combined with a Bayesian regression analysis. Due to the lack of an appreciable dipole tilt, current sheet encounters during the passage of aperiodic waves (Martin & Arridge, 2017) are used to obtain the profile of the magnetic field through the current sheet. Through each current sheet encounter the full time derivative of the $B_z$ component of the field was binned as a function of $B_z$. A simple model based on the sum of Gaussians is used to identify profiles with a current density peak near the center of the current sheet (Harris-like) or with off-center peaks. Model parameters were obtained via Bayesian inference. We find that 78% of the current sheet profiles show a Harris-like structure, 10% are bifurcated, and 12% are unclassified. This compares with 25% in Earth’s magnetotail.

Phenomenologically, at Earth bifurcated current sheets are more often found during fast flow events and are associated with substorms (Saito, 2015), thus related to magnetic reconnection. Theory and simulations have explored the role of instabilities or plasma anisotropy that can give rise to bifurcations. We must also discuss the possibility of the aperiodic waves themselves affecting or being affected by the bifurcation or source of bifurcation. Fast flows in the current sheet may inhibit the kinking of the current sheet during the passage of a wave and so would limit the amplitude of the wave. Additionally, passage of an aperiodic wave may modify the current sheet to encourage or inhibit reconnection through changes in the stress balance. We have insufficient information of the role of these processes at Saturn to definitively identify the process and its impact on both aperiodic waves and bifurcation.

Future observational work should focus on attempting to identify correlations of bifurcated current sheets with faster flows/reconnection events at Saturn and studying the plasma/energetic particle differences between Harris-like and bifurcated current sheets. More detailed surveys of the Jovian system should also be carried out to statistically determine the prevalence of bifurcated current sheets at Jupiter. There is also theoretical and simulation work that can be done to examine the generation of bifurcations for conditions compatible with Saturn and Jupiter.

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