

## RESEARCH ARTICLE

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## Key Points:

- Periodic crossings of Saturn's tail current sheet often are asymmetric such that northbound crossings are faster or slower than southbound
- Character of crossings depends on relative phase of the northern versus southern perturbation currents previously derived from magnetic data
- Observed asymmetries are consistent with a periodically variable thickness of the magnetospheric current sheet, as theoretically expected

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## Evidence for periodic variations in the thickness of Saturn's nightside plasma sheet

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**Abstract** During certain portions of the Cassini mission to Saturn, Cassini made repeated and periodic crossings of the magnetospheric current sheet that lies near the magnetic equator and extends well down the magnetospheric tail. These repeated crossings are part of the puzzling set of planetary period variations in numerous magnetospheric properties that have been discovered at Saturn. During 2010 these periodic crossings often display asymmetries such that the northbound crossing occurs faster than the southbound crossing or vice versa, while at other times the crossings are more symmetric. The character of the crossings is well organized by the relative phase of the northern versus southern perturbation currents inferred in earlier analyses of the magnetic field observations. Further, the dependence of the character of the crossings on the relative phase is consistent with similar asymmetries predicted both by the dual rotating current systems inferred from magnetic field observations and by global MHD models that incorporate the effects of hypothesized atmospheric vortices. The two models are themselves in generally good agreement on those predictions. In both models the asymmetries are attributable to a periodic thickening and thinning of the magnetospheric current sheet, combined with a periodic vertical flapping of the sheet. The Cassini observations thus provide additional observational support to such current systems as a likely explanation for many of the known magnetospheric planetary period variations.

## 1. Introduction

Saturn's magnetosphere has now been visited by four spacecraft (Pioneer 11, Voyager 1 and 2, and Cassini) and remotely observed by the Ulysses radio wave experiment. One of the most puzzling discoveries from these missions has been the occurrence of periodic variations in a wide range of magnetospheric observables, from bursts of Saturn kilometric radiation (SKR) [e.g., Warwick et al., 1981; Desch and Kaiser, 1981; Galopeau and Lecacheux, 2000; Gurnett et al., 2009; Lamy, 2011] to in situ magnetic field [e.g., Espinosa and Dougherty, 2000; Cowley et al., 2006; Southwood and Kivelson, 2007; Andrews et al., 2008], energetic particle [e.g., Carbary and Krimigis, 1982; Carbary et al., 2007, 2008], and plasma [e.g., Burch et al., 2009; Arridge et al., 2011; Nemeth et al., 2016] properties. These periodicities occur at approximately the planetary rotation rate, which is inferred from tracking identifiable cloud features in the atmosphere since at Saturn it is not possible to observe a solid planetary body. When they were first observed, the periodicity of the SKR bursts was taken to be the best determination of the planetary spin period.

The initial puzzling aspect of these periodicities was their very existence since Saturn's magnetic dipole is very nearly aligned with its rotational axis, with no tilt or offset to break the cylindrical symmetry. Further confounding the mystery was the discovery that the SKR period actually varied slowly in time [e.g., Galopeau and Lecacheux, 2000], clearly incompatible with a signature of underlying planetary rotation. Moreover, evidence was then found for not just one but two different periodicities, one associated with SKR and magnetic field variations in the northern hemisphere and the other associated with the southern hemisphere [e.g., Galopeau and Lecacheux, 2000; Kurth et al., 2008; Gurnett et al., 2009]. These findings were reviewed by Carbary and Mitchell [2013] and have subsequently been supplemented by a number of studies, many of which are summarized by Cowley et al. [2016].

These observations have given rise to a large number of hypothesized sources of the periodicities [e.g., Espinosa et al., 2003; Gurnett et al., 2007; Goldreich and Farmer, 2007; Carbary et al., 2007; Southwood and

Kivelson, 2007; Mitchell *et al.*, 2009a; Khurana *et al.*, 2009; Burch *et al.*, 2009; Brandt *et al.*, 2010] (for reviews see Mitchell *et al.* [2009b] and Carbary and Mitchell [2013]). Two of the models that have been particularly successful in reproducing a wide range of observed periodic features are the empirical dual rotating current system (which we will refer to as DRC henceforth) [e.g., Southwood and Kivelson, 2007; Andrews *et al.*, 2010, 2012; Provan *et al.*, 2012; Cowley *et al.*, 2017] and the atmospheric vortex model (referred to as AV) [Jia *et al.*, 2012; Jia and Kivelson, 2012]. These two models are closely related: The former is based on an analytical description of the periodic magnetic field perturbations, and the latter is based on a global magnetospheric MHD model that imposes in the ionosphere a rotating pattern of flow designed to drive the field-aligned currents (recently discussed by Hunt *et al.* [2015] and Southwood and Cowley [2014]) needed to account for the very same periodic magnetic field fluctuations. Both models predict periodic variations in the field and plasma properties throughout the magnetosphere, rather successfully explaining many of the observed periodicities. Two further advantages of these two models over many of the other proposed periodicity-producing mechanisms are that they provide natural explanations of how the phase of the periodic variations can remain constant over many months or years and they naturally allow for dual periodicities and slow temporal variations in the periods.

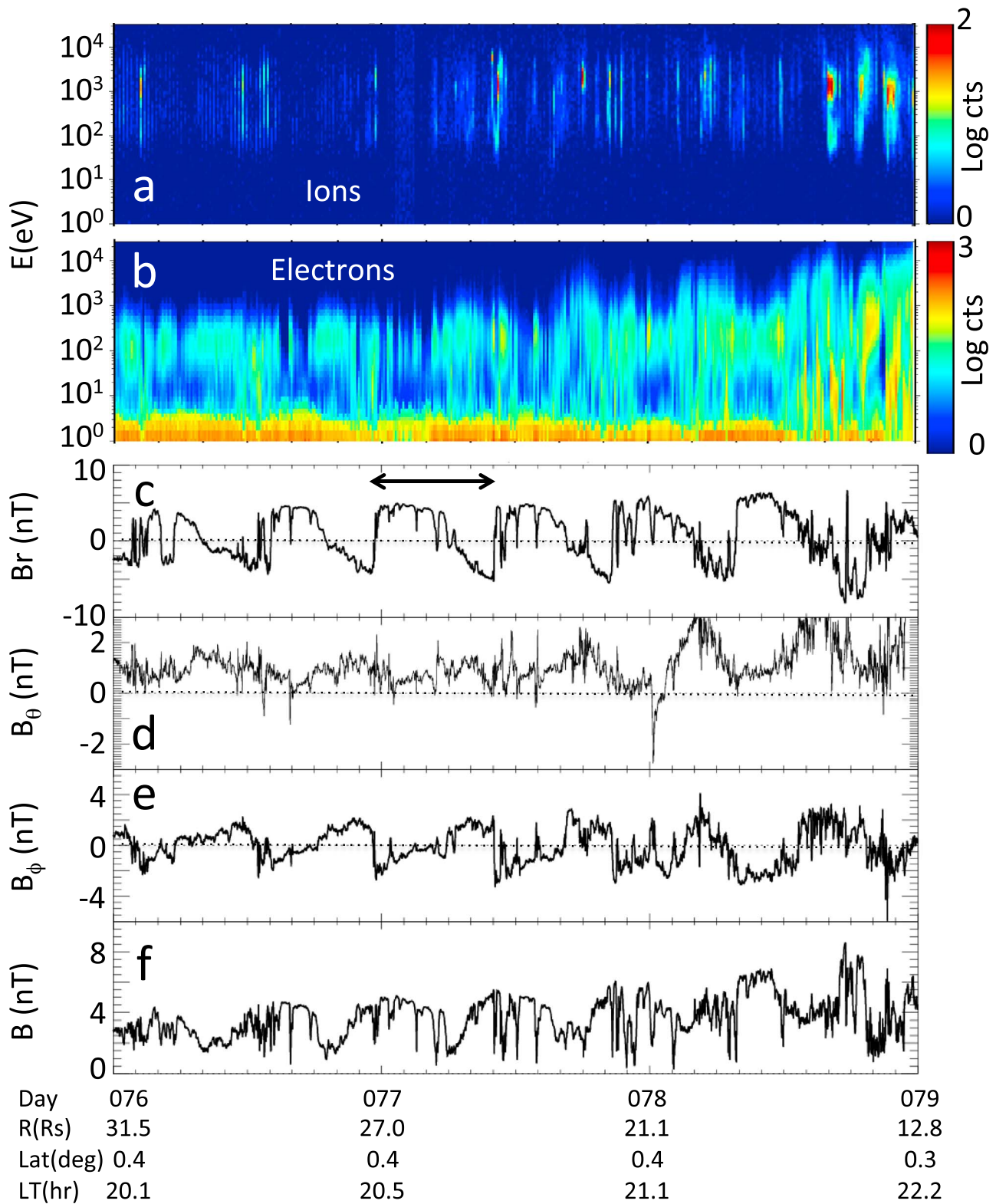
Of particular interest for the present study, both these models predict periodic vertical motions of the magnetospheric current sheet (accounting for the periodic current sheet encounters commonly seen with the Cassini spacecraft) and periodic thickening and thinning of the current sheet [e.g., Jia and Kivelson, 2012; Provan *et al.*, 2012; Cowley *et al.*, 2017]. Such modulation of the current sheet thickness has previously been inferred from Cassini observations [e.g., Morooka *et al.*, 2009; Provan *et al.*, 2012]. In the present work, we show observations of asymmetries in the north-to-south and south-to-north crossings of the tail current sheet that provide additional evidence for periodic modulation of the current sheet thickness. Further, we show that the nature of the asymmetries depends on the relative phase of the north and south current systems in a manner that is consistent with the expectations of both the DRC and AV models mentioned above.

## 2. Observations

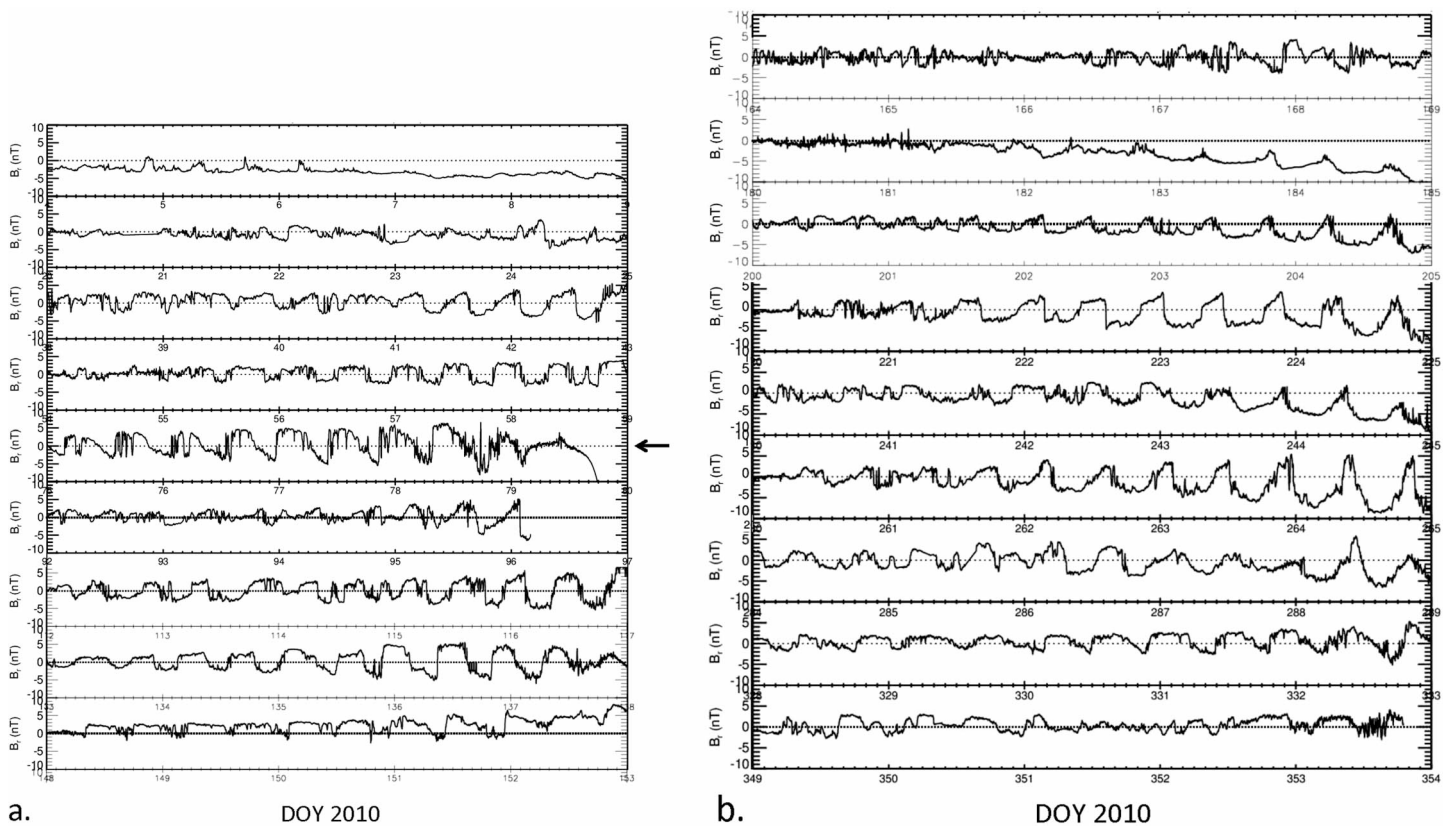
We report observations from the Cassini magnetometer (MAG) [Dougherty *et al.*, 2004] obtained during 2010, a time of repeated low-latitude orbits passing through the nightside region under near-equinoctial conditions (when the warping of the night-side current sheet is not strong [e.g., Arridge *et al.*, 2008]). For context, the plasma ion and electron data from the Cassini plasma spectrometer (CAPS) [Young *et al.*, 2004] are also presented for one of the intervals examined.

Figure 1 shows plasma and magnetic field measurements from CAPS and MAG for a 3 day interval in 2010 when Cassini was inbound at near-zero latitude and a local time of  $\sim 21$  h. During these 3 days, the spacecraft moved from  $31.5$  to  $12.8 R_S$  in radial distance from Saturn ( $1 R_S = 60,268$  km). Figures 1a and 1b show intermittent enhancements in the plasma fluxes, many associated with recurring encounters with the equatorially confined plasma sheet. Figures 1c–1f show the magnetic field components in the Kronocentric radial theta phi (KRTP) coordinate system ( $B_r$ ,  $B_\theta$ , and  $B_\phi$ ), and Figure 1f shows the field magnitude. The KRTP system is a spherical polar coordinate system referenced to Saturn's spin axis and is very useful for studying the tail current sheet [e.g., Jackman *et al.*, 2009]. In particular, the radial component provides a clear indication of whether the spacecraft is located north of the tail current sheet ( $B_r > 0$ ) or south of it ( $B_r < 0$ ). The times where  $B_r$  passes through zero are the times when the spacecraft is crossing the current sheet and are generally associated with enhancements in the plasma flux [e.g., Szego *et al.*, 2012].

Figure 1c shows that during this 3 day interval, the current sheet repeatedly swept up and down across Cassini, with a clear periodicity of  $\sim 10.7$  h (double-headed arrow in the upper portion of that panel), with the radial component of the field periodically changing from positive to negative and back to positive again. That periodicity is reflected as well in the other components and in the field magnitude. These periodic encounters with the current sheet reflect the oscillatory motion of the tail structure that is one of the clear features of Saturn's puzzling planetary period oscillations discussed above (and modeled in work such as Arridge *et al.* [2011]). In addition to the large-scale oscillations, there are numerous shorter-scale variations in  $B_r$ , indicating brief approaches to or penetrations of the current sheet. These do not appear to be systematic, and we assume that they reflect more rapid fluctuations in the location of the current sheet, perhaps due to propagating waves. In this work we are primarily interested in the planetary period oscillations.



**Figure 1.** Cassini plasma and magnetic field measurements from a 3 day interval in 2010, during which the spacecraft made repeated periodic crossings of the tail current sheet. (a and b) Color-coded logarithm of the ion and electron count rates (proportional to energy flux) as a function of energy. (c–e) Magnetic field  $r$ ,  $\theta$ , and  $\phi$  components in the KRTP coordinate system. (f) Magnetic field magnitude. Reversals in the  $r$  component of the field indicate crossings of the current sheet from one hemisphere to the other (positive  $B_r$  indicates northern hemisphere). The double-headed arrow in Figure 1c shows the duration of the  $\sim 10.7$  h planetary rotation period.



**Figure 2.** Radial component of the magnetic field observed by Cassini on 5 day segments of the 18 orbits of 2010 that featured periodic crossings of the tail current sheet, as indicated by reversals of the sign of  $B_r$ : (a) prior to DOY 153 and (b) after DOY 164. The arrow in the right-hand column of Figure 2a indicates the interval featured in Figure 1.

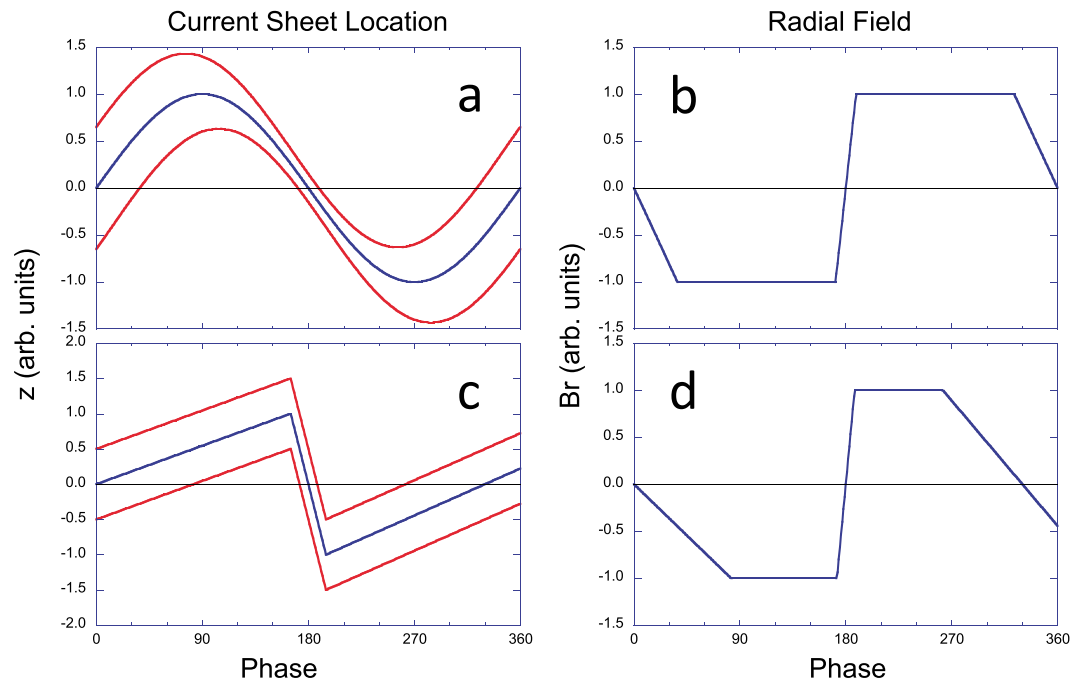
Another feature of the  $B_r$  signature of the large-scale current sheet crossings seen in Figure 1 is a clear asymmetry between the north-to-south and south-to-north crossings. When the spacecraft moves from the southern hemisphere ( $B_r < 0$ ) to the northern hemisphere ( $B_r > 0$ ), it does so quite rapidly, whereas the reverse transition appears to be much more gradual. A similar asymmetry is reflected in the  $B_\phi$  component, which shows an almost sawtooth-like behavior.

Cassini's 2010 season featured 18 orbits (Revs 124–142) with characteristics very similar to the one that produced the data in Figure 1. Figure 2 shows the radial magnetic field component for 5 day intervals from each of those orbits. In every case the signature of the periodic approach to or crossing of the current sheet is evident, as  $B_r$  periodically nears or crosses zero. (The interval featured in Figure 1 is indicated by the arrow in the right-hand margin of Figure 2a.) Figure 2 shows a wide diversity of  $B_r$  signatures: Some show an asymmetry similar to that seen in Figure 1 (e.g., day of year (DOY) 151–152 and DOY 167–168). Others show the opposite asymmetry, i.e., slow south-to-north and more rapid north-to-south transitions (e.g., DOY 40–43 and DOY 95–96). Still others seem to be roughly symmetric (e.g., DOY 56–59 and DOY 115–117). And yet others are indeterminate, or the spacecraft only approaches but does not actually cross the current sheet.

### 3. Discussion

Asymmetric crossings of the current sheet, in which the passage in one direction is faster than the return passage, would not be expected from a simple periodic flapping up and down of an otherwise rather uniform current sheet. Two possible scenarios that could produce such an asymmetry are illustrated schematically in Figure 3. Both cases are meant to illustrate how the  $z$  extent of the current sheet varies at a particular local time as the current sheet rotates at a uniform rate around the planet. The phase is thus related to the time,





**Figure 3.** Schematic illustration of how asymmetric  $B_r$  signatures of northward versus southward crossings of the current sheet could arise from (a and b) a variable current sheet thickness or (c and d) a steepening of the current sheet in the azimuthal direction. Figures 3a and 3c show the hypothesized vertical location of the center (blue curve) and north and south edges (red curves) of the current sheet as a function of azimuthal phase angle. Figures 3b and 3d show the resulting  $B_r$  signature that would be observed at a point in the equatorial plane as the corresponding current sheet structure rotated past it. The field structure is taken to be a simple form: constant but opposite values of  $B_r$  in the lobes outside of the current sheet boundaries, with a linear variation from one boundary to the other across the current sheet.

with  $360^\circ$  corresponding to a full rotational period. Figure 3a shows the case where a current sheet not only has a sinusoidally varying vertical ( $z$ ) displacement but also varies periodically in thickness, such that it is thickest at zero phase and thinnest at a phase of  $180^\circ$ . Figure 3b illustrates the radial field component that would be observed at  $z=0$  as the structure in Figure 3a is swept past an observing spacecraft. The field model is a very simple one with constant (but opposite) values of  $B_r$  in the lobes outside of the current-sheet boundaries marked by the red curves in Figure 3a, and with a linear variation from one lobe to the other across the current sheet between the red curves, with  $B_r=0$  at the blue curve. The results in Figure 3b illustrate what one would qualitatively expect: The transition from the south lobe to the north lobe at a phase of  $180^\circ$  (thin current sheet) is considerably sharper than the transition from north to south lobes near zero phase (thick current sheet). Figures 3c and 3d illustrate that a similar asymmetry in the south-to-north and north-to-south crossings could arise if the current sheet itself is particularly steep in some phase range, even if the current sheet is uniformly thick.

The two scenarios presented in Figure 3 are just illustrative of a range of possible conditions that might give rise to asymmetric current sheet crossings. Other possibilities include propagating pressure waves that cause current-sheet stretching and vertical motions [e.g., Kivelson and Jia, 2014; Jia and Kivelson, 2012]. From single-point measurements it would be difficult to distinguish between any of these scenarios, but analytical and numerical models offer insight into what may be the actual physical cause of the asymmetric crossings. As mentioned in section 1, both the DRC and the AV models predict not only periodic vertical motion of the current sheet (accounting for the periodic crossings seen in Figures 1 and 2) but also periodic variations in the thickness of the current sheet. The current sheet thickness in the AV model is measured by the scale height of a fit of the simulated field to a Harris sheet function [Jia and Kivelson, 2012], and the current sheet thickness in the DRC model can be specified [Cowley et al., 2017] as the sum of three terms: a uniform thickness of the underlying current sheet, plus contributions from both the southern rotating dipole and the northern rotating dipole. As described fully in Cowley et al. [2017], for the illustrative examples in that paper the undisturbed current sheet half-thickness ( $2.5 R_s$ ) and oscillation amplitude ( $4 R_s$  for the southern

system) were chosen based on fits done to tail observations by Arridge *et al.* [2011]. In both models, the northern and southern sources rotate at different rates and hence at times add together and at other times counteract each other in their effects on the current sheet thickness. The resulting effects on the location and thickness of the current sheet can be seen in Figure 9b of Jia and Kivelson [2012] and in Figures 3–6 of Cowley *et al.* [2017]. In both models both the  $z$  position and the thickness of the current sheet vary with the planetary period, with an amplitude that depends on the relative phase between the north and south current sources and is modulated at the beat frequency between them.

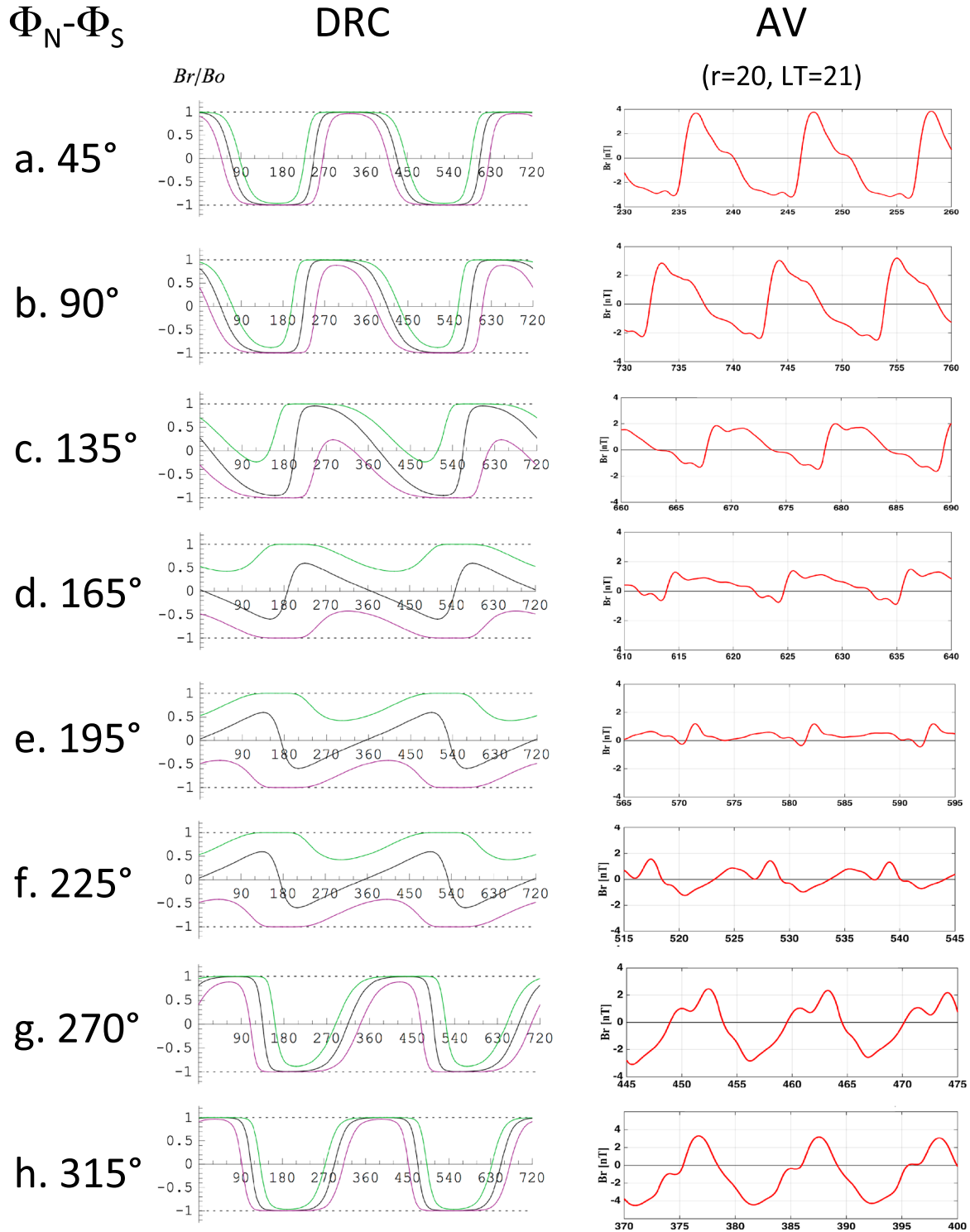
Because of the time-varying position and thickness of the current sheet, both the DRC and AV models result in a complicated temporal variability in the magnetic field at any given location in the magnetosphere, and the magnetic signature depends on the relative phase of the north and south current sources. Figure 4 (left column) illustrates how the radial magnetic field component varies with southern phase (as a proxy for time) within the analytical model of Cowley *et al.* [2017], which is designed to represent the behavior of the two current sources in the DRC model. In each panel, the radial component of the field is shown as a function of phase at three different positions relative to the nominal  $z=0$  plane ( $z=0$  and  $z=\pm 2.5 R_S$ ). The different panels correspond to different values of the relative phase ( $\Phi_N - \Phi_S$ , listed along the left-hand margin), where the north and south phases are defined as described in Cowley *et al.* [2017]: Both phases increase linearly with time as viewed by a stationary observer (hence in a left-hand sense with respect to Saturn's spin axis), and the zero phase value of each system occurs where its equatorial perturbation field is radially outward.

Figure 4 (right column) shows the radial magnetic field component measured at the location of  $r = 20 R_S$  and  $LT = 21$  (chosen for direct comparison with the Cassini data in Figure 1) in the global MHD simulation of Jia and Kivelson [2012]. The different panels correspond to times within the simulation when the relative phases of the northern and southern vortices were approximately as given in the left-hand margin of the figure. Note that the phases of the two systems were defined by Jia and Kivelson [2012] to increase in a right-hand sense relative to Saturn's north pole, i.e., the negative of the phases defined by Cowley *et al.* [2017] and previous discussions of the DRC model [cf. Jia and Kivelson, 2012, equation (2)]. Thus, we have selected the panels in Figure 4 (right column) from times where the phase differences defined within the code are the negative of the values shown in the left-hand margin of Figure 4 (modulo 360).

There are strong qualitative similarities between the two columns in Figure 4: Both models exhibit periodic northward and southward crossings of the current sheet, as indicated by the recurrent reversals of the  $B_r$  component, and the  $B_r$  signatures in both models show considerable diversity, with the character varying with the relative phase. Both the amplitude of the  $B_r$  variations and the symmetry (or asymmetry) of the northward versus southward crossings vary systematically with  $\Phi_N - \Phi_S$ . For relative phases of  $165^\circ$  and  $195^\circ$ , both the DRC and AV models show low-amplitude variations in  $B_r$ . At relative phases of  $90^\circ$  and  $135^\circ$ , both models show larger-amplitude variations, with a distinct asymmetry between the south-to-north crossings (rapid) and the north-to-south crossings (slow). The opposite asymmetry occurs for  $225^\circ$  and to a lesser extent  $270^\circ$ . At  $315^\circ$  the crossings are more symmetric. Thus, both models appear to be able to reproduce qualitatively the variety of  $B_r$  signatures seen in the Cassini observations of Figure 2, and the organizing property is the relative phase between the north and south current sources.

To test whether the relative phase of the north and south current sources might likewise organize the character of the magnetic field signatures seen in the Cassini data (Figure 2), we use the time-dependent north and south system phases derived from the Cassini magnetic field data by Provan *et al.* [2011] and Andrews *et al.* [2012] (see, e.g., Jackman *et al.* [2016] for discussion of the link between northern and southern phases and the occurrence of tail reconnection events). The phase angle is the azimuth about Saturn's spin axis, relative to noon, at which the equatorial perturbation field from each current source points radially outward from Saturn. Jackman *et al.* [2016] adopted an additional correction to the phases to account for the radial propagation of the perturbation field signal, but since our interest is in the relative phase difference between the two systems, that correction would cancel out and can be ignored. Likewise, the dependence of the individual phases on local time also cancels out when the relative phase is computed. Each of the intervals in Figure 2 is assigned a value of the relative phase  $\Phi_N - \Phi_S$  appropriate to the center time of the interval, as listed in Table 1.

Further, each interval is assigned a "character" based on visual inspection of the  $B_r$  signature. We use four values of the character: Indet = indeterminate, FN/SS = fast south-to-north crossing/slow north-to-south



**Figure 4.** Variation of the radial magnetic field component with time for (left column) the DRC model of Cowley *et al.* [2017] and (right column) the AV model of Jia and Kivelson [2012]. The different panels show the  $B_r$  variation for the different values of the relative phase between the northern and southern current systems ( $\Phi_N - \Phi_S$ ) listed along the left-hand margin. The three curves in the DRC panels show the  $B_r$  value expected at three different vertical locations relative to the nominal center of the current sheet: green ( $z = +2.5 R_s$ ), black ( $z = 0$ ), and purple ( $z = -2.5 R_s$ ). The AV panels on the right-hand side are extracted from the position ( $r = 20 R_s$  and 21 LT) at epochs in the global MHD simulation of Jia and Kivelson [2012] when the relative phase of the two atmospheric vortices is approximately the negative of the values in the left-hand column of the figure (modulo 360) to account for the different handedness of the definition of phase in Jia and Kivelson compared to that used here (which follows Cowley *et al.* [2017] and previous related works). The DRC calculations in the left-hand column assume a ratio of north-to-south current densities of 1:1, while the AV simulation in the right-hand column assumed a current density ratio of 1:3.

**Table 1.** Character of 2010 Current Sheet Crossings

DOY Range	$R^a$ ( $R_S$ )	Latitude <sup>a</sup> (deg)	Local Time <sup>a</sup> (h)	$\Phi_N - \Phi_S^a$ (deg)	Character <sup>b</sup> (Observer 1)	Character <sup>b</sup> (Observer 2)
4–9	33.0	–14.5	19.7	115	Indet	Symm
20–25	33.6	–3.3	19.6	202	Indet	Indet
38–43	32.7	0.1	20.1	298	SN/FS	SN/FS
54–59	37.1	0.1	19.7	9	Symm	Symm
75–80	24.2	0.4	20.8	94	FN/SS	FN/SS
92–97	27.7	0.3	20.4	168	SN/FS	SN/FS
112–117	29.8	0.2	20.2	269	Symm	Symm
133–138	27.0	0.3	20.4	9	FN/SS	FN/SS
148–153	30.6	8.7	19.1	65	FN/SS	FN/SS
164–169	30.7	–1.0	19.1	123	FN/SS	Indet
180–185	30.0	–13.9	19.2	168	Indet	Indet
200–205	30.8	–3.8	19.9	206	Symm	Indet
220–225	30.4	–3.8	19.9	245	SN/FS	SN/FS
240–245	30.5	–3.9	19.9	299	Indet	Indet
260–265	30.2	–3.9	19.9	339	Indet	SN/FS
284–289	29.3	–2.8	20.6	15	Indet	Indet
328–333	32.1	–0.1	19.7	104	FN/SS	FN/SS
349–354	30.0	–0.1	19.8	118	Indet	Indet

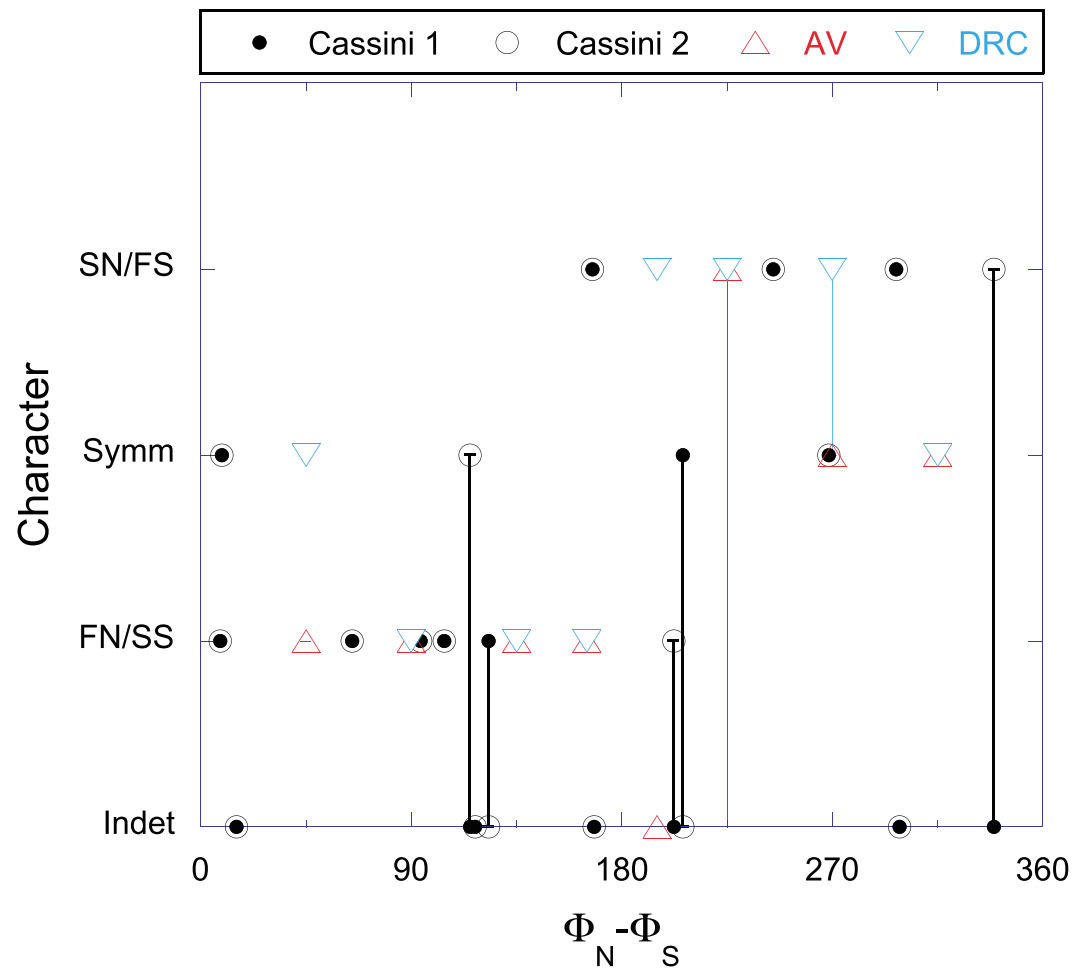
<sup>a</sup>Specified at center of interval.<sup>b</sup>Character definitions: Indet = indeterminate, FN/SS = fast south-to-north crossing/slow north-to-south crossing, Symm = symmetric, SN/FS = slow south-to-north crossing/fast north-to-south crossing.

crossing, Symm = symmetric, and SN/FS = slow south-to-north crossing/fast north-to-south crossing, where the direction refers to the apparent motion of the spacecraft (e.g., negative  $B_r$  followed by positive  $B_r$  corresponds to a south-to-north crossing). Because the determination of the character of the crossings is subjective, we compile the assessments of two independent observers. The resulting characters are listed in Table 1 for the full set of intervals shown in Figure 2.

Figure 5 is a graphical summary of the phase differences and characters listed in Table 1. Also shown in Figure 5 are similar assessments of the  $B_r$  signatures shown for the two models in Figure 4, performed by the same two independent observers whose character identifications are listed in Table 1. With the exception of just a few points, it is clear from Figure 5 that the relative phase of the two current systems does indeed order the character of the  $B_r$  signatures seen by Cassini, in the same sense that emerges for both the DRC and AV models: Asymmetric current sheet crossings in which the northbound crossing occurs more rapidly than the southbound crossing (character = FN/SS) are seen when the relative phase lies between  $0^\circ$  and  $180^\circ$ , while the reverse asymmetry is seen between  $180^\circ$  and  $360^\circ$ . Symmetric crossings, with a couple of exceptions, occur near  $0^\circ$  and  $180^\circ$ .

It should be noted that asymmetric structure in the  $B_r$  profiles for northward versus southward crossing of the current sheet is also found in the AV model even when it is run with only a single atmospheric vortex [Jia *et al.*, 2012], as illustrated in Figure 6. The variation of  $B_r$  from an AV run with a source only in the south arises from the combination of a periodically varying current sheet thickness and a periodically varying current sheet position, which are dynamical changes arising from compressional waves generated by the vortical ionospheric flow and propagating through the magnetotail [Kivelson and Jia, 2014]. Importantly, these variations, while periodic, are not sinusoidal and are not in phase with each other as assumed by the DRC formalism (Figure 6a). The primary asymmetry arises because the current sheet moves southward from  $z=0$  to  $z=-0.5 R_S$  much more rapidly than it returns northward from  $-0.5 R_S$  to  $0 R_S$ , a behavior similar to that depicted in Figure 3c. The current sheet is thicker when it approaches  $z=0$  going southward than when it approaches  $z=0$  going northward, but this produces only a small bump in the  $B_r$  profile. Thus, it is not necessary to have current sources in both hemispheres to produce asymmetric current sheet crossings per se, but the crucial finding in this study is that the character of the asymmetry varies with time in such a way that it is well organized by the relative phase of a northern and southern source, as inferred from magnetic field measurements, and that variation requires dual sources of changing relative phase. That element of the asymmetry is well captured by both the DRC and the AV model with dual sources [Jia and Kivelson, 2012]. We believe that the nonsinusoidal variation of the thickness and position of the



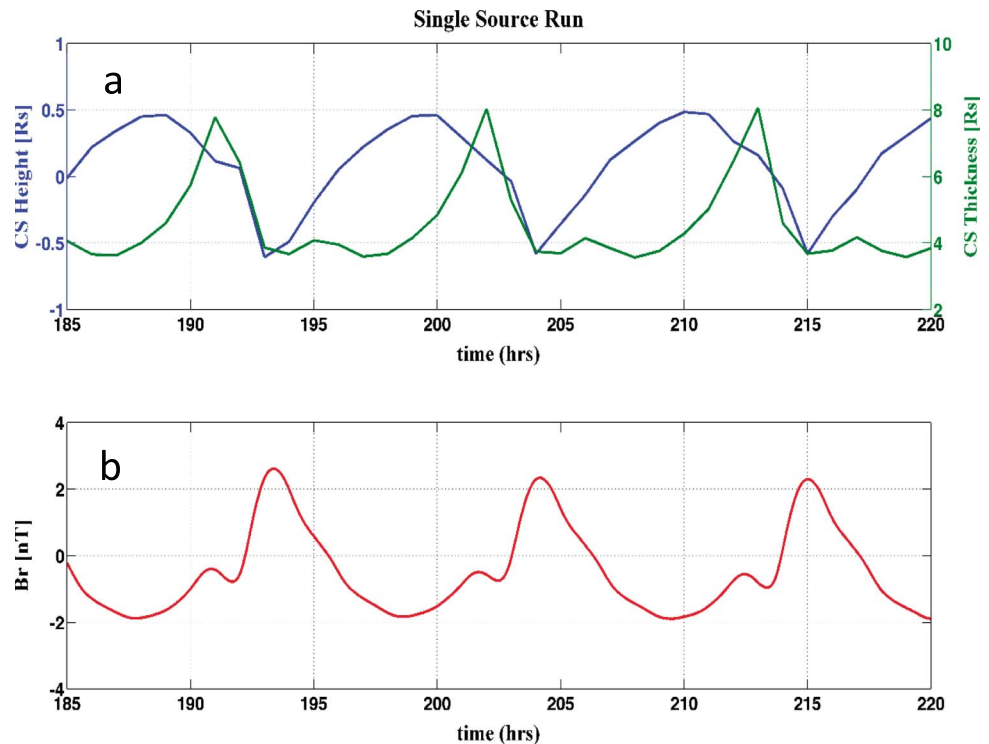


**Figure 5.** Graphical summary of the character of the current sheet crossings at various values of the relative phase of the north and south current systems as inferred from the 2010 Cassini observations in Figure 2 (black filled and open circles), the AV model of Jia and Kivelson [2012] (red open triangles), and the DRC model of Cowley *et al.* [2017] (blue inverted triangles). Character abbreviations correspond to the following: Indet = indeterminate, FN/SS = fast northward crossing/slow southward crossing, Symm = symmetric, and SN/FS = slow northward crossing/fast southward crossing, where the direction refers to the apparent motion of the spacecraft (e.g., negative  $B_r$  followed by positive  $B_r$  corresponds to a northward crossing). There are two Cassini points (Cassini 1 and Cassini 2, connected by vertical lines) for each of the intervals in Figure 2 and Table 1, corresponding to assessments of Figure 2 by two independent observers. This procedure provides a rough guide to the uncertainty of the various determinations. Likewise, the error bars on the AV and DRC points indicate disparities in the determinations by the same two observers.

current sheet is probably responsible for the double-humped substructure that appears in a number of the  $B_r$  profiles from the AV model in Figure 4.

The clear dependence in Figure 5 of the character of the current sheet crossings on the relative phase of the two perturbation current systems provides additional observational support to the DRC and AV models of the planetary period oscillations. The observed asymmetries in the crossings are thus quite consistent with periodic variations of both the location and thickness of the tail current sheet as predicted by both models and previously inferred from other data [e.g., Morooka *et al.*, 2009; Provan *et al.*, 2012].

The discussion above emphasized the importance of the relative phase of the two current systems in determining the nature of the current sheet crossing. However, as described in detail by Cowley *et al.* [2017], another similarly important parameter is the relative amplitudes of the two current systems. As shown in that study, asymmetric (“sawtooth”-like) crossings are most pronounced for near-equal amplitudes of the two systems. For the DRC calculations shown in Figure 4 (left column), a north-to-south amplitude ratio of 1:1 was



**Figure 6.** From the AV simulation of Jia *et al.* [2012] at the location ( $20 R_S$ ,  $21^\circ$  LT): (a) the height in  $R_S$  (blue) and the thickness in  $R_S$  (green) of the current sheet. (Thickness is evaluated from a fit to a Harris equilibrium model.) (b) The radial component of the magnetic field ( $B_r$ ) at the equator ( $z = 0$ ). Both are plotted versus simulation time in hours.

used, producing a very marked asymmetry. In the AV simulation that produced Figure 4 (right column), the ratio of northern vortex current density to southern was only 1:3 [Jia and Kivelson, 2012], and we might expect a smaller asymmetry, but at least in the range of  $\Phi_N - \Phi_S \sim 0 - 180^\circ$  the asymmetry is quite evident.

With regard to the observations, fits to Cassini magnetometer data have found that the ratio of the north and south current densities varies substantially on the time scale of months [Andrews *et al.*, 2012; Provan *et al.*, 2013; Cowley *et al.*, 2017]. During the 2010 season shown in Figure 2 the ratio of the north to south perturbation field amplitudes was found to be  $\sim 1.03$ , consistent with the clear asymmetries seen when the relative phases were favorable (Figure 5). However, as discussed by Cowley *et al.* [2017], there were other intervals in the Cassini mission during which the ratio was significantly different from 1.0, which might be suitable for examining this dependence. In particular, low-latitude, nightside passes somewhat similar to those in 2010 occurred in 2006, 2009, and 2015 [cf. Cowley *et al.*, 2017, Figure 1], and we have examined MAG data from these periods as well. Unfortunately, for a combination of reasons we note below, the observations from those intervals were less than ideal for this study.

During 2006 the derived ratio of field amplitudes was 0.38 [Andrews *et al.*, 2012], for which less asymmetry in  $N \rightarrow S$  versus  $S \rightarrow N$  crossings might be expected [Cowley *et al.*, 2017]. An examination of the intervals of multiple current sheet crossings from the 2006 Cassini tail season similar to Figure 2 reveals no evidence for clear and repeated asymmetric crossings. In part, this is because the spacecraft orbit and current sheet deflection [e.g., Arridge *et al.*, 2008] were such that many of the current sheet encounters were just brief dips into the field reversal region, rather than full-blown crossings back and forth. At other times the orbit was such that there was only a single transition from the northern hemisphere to the southern, without the multiple back-and-forth crossings needed to establish the character of the northward versus southward crossings. Still other intervals showed rather disturbed fields, with no clear pattern of crossings or character. Nonetheless, during the few intervals when the crossings were suitable to determine the character, no pronounced asymmetries were observed.

We have also examined the  $B_r$  data for current sheet crossings in 2009, when the inferred N/S amplitude ratio was 0.87 for the first half of the year and 1.02 for the second half [Andrews *et al.*, 2012], both apparently

favorable for pronounced asymmetries. While many of the crossings were again single transitions from one hemisphere to the other, particularly in the first half of the year, there were several intervals with repeated crossings. Two of those showed FN/SS asymmetries like those in Figure 2, but generally weaker. The relative phase of the N and S systems for those intervals was 48° and 65°, consistent with the relationship shown in Figure 5. There were three sets of crossings that were more nearly symmetric, and they had relative phases of 279°, 287°, and 304°, consistent with other symmetric crossings found in 2010 (Figure 5). None of the 2009 intervals that were suitable for examining the symmetry of the crossings were of the SN/FS character.

Finally, we examined the  $B_r$  data for 2015, when the inferred N/S amplitude was  $>2$  [Provan *et al.*, 2016; see also Cowley *et al.*, 2016], for which little asymmetry would be expected. Again, there were very few intervals of repeated crossings that would be suitable to determine the character of the crossings. Only three sets of repeated crossings were found to be useful, and all three intervals (corresponding to relative phases of 45°, 130°, and 330°) were essentially symmetric with respect to northward and southward crossings. Examination of Figure 5 suggests that while crossings at 45° and 330° might well be expected to be symmetric, the event at 130° should have been FN/SS if it followed the 2010 trend. Thus, this one event seems to support the expectation that N/S amplitude ratios well away from 1.0 would not produce a pronounced asymmetry.

While the observing conditions were not ideal during 2006, 2009, and 2015, the observation of clear asymmetries in 2010 and a few asymmetries in 2009, while none was seen in 2006 or 2015, is at least modestly consistent with the expectation of stronger asymmetries for nearly equal amplitudes of the north and south systems, as discussed by Cowley *et al.* [2017].

#### 4. Summary

Repeated crossings of Saturn's magnetospheric current sheet observed by the Cassini spacecraft during 2010 often display asymmetries such that the northbound crossing occurs faster than the southbound crossing or vice versa, while at other times the crossings are more symmetric. The character of the crossings is well organized by the relative phase of the northern versus southern perturbation currents inferred in earlier analyses of the magnetic field observations [e.g., Andrews *et al.*, 2012; Provan *et al.*, 2012]. Further, the dependence of the character on the relative phase is consistent with similar asymmetries predicted by the dual rotating current systems inferred from those magnetic field observations [Cowley *et al.*, 2017] and predicted by global MHD models that incorporate the effects of hypothesized atmospheric vortices [e.g., Jia and Kivelson, 2012]. We thus conclude that the observed asymmetries are consistent with a periodic thickening and thinning of the magnetospheric current sheet as predicted by these two models.

Current sheet crossings observed in 2006, 2009, and 2015 are also basically supportive of theoretical expectations [Cowley *et al.*, 2017] that asymmetric crossings should be most pronounced during epochs when the perturbation amplitudes of the two current systems are near equal. However, because of the nature and orientation of the orbits during these years, Cassini spent less time near the current sheet, and the effect is less definitively visible. It is further likely that other effects (e.g., solar wind pressure variations) may also affect the location and apparent thickness of the current sheet, yielding a few discrepancies between the observations and expectations. Nonetheless, the evidence presented here is clearly consistent with the periodic thickening and thinning of Saturn's magnetospheric current sheet in response to perturbations produced by the current systems hypothesized in earlier studies.

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