

Vertical Current Density Structure of Saturn's Equatorial Current Sheet

C. J. Martin¹, C. S. Arridge¹, N. A. Case¹, L. C. Ray¹

¹Physics Department, Lancaster University, Bailrigg, Lancaster, LA1 4YB, United Kingdom.

Key Points:

- Aperiodic waves on Saturn's current sheet are utilised to estimate the current density profile.
- The average full time derivative of the component of magnetic field in the exterior field direction is used to infer the current density.
- 10% of the time we sample Saturn's magnetospheric current sheet it is bifurcated, which is lower than the occurrence rate at Earth.

Corresponding author: C. J. Martin, c.martin1@lancaster.ac.uk

Abstract

Routine spacecraft encounters with the Saturn current sheet due to the passage of aperiodic waves provide the opportunity to analyse the current sheet structure. The current density is expected to peak where the field strength reaches a minima if approximated as a Harris current sheet. However, in Earth's magnetotail that this is not always the case as the sheet is sometimes bifurcated (having two or more maxima in the current density). We utilise measurements of Saturn's magnetic field to estimate the current density during crossings of the current sheet by time differentiating the B_a component of the field in a current sheet coordinate system, where B_a is perpendicular to both the current and current sheet normal. This is then averaged and organised by the magnitude of B_a . Using this method, we can identify a classical Harris-style or bifurcated current sheet as a peak at the centre or two distinct maxima on either side of $B_a = 0$, respectively. We find that around 10% of current sheet profiles exhibit a bifurcated current sheet signature, which is substantially lower than a ~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. Pontius *et al.*, 2006; Tokar *et al.*, 2005; Jurac *et al.*, 2002; Felici *et al.*, 2016]. The internal plasma and fast rotation result in centrifugal stresses [Arridge *et al.*, 2007] that cause the planet's magnetic field to stretch outwards 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 *et al.*, 2008b]. The a thin current sheet extends outward from $\sim 15 R_S$ (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

44 from pre-midnight to pre-noon and forms a region-2-like current system [*Martin & Arridge,*
45 2018].

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

54 The current sheet is also thought to vary in thickness due to oscillations near the plan-
55 etary rotation rate [*Thomsen et al., 2016*]. However, it is commonly assumed that the current
56 density peaks at the centre of the current sheet and that the current sheet magnetic field ex-
57 hibits Harris-like behaviour where the magnetic field increases as a hyperbolic tangent func-
58 tion away from the centre, and the current density decreases exponentially away from the
59 centre. Whilst this assumption is necessary for a number of analysis techniques, it might fail.
60 In this study we will test whether the assumption of a Harris-like current sheet at Saturn is a
61 discriminative or restrictive assumption to make. Throughout, we refer to 'Harris-like' cur-
62 rent sheets, this refers to a current sheet in which the current density peaks where the mag-
63 netic field passes through one minimum and is not necessarily a strictly Harris current profile
64 [*Harris, 1962*].

65 Bifurcation, or splitting of the current into two maxima of current that do not lie at
66 the expected current sheet centre, is a common occurrence in Earth's magnetotail. First ob-
67 served by *Hoshino et al. [1996]* using single spacecraft measurements and by *Runov et al.*
68 [*2003a*] using the Cluster mission. Around 25% of all current sheets encounters exhibit bi-
69 furcated behaviour [*Thompson et al., 2006*]. A dependance on the magnitude of V_x (velocity
70 along Earth-Sun line) in the tail is found by *Asano et al. [2005]*, where up to 50% of 'fast'
71 events, and around 10% of 'not-fast' events show bifurcations. A number of authors show,
72 with spacecraft data and models of the current sheet, that bifurcation in the tail current sheet
73 is a precursor to, or a result of reconnection occurring [e.g. *Hoshino et al., 1996; Nakamura*
74 *et al., 2002; Thompson et al., 2006; Birn & Hesse, 2014*]. More recently, bifurcation of the

75 current sheet has been linked to substorm onset and an increase in current density in the tail
76 current sheet [*Saito, 2015*].

77 Models have shown that a bifurcated current sheet can be caused by a number of in-
78 stabilities [*Ricci et al., 2004; Camporeale & Lapenta, 2005; Génot et al., 2005; Matsui &*
79 *Daughton, 2008; Zelenyi et al., 2002, 2003; Delcourt et al., 2006*] such as the lower hybrid
80 drift instability, and Kelvin-Helmholtz instabilities. These instabilities may be related to in-
81 creased reconnection [*Runov et al., 2003b; Mok et al., 2006*] and flapping motions of the
82 current sheet [*Sitnov et al., 2004; Runov et al., 2003a*].

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

91 At Earth, most studies make use of Cluster 4-point measurements to determine current
92 density, however, at Jupiter and Saturn single space craft measurements and other methods
93 must be used. Bifurcated current sheets at Jupiter have previously been investigated using the
94 full time derivative of the magnetic field component perpendicular to both the direction of
95 current flow and the current sheet normal [*Hoshino et al., 1996; Israelevich & Ershkovich,*
96 *2006*]. Several examples of bifurcated sheets were found using Voyager-2 and Galileo mag-
97 netometer data [*Israelevich & Ershkovich, 2008*]. The authors concluded that the bifurcation
98 is due to an ion pressure anisotropy perpendicular to the magnetic field. The total number of
99 bifurcated sheets detected is very small compared to the total number of current sheet cross-
100 ings, suggesting that this is a very rare phenomenon at Jupiter. The difference in the bifur-
101 cated and non-bifurcated ratio between Earth's tail current sheet and Jupiter's current sheet
102 is likely caused by the different ion distribution functions, initially due to the differing pro-
103 cesses of plasma transport that create the plasma sheet [*Israelevich & Ershkovich, 2008*].

104 To investigate the proportion of bifurcated sheets at Saturn, we utilise the aperiodic
105 wave structures [*Martin & Arridge, 2017*] that cause Cassini to encounter the current sheet.
106 The overall flapping motion of Jupiter's magnetosphere, due to the offset of the magnetic

107 axis from the rotational axis, allows for periodic sampling of the current sheet at Jupiter.
 108 This process does not occur at Saturn due to a near alignment of the magnetic and rotational
 109 axes [Acuña & Ness, 1980; Smith *et al.*, 1980; Dougherty *et al.*, 2018], and so we do not get
 110 constant periodic sampling of the current sheet. We note that the planetary period oscilla-
 111 tions allow for current sheet flapping [Arridge *et al.*, 2011; Provan *et al.*, 2012], however this
 112 does not frequently result in the sampling of both lobes but acts instead to move the current
 113 sheet towards and away from Cassini without a direct encounter.

114 The aperiodic waves are detected using Cassini magnetometer data [Dougherty *et al.*,
 115 2004], and appear as a traversal from one lobe to the other and back again to the original
 116 lobe. We consider waves that have a period of less than the global flapping waves (most
 117 waves have time periods of from 1-30 minutes), are non-repeating (solitary) and have a de-
 118 flection in the radial magnetic field of over 1 nT. The waves kink the field as they travel in
 119 a predominantly outward radial direction. All events occur planet-ward inside of the mag-
 120 netopause boundary, which is found by manual examination of the magnetic field data. The
 121 magnetic field magnitude and direction describe the regime in which Cassini resides, and
 122 hence a boundary between two regimes can be established by examining the changes in these
 123 parameters, i.e. the magnetosheath generally has a smaller magnitude than the current sheet
 124 and lobes. The direction of lobe magnetic field is mainly radial, whereas the current sheet
 125 has a predominantly north-south component. Between January 2005 to December 2012,
 126 1461 events fit these criteria from the equatorial revolutions of Cassini. For further analy-
 127 sis of aperiodic wave properties and applications, the authors direct the reader to *Martin &*
 128 *Arridge* [2017, 2018].

129 **2 Method**

135 Firstly, we must rotate the magnetic field into a current sheet coordinate system (A,B,C)
 136 where $\hat{\mathbf{a}}$ is positive in the direction of largest change in magnetic field (roughly in the posi-
 137 tive radial direction), $\hat{\mathbf{c}}$ is normal to the current sheet and $\hat{\mathbf{b}}$ completes the right handed sys-
 138 tem and is in the direction of the current density vector. A representation of the two coordi-
 139 nate systems can be found in figure 1. To rotate the original coordinates we must first find
 140 the normal to the current sheet which is done using a number of methods. We first find a nor-
 141 mal using minimum variance analysis (MVA), where we can use single spacecraft data to
 142 estimate the direction of minimum variance which is the normal to an approximately one-
 143 dimensional current layer [Sonnerup & Cahill, 1967].

144 However, if the variance ellipsoid (a 3-dimensional representation of the variance of
 145 the data in space) is degenerate such that we cannot separate the minimum and intermediate
 146 eigenvectors, then the uncertainty of the normal placement is high. In such cases, we then
 147 use a second method of finding the normal to reduce the uncertainty in the normal direc-
 148 tion. This second method, the coplanarity method, calculates the difference in northern and
 149 southern lobe fields ($\Delta\mathbf{B}$) and the cross product of the northern lobe magnetic field and the
 150 southern lobe magnetic field, ($\mathbf{B}_N \times \mathbf{B}_S$). As both of these vector products are in the plane of
 151 the current sheet, the cross product $\Delta\mathbf{B} \times (\mathbf{B}_N \times \mathbf{B}_S)$ will be in the normal direction of the
 152 current sheet.

153 We initially use MVA to determine the normal direction as the uncertainties ascer-
 154 tained using a bootstrapping method are on average much smaller than the uncertainties
 155 found when using the coplanarity method, under the assumption that the minimum and inter-
 156 mediate variance directions are not degenerate. Uncertainties in the coplanarity method are
 157 determined using the standard deviation of the mean values of \mathbf{B}_N and \mathbf{B}_S , which are then
 158 propagated to give an uncertainty on the variance directions. In the computational algorithm,
 159 we use coplanarity when we find that the MVA uncertainties are larger than the coplanarity
 160 uncertainties and/or the MVA analysis is degenerate. An additional feature of MVA is that
 161 the maximum variance direction is equivalent to the direction of $\Delta\mathbf{B}$, which can be used as
 162 a check for both methods as the maximum variance is often the least degenerate and most
 163 accurately calculated variance direction. In examples where both methods of finding the co-
 164 ordinate system give acceptable uncertainties, the results are in agreement.

165 Once we have the normal direction, we can establish the angles needed to rotate the
 166 magnetic field into the new (A,B,C) co-ordinate system described above. These angles (α, β, γ)
 167 give the angles in three planes of the normal from the radial direction for α and β , and from
 168 the ϕ direction for γ . Hence, we now have our new co-ordinate system ordered by the current
 169 sheet of Saturn.

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

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

173 For an aperiodic wave we find that $\langle \frac{dc}{dt} \rangle$ will equal zero over the course of one wave, assum-
 174 ing the current sheet returns to its original position and the spacecraft does not move during

175 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
 176 the current density in the sheet and so organising $\langle |\frac{dB_a}{dt}| \rangle$ versus B_a will show the peak in
 177 current density as Cassini measures the centre of the current sheet (assuming a Harris-like
 178 current sheet). A Harris-like current sheet will show a peak in $\langle |\frac{dB_a}{dt}| \rangle$ at $B_a = 0$ whereas a
 179 bifurcated current sheet will show two peaks either side of $B_a = 0$. Additionally, we note that
 180 these may be shifted from the zero line due to global motion of the current sheet that can-
 181 not be accounted for in this analysis, i.e. $\langle \frac{dB_a}{dt} \rangle \neq 0$. Most aperiodic waves occur on small
 182 timescales, and thus we can neglect global motion effect on a zero shift.

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

190 $\frac{dB_a}{dt}$ is calculated numerically by $[B_a(t + \Delta t) - B_a(t - \Delta t)]/2\Delta t$, where in this study
 191 $\Delta t = 1$ second. We bin the differential into B_a bins of size 0.1 - 0.25 nT to allow for at least
 192 reasonable number of data points ($N > 10$) in each bin for each aperiodic wave. Hence we
 193 can now relate a proxy for current density with a proxy for the distance from the centre of the
 194 current sheet (B_a).

195 To test whether we find a bifurcated, Harris-like or unclassified current density profile,
 196 we used a model made up of three Gaussian distributions. The first Gaussian is centred on a
 197 'centre' value (C) or close to $B_a = 0$, the second and third Gaussians are centred on an 'off-
 198 set' from the centre (ω), on either side (C - ω and C + ω). All distributions share the same
 199 'spread' (σ), the central Gaussian has an independent amplitude (A_{Harris}) to the peripheral
 200 Gaussians ($A_{Bifurcated}$). Hence, if we find a Harris-like current sheet, we expect the cen-
 201 tral Gaussian to have a considerably larger amplitude than the peripheral Gaussians, and vice
 202 versa for a bifurcated signature.

203 This model is fitted to $\langle |\frac{dB_a}{dt}| \rangle$ vs B_a as described above using Bayesian regression
 204 analysis, where prior knowledge of the probable outcome is used to give a probability dis-
 205 tribution of the final result. We find that the use of Bayesian regression analysis allows for
 206 a much more in-depth analysis of the uncertainties of the fitting of the model, this method

207 of fitting easily shows any covariance between the variables. Each unknown ($C, \omega, \sigma, A_{Harris}$
 208 and $A_{Bifurcated}$) is given a prior distribution, which for C_{prior} is a normal distribution around
 209 $B_a = 0$, ω_{prior} and σ_{prior} are positive only distributions with decreasing probability with
 210 larger offsets and spreads. Both amplitude priors are given as a positive only normal distri-
 211 bution around the median value of $\langle |\frac{dB_a}{dt}| \rangle$. These prior distributions are then multiplied by
 212 a likelihood distribution based on finding the lowest χ^2 value when comparing the data to
 213 100,000 randomly distributed samples taken from the prior distributions. The output for this
 214 method is hence a ‘posterior’ distribution of each fitted parameter which peaks at the most
 215 likely value and shows a spread (and hence uncertainty) in that value.

216 To algorithmically determine whether the profile is Harris-like or bifurcated, we imple-
 217 ment a number of criteria. To be bifurcated the distribution must have an $A_{Bifurcated}$ of at
 218 least 1.5 times an A_{Harris} . Additionally, the offset (ω) must be more than twice the spread
 219 (σ) and the absolute centre value (C) must be less than the offset (ω) value. To be considered
 220 a Harris-like sheet the criteria are as follows: an A_{Harris} of at least 1.5 times an $A_{bifurcated}$;
 221 σ must be less than twice the offset (ω); and the absolute centre value (C) must be less than
 222 the offset (ω). Distributions that do not comply with either criterions are considered unclas-
 223 sified and are visually inspected. Distributions that are borderline on either classification are
 224 also visually inspected as a secondary check.

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

230 **3 Results**

231 The normal vector can be found using either MVA or coplanarity in 1018 out of 1461
 232 aperiodic wave events, of these events 807 sample an adequate amount of both lobes to build
 233 up an acceptable picture of the current density profile. We find 79 bifurcated signatures and
 234 632 Harris-like signatures. From the total, 96 events give a striated, unclassified or ambigu-
 235 ous signature. Thus we find that 10% of current sheet profiles at Saturn are bifurcated, 78%
 236 of profiles show a Harris-like current sheet and 12% of current sheets show a unclassified
 237 signature.

238 Figure 2 shows an example of a Harris-like current sheet signature for Saturn’s equa-
 239 torial current sheet. The dotted line shows the mean value of $\langle |\frac{dB_a}{dt}| \rangle$ and the error bars give
 240 the standard deviation in each B_a bin. An orange solid line shows the most likely fitted dis-
 241 tribution from the Bayesian inference algorithm described in the previous section. Figure 3
 242 shows an example of a bifurcated current sheet. Figure 4 shows an example of an unclassi-
 243 fied/ambiguous profile.

265 Figure 5 shows the distribution of bifurcated and Harris-like current sheets around Sat-
 266 urn, with nominal magnetopause positions, Titan’s orbit at $20 R_S$ and Rhea’s orbit at $9 R_S$.
 267 Figure 5 a) shows the total number of aperiodic wave events in the magnetosphere, we see an
 268 asymmetry in dawn and dusk where a larger number are found along the dusk flank. Overall,
 269 we can assume that the number of events in each area of the magnetosphere scale with the
 270 time spent there by Cassini. 5 b) shows the number of bifurcated current sheets normalised
 271 by the total number of aperiodic wave events (and hence takes into account Cassini’s trajec-
 272 tory bias). We see a large asymmetry between dawn and dusk where no bifurcated signatures
 273 are seen in the dawn sector outside of Titan’s orbit.

274 In comparison, figure 5c), shows the number of Harris-like current sheets normalised
 275 to the total number of aperiodic waves. To compare, we divide the number of bifurcated
 276 sheets by the number of Harris-like current sheets to find the ratio of Bifurcated and Harris-
 277 like sheets (5 d) where 1 is Harris-like dominated, and -1 is bifurcated dominated. As Harris-
 278 like sheets are dominant, the plot shows mainly red values (+1). However, we also see the
 279 asymmetry shown in 5 a) with no bifurcation in the dawn section, and around double the
 280 number of Harris-like sheets than bifurcated sheets in the dusk sector. We show the number
 281 of striated and NaN (undefined number) and NED (not enough data) current sheets for com-
 282 pleteness in 5e and f, both are normalised to the total number of events.

283 Spatially, we find no strong correlation with radial distance or Saturn local time when
 284 normalised to the distributions of the entire catalogue of events for the Harris-like or un-
 285 classified. The only deviation from the distribution of all events is a lack of any bifurcated
 286 signatures outside of $20 R_S$ in the dawn flank, which may be linked to a more stable and on
 287 average thinner current sheet in this area [e.g. *Kellett et al. [2009]*, *Kidder et al. [2009]* &
 288 *Giampieri et al. [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 post-midnight 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 & 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_a component of the field was binned as a function of B_a . A simple model based on the sum of Gaussians is used to identify profiles with a current density peak near the centre of the current sheet (Harris-like) or with off-centre 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.

Acknowledgments

C.J.M. was funded by a Faculty of Science and Technology studentship from Lancaster University. C.S.A. was funded by a Royal Society Research Fellowship and STFC grant number ST/R000816/1. L.C.R & N.A.C. were supported during this study by STFC grant number ST/R000816/1. Cassini MAG data used in this study may be obtained from the Planetary Data System (<http://pds.nasa.gov/>).

References

- Acuña, M.H. and Ness, N.F., (1980). The magnetic field of Saturn: Pioneer 11 observations. *Science*, 207(4429), 444-446. doi:10.1126/science.207.4429.444
- Arridge, C. S., Russell, C. T., Khurana, K. K., Achilleos, N., Andre, N., Rymer, A. M., Dougherty, M. K., Coates, A. J., (2007). Mass of Saturn's magnetodisc: Cassini observations, *Geophysical Research Letters*, 34(A11), 8779–8789, doi:10.1029/2006GL028921
- Arridge, C.S., Khurana, K.K., Russell, C.T., Southwood, D.J., Achilleos, N., Dougherty, M.K., Coates, A.J. and Leinweber, H.K., (2008a). Warping of Saturn's magnetospheric and magnetotail current sheets, *Journal of Geophysical Research: Space Physics*, 113(A8), 2156–2202, doi:10.1029/2007JA012963
- Arridge, C.S., Russell, C.T., Khurana, K.K., Achilleos, N., Cowley, S.W.H., Dougherty, M.K., Southwood, D.J. and Bunce, E.J., (2008b). Saturn's magnetodisc current sheet. *Journal of Geophysical Research: Space Physics*, 113(A4), doi:10.1029/2007JA012540
- Arridge, C. S., André, N., Khurana, K. K., Russell, C. T., Cowley, S. W. H., Provan, G., Andrews, D. J., Jackman, C. M., Coates, A. J., Sittler, E. C., Dougherty, M. K., Young, D. T. (2011) Periodic motion of Saturn's nightside plasma sheet *Journal of Geophysical Research*, 116, doi:10.1029/2011JA016827
- Arridge, C. S., Kane, M. , Sergis, N., Khurana, K. K., Jackman, C. J., (2015) Sources of local time asymmetries in magnetodiscs *Space Science Reviews*, 187, 301–333, doi:10.1007/s11214-015-0145
- Asano, Y., Nakamura, R., Baumjohann, W., Runov, A., Vörös, Z., Volwerk, M., Zhang, T.L., Balogh, A., Klecker, B. and Reme, H., (2005). How typical are atypical current sheets?. *Geophysical Research Letters*, 32(3), doi:10.1029/2004GL021834
- Birn, J. and Hesse, M., 2014. Forced reconnection in the near magnetotail: Onset and energy conversion in PIC and MHD simulations. *Journal of Geophysical Research: Space Physics*, 119(1), pp.290-309, doi:10.1002/2013JA019354

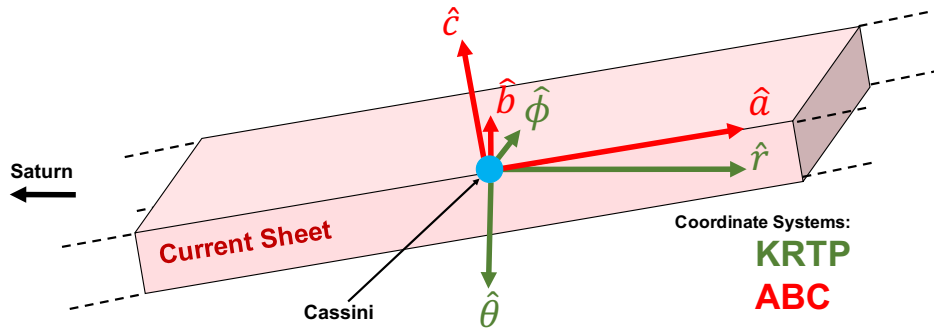
- 382 Camporeale, E. and Lapenta, G., (2005). Model of bifurcated current sheets in the Earth's
383 magnetotail: Equilibrium and stability. *Journal of Geophysical Research: Space Physics*,
384 *110*(A7), doi:10.1029/2004JA010779
- 385 Dalena, S., Greco, A., Zimbardo, G. and Veltri, P., (2010). Role of oxygen ions in the for-
386 mation of a bifurcated current sheet in the magnetotail. *Journal of Geophysical Research:*
387 *Space Physics*, *115*(A3), doi:10.1029/2009JA014710
- 388 Delamere, P.A., Otto, A., Ma, X., Bagenal, F. and Wilson, R.J., (2015). Magnetic flux circu-
389 lation in the rotationally driven giant magnetospheres. *Journal of Geophysical Research:*
390 *Space Physics*, *120*(6), pp.4229-4245. doi:10.1002/2015JA021036
- 391 Delcourt, D.C., Malova, H.V. and Zelenyi, L.M., (2006). Quasi adiabaticity in bifurcated
392 current sheets. *Geophysical Research Letters*, *33*(6), doi:10.1029/2005GL025463
- 393 Dougherty, M.K., Kellock, S., Southwood, D.J., Balogh, A., Smith, E.J., Tsurutani, B.T.,
394 Gerlach, B., Glassmeier, K.H., Gleim, F., Russell, C.T. and Erdos, G., Neubauer F. M.,
395 Cowley S. W. H., (2004), The Cassini Magnetic Field Investigation, *Space Science Re-*
396 *views*,*114*(1), 331–383, doi:10.1007/978-1-4020-2774-1
- 397 Dougherty, M.K., Cao, H., Khurana, K.K., Hunt, G.J., Provan, G., Kellock, S., Burton,
398 M.E., Burk, T.A., Bunce, E.J., Cowley, S.W. and Kivelson, M.G., (2018). Saturn's mag-
399 netic field revealed by the Cassini Grand Finale. *Science*, *362*(6410). doi: 10.1126/sci-
400 ence.aat5434
- 401 Felici, M., Arridge, C.S., Coates, A.J., Badman, S.V., Dougherty, M.K., Jackman, C.M.,
402 Kurth, W.S., Melin, H., Mitchell, D.G., Reisenfeld, D.B. and Sergis, N., (2016). Cassini
403 observations of ionospheric plasma in Saturn's magnetotail lobes. *Journal of Geophysical*
404 *Research: Space Physics*, *121*(1), 338-357, doi:10.1002/2015JA021648
- 405 Génot, V., Mottez, F., Fruit, G., Louarn, P., Sauvaud, J.A. and Balogh, A., (2005). Bifurcated
406 current sheet: Model and Cluster observations. *Planetary and Space Science*, *53*(1-3),
407 pp.229-235, doi:10.1016/j.pss.2004.09.048
- 408 Giampieri, G. and Dougherty, M.K., (2004). Modelling of the ring current in Saturn's mag-
409 netosphere. *Annales Geophysicae* *22* (2) 653-659, doi:10.5194/angeo-22-653-2004
- 410 Guo, R.L., Yao, Z.H., Wei, Y., Ray, L.C., Rae, I.J., Arridge, C.S., Coates, A.J., Delamere,
411 P.A., Sergis, N., Kollmann, P. and Grodent, D., (2018). Rotationally driven magnetic re-
412 connection in Saturn's dayside. *Nature Astronomy* *2*, 640-645, doi:10.1038/s41550-018-
413 0461-9

- 414 Harris, E. G., (1962). On a plasma sheath separating regions of oppositely directed magnetic
415 field, *Il Nuovo Cimento (1955-1965)*, 23(1), 115–121, doi:10.1007/BF02733547
- 416 Hoshino, M., Nishida, A., Mukai, T., Saito, Y., Yamamoto, T. and Kokubun, S., 1996. Struc-
417 ture of plasma sheet in magnetotail: Double peaked electric current sheet. *Journal of Geo-
418 physical Research: Space Physics*, 101(A11), pp.24775-24786, doi:10.1029/96JA02313
- 419 Israelevich, P.L. and Ershkovich, A.I., (2006). Bifurcation of Jovian magnetotail current
420 sheet. *Annales Geophysicae* 246, 1479-1481, doi:10.5194/angeo-24-1479-2006
- 421 Israelevich, P.L., Ershkovich, A.I. and Oran, R., (2007). Bifurcation of the tail current
422 sheet in Jovian magnetosphere. *Planetary and Space Science*, 55(15), pp.2261-2266,
423 doi:10.1016/j.pss.2007.05.006
- 424 Israelevich, P.L. and Ershkovich, A.I., (2008). Bifurcation of the tail current sheet and ion
425 temperature anisotropy. *Annales geophysicae: atmospheres, hydrospheres and space sci-
426 ences* Vol. 26, No. 7, p. 1759, doi:10.5194/angeo-26-1759-2008
- 427 Jurac, S., McGrath, M.A., Johnson, R.E., Richardson, J.D., Vasyliunas, V.M. and Eviatar, A.,
428 2002. Saturn: Search for a missing water source. *Geophysical Research Letters*, 29(24),
429 doi:10.1029/2002GL015855
- 430 Kellett, S., Bunce, E. J., Coates, A. J., Cowley, S. W. H., (2009). Thickness of Saturn’s ring
431 current determined from north-south Cassini passes through the current layer, *Journal of
432 Geophysical Research*, 114(A4), doi:10.1029/2008JA013942
- 433 Kellett, S., Arridge, C.S., Bunce, E.J., Coates, A.J., Cowley, S.W.H., Dougherty, M.K., Per-
434 soon, A.M., Sergis, N. and Wilson, R.J., (2011). Saturn’s ring current: Local time de-
435 pendence and temporal variability. *Journal of Geophysical Research: Space Physics*,
436 116(A5),doi:10.1029/2010JA016216
- 437 Khurana, K.K., Kivelson, M.G.,(1989). On Jovian Plasma Sheet Structure, *Journal of Geo-
438 physical Research*, 94(A9), 11,791–11,803, doi:10.1029/JA094iA09p11791
- 439 Khurana, K.K. (2001). Influence of solar wind on Jupiter’s magnetosphere deduced from cur-
440 rents in the equatorial plane. *Journal of Geophysical Research: Space Physics*, 106(A11),
441 25999-26016, doi:10.1029/2000JA000352
- 442 Kidder, A., Winglee, R.M. and Harnett, E.M., (2009). Regulation of the centrifugal inter-
443 change cycle in Saturn’s inner magnetosphere. *Journal of Geophysical Research: Space
444 Physics*, 114(A2), doi:10.1029/2008JA013100
- 445 Krupp, N., Dougherty, M. K., Woch, J., Seidel, R., Keppler, E., (1999). Energetic particles in
446 the duskside Jovian magnetosphere, *Geophysical Research Letters*, 34(A11), 8779–8789,

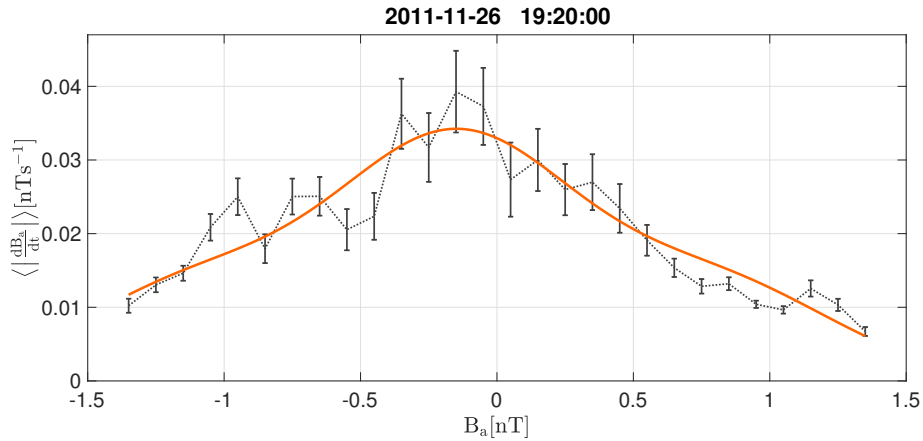
- 447 doi:10.1029/1999JA900156
- 448 Martin, C. J. and Arridge, C. S., (2017). Cassini observations of aperiodic waves on Saturn's
449 equatorial current sheet. *Journal of Geophysical Research: Space Physics*, 122(8) 8063-
450 8077, doi:10.1002/2017JA024293
- 451 Martin, C. J. and Arridge, C. S., (2018). Current Density in Saturn's equatorial current sheet:
452 Cassini magnetometer observations. *Journal of Geophysical Research: Space Physics* 124
453 279-292 doi:10.1029/2018JA025970
- 454 Matsui, T. and Daughton, W., 2008. Kinetic theory and simulation of collisionless tearing in
455 bifurcated current sheets. *Physics of Plasmas*, 15(1), p.012901, doi:10.1063/1.2832679
- 456 Mok, C., Ryu, C.M., Yoon, P.H. and Lui, A.T., 2006. Global two fluid stability of bi-
457 furcated current sheets. *Journal of Geophysical Research: Space Physics*, 111(A3),
458 doi:10.1029/2005JA011424
- 459 Nakamura, R., Baumjohann, W., Runov, A., Volwerk, M., Zhang, T.L., Klecker, B., Bog-
460 danova, Y., Roux, A., Balogh, A., Reme, H. and Sauvaud, J.A., (2002). Fast flow during
461 current sheet thinning. *Geophysical Research Letters*, 29(23), doi:10.1029/2002GL016200
- 462 Paranicas, C.P., Mauk, B.H. and Krimigis, S.M., 1991. Pressure anisotropy and radial stress
463 balance in the Jovian neutral sheet. *Journal of Geophysical Research: Space Physics*,
464 96(A12), pp.21135-21140. doi:10.1029/91JA01647
- 465 Pontius, D. H., and T. W. Hill., (2006) Enceladus: A significant plasma source for Sat-
466 urn's magnetosphere. *Journal of Geophysical Research: Space Physics*, 111 (A9),
467 doi:10.1029/2006JA011674
- 468 Provan, G., Andrews, D. J., Arridge, C. S., Coates, A. J., Cowley, S. W. H., Cox, G.,
469 Dougherty, M. K., Jackman, C. M. (2012). Dual periodicities in planetary-period mag-
470 netic field oscillations in Saturn's tail. *Journal of Geophysical Research*, 117 A1,
471 doi:10.1029/2011JA017104
- 472 Ricci, P., Lapenta, G. and Brackbill, J.U., (2004). Structure of the magnetotail current: Ki-
473 netic simulation and comparison with satellite observations. *Geophysical Research Let-
474 ters*, 31(6), doi:10.1029/2003GL019207
- 475 Runov, A., Nakamura, R., Baumjohann, W., Zhang, T.L., Volwerk, M., Eichelberger, H.U.
476 and Balogh, A., (2003). Cluster observation of a bifurcated current sheet. *Geophysical
477 Research Letters*, 30(2), doi:10.1029/2002GL016136
- 478 Runov, A., Nakamura, R., Baumjohann, W., Treumann, R.A., Zhang, T.L., Volwerk, M.,
479 Vörös, Z., Balogh, A., Glaßmeier, K.H., Klecker, B. and Reme, H., 2003. Current sheet

- 480 structure near magnetic X-line observed by Cluster. *Geophysical Research Letters*, 30(11),
481 doi:10.1029/2002GL016730
- 482 Saito, M., 2015. THEMIS two point measurements of the cross tail current density: A thick
483 bifurcated current sheet in the near Earth plasma sheet. *Journal of Geophysical Research:*
484 *Space Physics*, 120(8), pp.6258-6275, doi:10.1002/2015JA021142
- 485 Sergis, N., Jackman, C.M., Thomsen, M.F., Krimigis, S.M., Mitchell, D.G., Hamilton, D.C.,
486 Dougherty, M.K., Krupp, N., Wilson, R.J. (2017). Radial and local time structure of the
487 Saturnian ring current, revealed by Cassini, *Journal of Geophysical Research: Space*
488 *Physics*, 122(2) 1803-1815, doi:10.1002/2016JA023742
- 489 Sitnov, M.I., Guzdar, P.N. and Swisdak, M., (2003). A model of the bifurcated current sheet.
490 *Geophysical Research Letters*, 30(13), doi:10.1029/2003GL017218
- 491 Sitnov, M.I., Swisdak, M., Drake, J.F., Guzdar, P.N. and Rogers, B.N., (2004). A model of
492 the bifurcated current sheet: 2. Flapping motions. *Geophysical Research Letters*, 31(9)
493 doi:10.1029/2004GL019473
- 494 Sitnov, M.I. and Merkin, V.G., 2016. Generalized magnetotail equilibria: Effects of the
495 dipole field, thin current sheets, and magnetic flux accumulation. *Journal of Geophysical*
496 *Research: Space Physics*, 121(8), 7664-7683, doi:10.1002/2016JA023001
- 497 Smith, E.J., Davis, L., Jones, D.E., Coleman, P.J., Colburn, D.S., Dyal, P. and Sonett,
498 C.P., 1980. Saturn's magnetic field and magnetosphere. *Science*, 207(4429), 407-410.
499 doi:10.1126/science.207.4429.407
- 500 Sonnerup, B.Ö. and Cahill Jr, L.J., (1967). Magnetopause structure and attitude
501 from Explorer 12 observations. *Journal of Geophysical Research*, 72(1), 171-183,
502 doi:10.1029/JZ072i001p00171
- 503 Southwood, D.J., Kivelson, M. G., (2001). A new perspective concerning the influence of the
504 solar wind on the Jovian magnetosphere *Journal of Geophysical Research: Space Physics*,
505 106(A4), doi:10.1029/2000JA000236
- 506 Thompson, S.M., Kivelson, M.G., El Alaoui, M., Balogh, A., Reme, H. and Kistler, L.M.,
507 (2006). Bifurcated current sheets: Statistics from Cluster magnetometer measurements.
508 *Journal of Geophysical Research: Space Physics*, 111(A3), doi:10.1029/2005JA011009
- 509 Thomsen, M. F., Jackman, C. M., Cowley, S. W. H., Jia, X., Kivelson, M. G. and Provan,
510 G., (2016). Evidence for Periodic Variations in the Thickness of Saturn's Nightside
511 Plasma Sheet, *Journal of Geophysical Research: Space Physics*, 122(1), 280-292,
512 doi:10.1002/2016JA023368

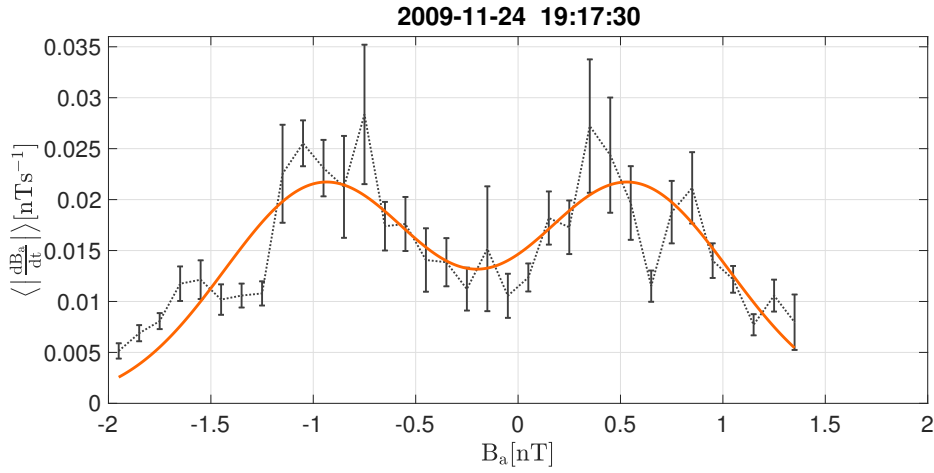
- 513 Tokar, R.L., Johnson, R.E., Thomsen, M.F., Delapp, D.M., Baragiola, R.A., Francis, M.F.,
514 Reisenfeld, D.B., Fish, B.A., Young, D.T., Crary, F.J. and Coates, A.J., 2005. Cassini ob-
515 servations of the thermal plasma in the vicinity of Saturn's main rings and the F and G
516 rings. *Geophysical Research Letters*, 32(14), doi:10.1029/2005GL022690
- 517 Zelenyi, L.M., Delcourt, D.C., Malova, H.V. and Sharma, A.S., (2002). 'Aging'
518 of the magnetotail thin current sheets. *Geophysical Research Letters*, 29(12),
519 doi:10.1029/2001GL013789
- 520 Zelenyi, L.M., Malova, H.V. and Popov, V.Y., (2003). Splitting of thin current sheets in the
521 Earth's magnetosphere. *Journal of Experimental and Theoretical Physics Letters*, 78(5),
522 pp.296-299, doi:10.1134/1.1625728



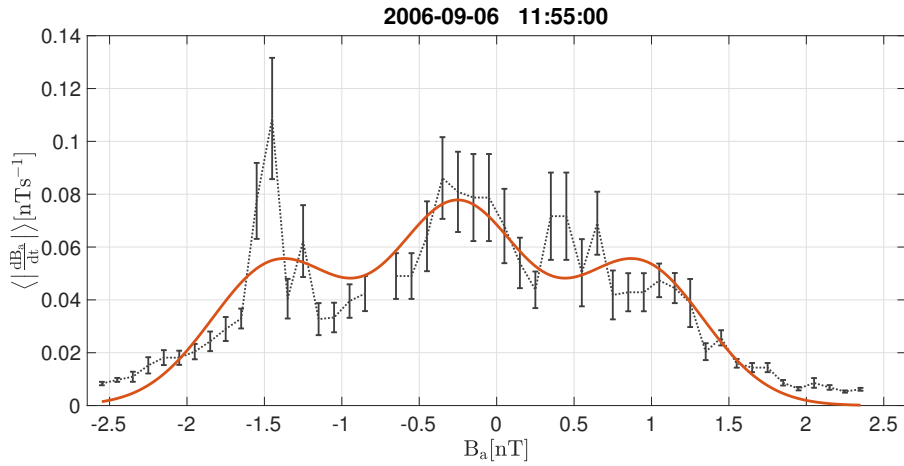
130 **Figure 1.** Cartoon of the relation between the current sheet coordinate system (ABC) and the KRTP (Kro-
 131 nian Radial, Theta, Phi) coordinates with respect to the current sheet and Saturn. KRTP is used here, however
 132 the method is independent of original co-ordinate system. KRTP is a spherical system with Saturn at the cen-
 133 tre. The radial component is positive radially outwards from the planet, θ is positive southwards at the equator
 134 and ϕ is positive in the corotation direction.



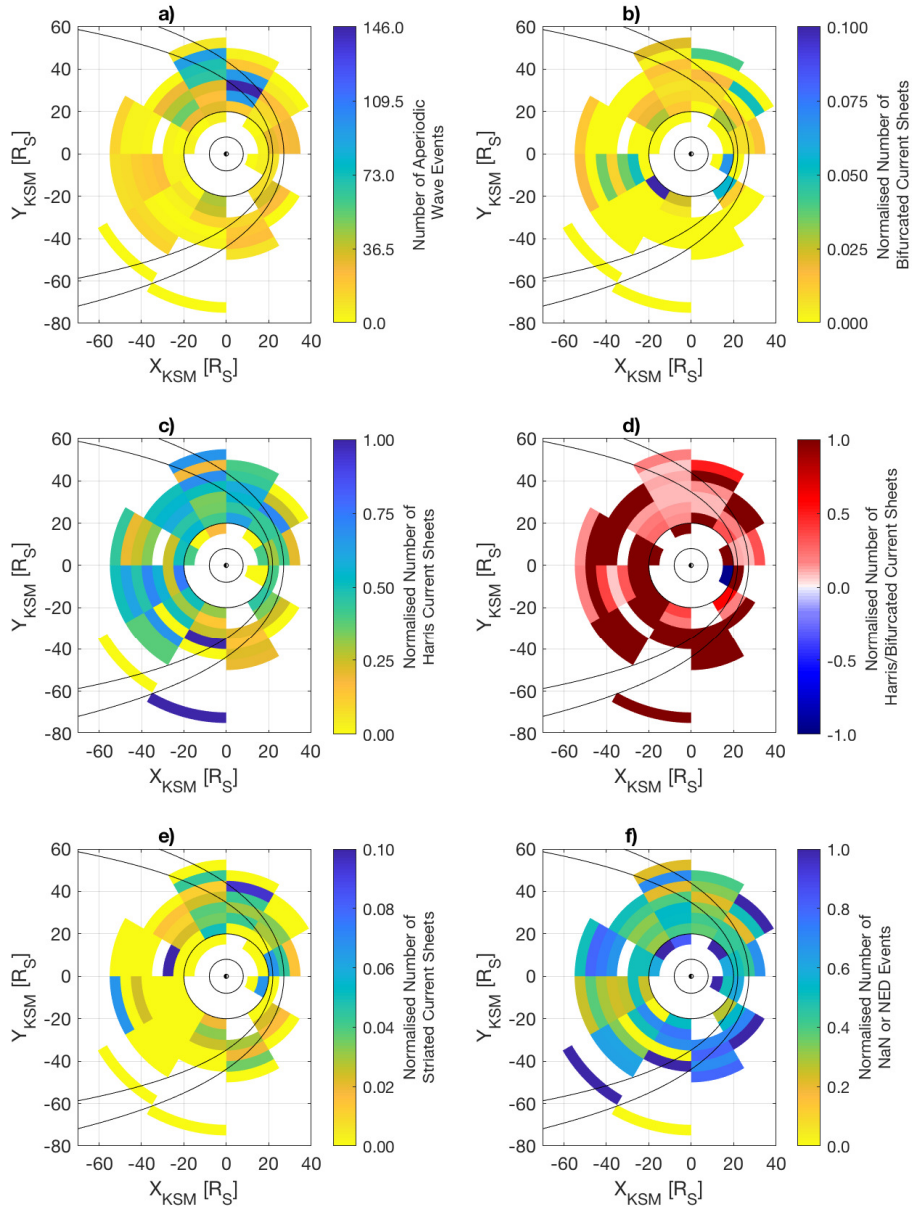
244 **Figure 2.** Proxies for the distance from the current sheet versus current sheet density for a Harris-like
 245 profile. The dotted line shows the mean of current density as a function of distance from the centre of the
 246 current sheet, with standard deviation shown by the error bars. The solid orange line is the fitted model of
 247 three Gaussians, where the central Gaussian is dominant and hence the example is a Harris-like current sheet.
 248 This example is found at $25.3 R_S$ and 13.5 SLT.



249 **Figure 3.** Proxies for the distance from the current sheet versus current sheet density for a bifurcated pro-
 250 file. The dotted line shows the mean of current density as a function of distance from the centre of the current
 251 sheet, with standard deviation shown by the error bars. The solid orange line is the fitted model of three Gaus-
 252 sians, where the peripheral Gaussians are dominant and hence the example is a bifurcated current sheet. This
 253 example is found at $30.5 R_S$ and 17.9 SLT.



254 **Figure 4.** Proxies for the distance from the current sheet versus current sheet density for a unclassi-
 255 fied/ambiguous profile. The dotted line shows the mean of current density as a function of distance from
 256 the centre of the current sheet, with standard deviation shown by the error bars. The solid orange line is the
 257 fitted model of three Gaussians, where the peripheral Gaussians are dominant and hence the example is a
 258 bifurcated current sheet. This example is found at $29.2 R_S$ and 1.6 SLT.



259 **Figure 5.** Distribution of total number of aperiodic wave events (a), number of bifurcated sheets normalised
 260 by total number of events (b) and number of Harris-like normalised by total number of events(c). d) shows the
 261 ratio of bifurcated to Harris-like current sheets. e) shows the number of unclassified or striated current sheets
 262 normalised by total number of events and the number of NaN and NED events normalised by total number of
 263 events is shown in f). Nominal magnetopause positions guide the eye in black, along with Titan's orbit at 20
 264 R_S and Rhea's orbit at $9 R_S$.