Magnetic phase structure of Saturn’s 10.7 h oscillations

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Abstract A source of Saturn’s magnetic 10.7 h period oscillations has yet to be identified. The oscillations are known to consist of signals with slightly different periods from separate northern and southern sources. Here we present a novel way of examining observations, focusing on signal phase. We show that although the signals are highly periodic they are usually not sinusoidal and that there are differences in both phase structure and polarization between the outer magnetosphere (on the nightside) and the inner dipolar region. Paying particular attention to the deep midtail passes of 2006, the contrasting behavior between the inner and outer regions is clear with approximate sinusoidal behavior in the dipolar region and a pulse-like signal once per cycle in the tail. The latter structure seems to indicate that tail magnetic stress is released impulsively once per cycle in the tail. After equinox, in 2010–2011, we find a different picture in the premidnight sector. The predetermined northern and southern frequencies are closer together and apparently show sudden shifts. Our signal reconstruction approach finds instances where it is likely that the narrow band filtering is not able to track completely the basic north and south periods as we find phase jumps indicating unpredictable beats.

1. Introduction

The Cassini spacecraft has been in orbit around Saturn for 10 years. One remarkable discovery was that the Saturn Kilometric Radiation (SKR) emissions identified from previous space missions consist of two separate signals: one emanating from the southern auroral region and the other from the northern auroral region, having respective periods of ∼10.8 and ∼10.6 h [Gurnett et al., 2009]. The signal frequencies were found to vary slowly with time [Galopeau and Lecacheux, 2000] before starting to converge at a faster rate of ∼5 min/yr before either crossing [Gurnett et al., 2010, 2011] or coalescing [Lamy, 2011] in early 2010, an issue to which we will return.

Magnetic field observations have also revealed oscillations of order of the planetary period (∼10–11 h) [Espinosa and Dougherty, 2000; Espinosa et al., 2003; Giampieri et al., 2006; Cowley et al., 2006; Southwood and Kivelson, 2007; Andrews et al., 2008; Provan et al., 2009; Southwood, 2011; Andrews et al., 2011; Provan et al., 2011; Andrews et al., 2012; Provan et al., 2013]. The radio signals almost certainly originate from regions of field-aligned currents. Southwood and Kivelson [2007, 2009] proposed that a rotating field-aligned current system was a source of the magnetic signals and proposed a mechanism for the modulation of SKR. They were also the first authors to present magnetometer observations using phase as a coordinate. They overlaid magnetic field observations (azimuthal component) from successive periapsis passes as a function of spacecraft local time (LT)-adjusted phase based on the SKR period [Kurth et al., 2007]. They showed that the field is well organized by the LT-adjusted phase and indeed showed not only that the signals had azimuthal wave number $m = 1$ but also that they were rotating in the sense of planetary rotation. The work of Southwood and Kivelson [2007, 2009] was made under the assumption that there was a single, dominant magnetic period. In fact, the magnetic field data that they used were observed at a time when the southern period signal was dominant. Shortly after publication of Southwood and Kivelson [2009], Gurnett et al. [2009] announced the detection of two separate radio signals with ∼10.7 h period, one originating in the northern and the other in the southern hemisphere.

Using the rotating magnetic phase as a coordinate as had been done by Southwood and Kivelson [2007, 2009], Southwood [2011] demonstrated directly the presence of separate northern and southern signals in the magnetometer data. Using data from a series of highly inclined orbits where the spacecraft spent most of the orbit on field lines above 75° magnetic invariant latitude, he not only demonstrated that separate periods were detected in northern and southern polar caps but also was able to show the conservation of both northern and southern phases. His technique worked by overlaying magnetic field data plotted against...
the rotating phase coordinate introduced in Southwood and Kivelson [2007]. He was able to do this by selecting a sequence of orbits where the orbit parameters remained fixed from orbit-to-orbit. The orbital period of Cassini was around 20 days and remarkably close to the beat period between northern and southern signals at the time. The passage from northern and southern domains was marked by sudden jumps in the oscillating ~10.7 h period signal due to the slightly different northern and southern periods. By tracing from pass to pass it was shown that northern and southern phases were well conserved over many tens of days.

Andrews et al. [2012] and Provan et al. [2013] used “core region” (L ≤ 12 R_J) magnetometer observations to determine magnetic oscillations and show how they evolved over essentially the entire Cassini mission to date. The periods are determined from band-pass filtering the magnetic field oscillations. Most importantly, they were able to distinguish separate polarizations of the two signals. For the southern signal \( B_s \) is in lagging quadrature with both \( B_n \) and \( B_b \) which are in phase, while for the northern signal \( B_n \) and \( B_b \) are in antiphase and \( B_s \) is in lagging quadrature with \( B_n \) and thus leading quadrature with \( B_b \).

Andrews et al. [2012] also showed, just as Southwood [2011], found, that quite generally on Cassini’s inclined orbits, the signals in respective polar caps were pure with less than 10% contamination by the signal associated with the opposite hemisphere. This result suggests that the two magnetic signals originate from their respective polar regions and that the SKR emissions are directly linked to these signals via field-aligned currents associated with each perturbation field [Southwood and Cowley, 2014].

The southern magnetic period determined by Andrews et al. [2012] closely matches that of the reported southern SKR period to within a few tens of seconds up to equinox [Andrews et al., 2012]. However, as we have already alluded, matters become less clear near equinox. By equinox, the difference between the derived northern magnetic and reported SKR periods is on the order of 1 min. Such a discrepancy would mean an apparent difference in phase of the order half a cycle appearing in 300 cycles or approximately 4–5 months. Of course, such results showing a lack of phase lock could indicate that the radio and magnetic signals have different sources. We doubt this. It is rather that when the northern and southern periods are so close the period-detection methods are nearing the limit of capability.

As noted already the SKR observations were reported to either coalesce together [Lamy, 2011] or cross [Gurnett et al., 2010] each other shortly after equinox. In contrast, the period determined from the magnetic field observations (which are aided by the polarization mode separation) appeared to show that the two periods began diverging ~200 days after equinox with the southern period remaining greater than the northern.

Recent SKR period determinations have reported that, postequinox (up to mid-2012), both the northern and southern periods are very similar [Fischer et al., 2014]. Both show small-scale time variation and differ significantly only during March to August 2011. Fischer et al. argue that this sudden change in behavior could be related to the presence of the Great White Spot during this interval. Provan et al. [2013] has shown evidence that the behavior of the magnetometer-derived periods changes significantly after equinox. In this interval the determined magnetic periods change very little with time, but there are abrupt changes in the amplitude ratio (determines which period is dominant) from orbit to orbit (≤20 days) [Provan et al., 2013]. This is demonstrated in Figure 1, which has been adapted from Provan et al. [2013], and shows the variation with time of the magnetic periods (Figure 1a: southern and northern periods are represented by red and blue colors, respectively) and amplitude ratio \( k \) (Figure 1b). Therefore, the inner Kronian magnetosphere appeared to undergo abrupt changes concerning which hemisphere was dominant with no corresponding, or limited, changes in period (~10.7 h for the southern hemisphere and ~10.63 h for the northern). The difference between both magnetic periods can yield insight into the limit of applicability of the Andrews and Provan method. During southern summer the difference between periods is ~12 min; therefore, to differentiate between the two signals (assuming that the signals are at least in antiphase in order to be differentiated) one would need to track both signals for at least ~13 days or ~26 cycles. After equinox the difference in the period is as small as ~1.5 min. Therefore, the signal period difference would be distinguishable only on a scale ~90 days (or ~180 cycles). This is longer than the reported abrupt changes in northern to southern dominance. The above statements have assumed that the period determination analysis is undertaken within the “time domain” as in Andrews et al. [2012] and Provan et al. [2013]. If the analysis was carried out in the “frequency domain” using, for example, Lomb-Scargle analysis, the time required to differentiate between two similar signals may be less than those stated above.
Figure 1. Variation of (a) magnetic periods and (b) amplitude ratio with time. In Figure 1a red lines correspond to the southern magnetic period and the blue line corresponds to the northern period. The dotted lines in both plots indicate values determined in Andrews et al. [2012], and the crosses represent ten 150 day fits to the five-parameter model described in Provan et al. [2013]. The solid lines indicate regions where linear fits to the phase data were used while the dashed lines show regions where the southern phase was linearly interpolated between solid line regions. The gray shaded regions marked B and C are two of the three regions of interest discussed in this work. Figure adapted from Provan et al. [2013].

Altogether, although major advances have been made in separating the subtle differences between northern and southern magnetic and radio periods, the Saturn equinox and the subsequent time has proved difficult and different analysis procedures for radio and magnetic field data have provided apparently different period structure. Cleaving firmly on the idea that the SKR and magnetic period patterns are the same, we propose further refinement of analysis of the magnetometer data.

1.1. The Current Work
Here we intend to build on the work of Andrews and Provan in identifying the northern and southern frequencies. We use the frequencies and phase that they have derived as a reference for investigating the nonsinusoidal nature of the signals. The amplitudes and periods found by Andrews et al. have been identified by narrow band filtering of the magnetometer data. They use a 5–20 h Lanczos band-pass filter to isolate the \( \sim 10.7 \) h oscillations in the magnetic field observations and then fit a sinusoidal function. This function takes into account the local time of the spacecraft and the polarization of the magnetic field components, which differ for sources in each hemisphere. The extreme filtering employed by Andrews and Provan is suitable in discerning and distinguishing the preequinox signals with the aide of a priori knowledge of the magnetic field component polarization and the well-defined SKR periods and phases being used as guides. One caveat of such filtering, however, is that it renders the magnetometer time series into a sinusoid—a good first-order approximation for core region, preequinox magnetic field observations when assuming that the frequencies change slowly with time (on the order of the spacecraft orbits). This approximation is less useful for observations farther from Saturn or after equinox, as we shall show in this study.

We use the Andrews et al. results to investigate aspects of the signals hidden by the filtering. We shall show that the signals show every sign of being periodic with two basic frequencies, but they are in many regions nonsinusoidal. In particular, we distinguish behavior in the dipolar magnetosphere and the radially extended “tail” region. In section 2 we discuss the use of phase as a coordinate. We introduce our observations in section 3 and present our results in section 4. In section 5 we discuss the limits of the Andrews and Provan method. The implications and conclusions of this work are discussed in section 6.

2. Saturn’s Magnetic Rotation Phase
In any rotating system, phase is a natural coordinate. What is novel in the Saturn system is that the magnetic field can contain signals apparently rotating at two different rates. The result is that there are three closely linked rotating phases that we need to treat, the basic northern and southern signal phases (which we derive from the results of previous work), and where the magnetic field contains signals from both sources, one also needs to consider the phase with respect to the beating signals.

The general form of the magnetic phase employed herein for analysis of the magnetic data is given by

\[
\Phi(t, \phi) = \Omega(t)t - \phi.
\]
where $\Phi$ is magnetic phase in cycles, $\Omega$ is the angular frequency in days$^{-1}$, $t$ is time in days, and $\phi$ is the local time (LT) of the spacecraft. The subscript $i$ identifies the three different phase possibilities, i.e., northern ($\Omega_n$), southern ($\Omega_s$), or the mean ($\Omega_m$), where the mean $\Omega_m$ is given by

$$\Omega_m(t) = \frac{\Omega_n(t) + \Omega_s(t)}{2}. \quad (2)$$

The basic northern and southern frequencies, $\Omega_n(t)$, $\Omega_s(t)$ that we shall use in the paper are obtained from the time-varying Kronian magnetic periods determined by Andrews et al. [2012] and Provan et al. [2013].

The term - $\phi$ in equation (1) represents the rotating aspect of the signals independent of the spacecraft angular velocity with respect to Saturn. That $\phi$ orders the data so well shows that the signals do indeed rotate in the sense of planetary rotation (eastward). It should be recognized that the -10.7 h period signals do appear to exhibit a radial phase variation that was first noted by Espinosa et al. [2003] and quantified by Arridge et al. [2011] and Provan et al. [2012]. It is small but its effect will appear in some of the data shown. We make no attempt to assimilate this dependence although we will discuss it in section 4 of the paper.

2.1. Beating Signals

Saturn appears to possess two magnetic signals oscillating with similar frequencies. It is thus natural to consider how these similar signals interact with each other. The presence of two magnetic signals is in line with previous work [e.g., Andrews et al., 2012; Provan et al., 2013; Southwood and Cowley, 2014]. One might ask whether similar modulation of the magnetic signals could be achieved using more than two source signals. It cannot be ruled out, but the specific hemispheric difference between signals detected by Gurnett et al. [2009], Southwood [2011], and Andrews et al. [2012] suggest that before pursuing any possibility we exhaust what can be learned from the simplest option. The interaction between two such signals will result in constructive and destructive interference manifesting in beats. The effects of beats on the north and southern magnetic oscillations have been discussed at length in Andrews et al. [2012] and Provan et al. [2013]; therefore, here we briefly summarize the theoretical effects of interference between the two magnetic signals. We pay particular attention to the effect of beats on the mean (frequency) oscillation between the northern and southern signals, as is applicable post-equinox where the magnetic oscillations possess comparable frequencies and amplitudes.

Let us first consider the addition of two separate cosine waves with frequencies $\Omega_1$ and $\Omega_2$, time-dependent amplitudes $S_1(t)$ and $S_2(t)$, and phases $\phi_1$ and $\phi_2$,

$$S(t) = S_1(t) \cos(\Omega_1 t + \phi_1) + S_2(t) \cos(\Omega_2 t + \phi_2). \quad (3)$$

For consistency with previous studies [Andrews et al., 2012; Provan et al., 2013; Jia and Kivelson, 2012], we now assume the special case where $S_1(t) = 1$ and $S_2(t) = k$. If we rearrange equation (3) in terms of the difference between frequencies $\delta \Omega = \Omega_2 - \Omega_1$, $S(t)$ becomes

$$S(t) = A(t) \cos(\Omega_1 t + \kappa(t)), \quad (4)$$

where $A(t)$ and $\kappa(t)$ are given by

$$A(t) = \left[1 + k^2 + 2k \cos \delta \Omega t\right]^\frac{1}{2}, \quad (5)$$

$$\kappa(t) = \tan^{-1}\left[\frac{k \sin(\delta \Omega t)}{1 + k \cos(\delta \Omega t)}\right]. \quad (6)$$

If we were to use the mean frequency as the base, then $\kappa(t)$ would be given by

$$\kappa(t) = \tan^{-1}\left[\frac{(1-k) \sin(\delta \Omega t)}{(1+k) \cos(\delta \Omega t)}\right]. \quad (7)$$

In equation (4) $A(t)$ represents the time-dependent amplitude of the combined waveform over the period $2\pi/\delta \Omega$ and $\kappa(t)$ represents the time-dependent phase shift from the $\Omega_1$ wave over the same period.
The variations of $k$ for different amplitude ratios $k$ over the period $2\pi/\delta\Omega$ are shown in Figure 2. Figure 2a shows that for $k \ll 1$ there are small phase shifts (~30°) due to the interference of the two waveforms. Provan et al. [2011] refers to this as the phase “jitter” associated with the superposition of the northern and southern signals. Figure 2b also shows how $\delta$ varies with the amplitude ratio but now using the mean frequency as the base. Clearly evident is the half cycle jumps in phase as $k$ approaches unity.

Now we focus on the case when $k = 1$, i.e., both waves have equal amplitudes. Adding these two waves results in a combined waveform with a carrier frequency equal to the mean of the two sine waves $\Omega_m$ and the envelope frequency equal to half the beat frequency $\Omega_B = \Omega_2 - \Omega_1$. The combined waveform in equation (4) now simplifies to

$$\cos \Omega_1 t + \cos \Omega_2 t = 2 \cos \Omega_m t \cos \frac{1}{2} \Omega_B t,$$

which is obtained using standard trigonometric identities. Figure 3 shows how a signal with frequency equal to $\Omega_m$ is modulated by the difference between frequencies $\Omega_1$ and $\Omega_2$. Note that we have normalized the combined waveform to make the maximum amplitude equal to unity. During half of the beat cycle (180°) the combined waveform (equation 8) is in phase with the mean waveform (the mean waveform has a frequency equal to $\Omega_m$). In the other half of the beat cycle the combined waveform is now in antiphase with the mean waveform. This phase jump occurs at a beat node where the waveforms amplitude is minimized. The 180° phase jump only occurs with respect to the mean waveform (see $k = 1$ in Figure 2b); there is a phase shift with respect to the two original waveforms but this is gradual (see $k < 1$ in Figure 2b).

3. Fluxgate Magnetometer Observations

Data from the Fluxgate Magnetometer instrument (MAG) [Dougherty et al., 2004] on board the Cassini spacecraft are used throughout this study. In particular, we use nightside data obtained while Cassini was in Saturn’s equatorial plane (which also means that the magnetic latitude is small). Andrews et al. [2012] shows that both the northern and southern magnetic signals are normally found to be present here. The intervals studied are 2006 (day of year (DOY) 1 to 181) and in 2010–2011 (data set 1: DOY 182 in 2010 to 019 in 2011; data set 2: DOY 045 to 229 2011). These data were obtained from either side of the Kronian equinox (August 2009). This, in addition...
to investigating the magnetic field structure and phase in the equatorial plane, allows us to compare how conditions differ with Saturn’s seasons where the spacecraft is located either below or above Saturn’s current sheet (see Figure 4b below). For brevity we assign the labels A, B, and C respectively to the 2006, 2010–2011, and 2011 intervals being investigated here.

Figure 4 shows the Cassini spacecraft’s trajectory in the Kronocentric Solar Magnetospheric coordinate system (gray), which is centered on Saturn with the positive $X$ axis pointing toward the Sun, the $Z$ axis is chosen such that the $X-Z$ plane contains Saturn’s magnetic dipole axis, with positive $Z$ pointing northward, and the $Y$ axis completes the orthogonal set, with positive $Y$ toward dusk. Figure 4a shows the trajectories in the $X-Y$ plane while Figure 4b shows the same trajectories but in the $X-Z$ plane. The blue lines indicate the outbound passes from period A and the red lines the inbound passes from periods B and C. A model magnetopause boundary obtained using a solar wind dynamic pressure of 0.02 nPa which gives a typical subsolar magnetopause standoff distance of $\sim 22 R_S$ is also shown in black [Kanani et al., 2010]. At first glance, these orbits yield good sector coverage between dusk and dawn but it is worth adding caution to this as these orbital intervals are separated by 4 years and occur at different Kronian seasons (see Figure 4b).

Figure 5 shows the residual magnetic field components as a function of day of year (DOY) in the Kronocentric radial, theta, phi (KRTP) coordinate system, where the radial axis points radially outward from the planet, the $\theta$ axis points southward, and the $\phi$ axis is in the direction of planetary rotation. The residual field is calculated by subtracting the internal magnetic field model given by Dougherty et al. [2005] from the magnetometer data, i.e., $d\mathbf{B} = \mathbf{B} - B_{int}$. Figure 5a shows the first 2006 outbound pass and Figure 5b shows the first 2011 inbound pass. The blue, red, and green lines indicate the radial ($r$), $\theta$, and $\phi$ components of the residual magnetic field, respectively. The black lines represent $\pm |d\mathbf{B}|$, plus and minus the magnitude of the residual magnetic field. The inclusion of these traces allows the reader to identify which is the dominant component in any particular region. Each plot has an inset showing the respective normalized magnetic field components. One can immediately see that the passes, which are typical of the time period from which they come, are quite different despite coming from the nightside region.

Let us first consider the 2006 outbound pass (Figure 5a). Near periapsis/closest approach (which occurred at 06:58 on DOY 017 and a radial distance of 5.59 $R_S$), the magnetic field is predominantly in the $\theta$ direction and as Cassini moves outbound the field becomes dominated by the radial component. Clearly evident is that near periapsis all three magnetic field components vary, for the most part, sinusoidally, subsequently transitioning to flat peaks and periodic pulse-like excursions toward zero. In 2006, the spacecraft’s trajectory was in Saturn’s equatorial plane and hence lying below Saturn’s current sheet for sufficiently large distances from the planet [Arridge et al., 2008; Khurana et al., 2009]. The pulse-like changes where the magnetic field...
approaches zero arise from the center of the current sheet moving down near the equatorial plane where the spacecraft was located.

During the 2011 inbound pass (Figure 5b) the field behavior near periapsis is as described for 2006 with sinusoidal oscillations and the dominant field component being $\theta$. The magnetic field structure farther (decreasing in time) from Saturn is noticeably very different from the 2006 example. There is a considerable increase in high-frequency fluctuations and while periodic behavior is evident, it is not as clear as in the preequinox example. The relatively equal displacements of the magnetic field components about zero combined with the high-frequency fluctuations indicate that the Cassini spacecraft is traversing Saturn’s current sheet throughout this inbound pass.

Time, in days, has been used as a common scaling in Figure 5. Let us now examine what happens when we use one of the phases of the $10.7\ h$ oscillations as a coordinate. We shall use this, as indicated earlier, as a basis for setting up the rotating phase of the periods determined by Andrews and Provan. We, therefore, present the same data set as in Figure 5a but now as a function of the time-dependent southern and northern magnetic phases as determined by Andrews and Provan. For clarity and distinction from the SKR phase models in the literature (Kurth et al., 2008; Gurnett et al., 2009; Lamy, 2011) we subsequently refer to the magnetic phase used herein as “AP phase” where the “AP” represents Andrews and Provan.

Figure 6a shows how the $r$, $\theta$, and $\phi$ components of the residual magnetic field vary with southern AP phase (in cycles) for the first outbound pass in 2006. The magnetic field components are shown as a function of AP phase cycles from periapsis where we take the first integer cycle since periapsis and subtract this value from the subsequent phase values in order to begin the plots at zero phase. Figure 6a clearly shows two distinct patterns in the magnetic field components: (i) close to periapsis (cycles 1–3), the field components, particularly the $r$ and $\phi$, exhibit sinusoidal behavior, and (ii) beyond cycle 4 the field shows a pulse-like structure. This pulse-like region shows that magnetic minima (minima in the magnetic field magnitude—black line in Figure 6a) occur periodically, once per cycle, and are in phase. Beyond cycle 7 these magnetic nulls are aligned with integral multiples of southern phase (gray dashed lines in Figure 6a). Figure 6b shows the same data set as Figure 6a but now plotted as a function of northern AP phase. One can clearly see that there is a systematic drift of the periodic oscillations with respect to the integral multiples of AP phase.

Figure 6 demonstrates how using magnetic phase as a coordinate can be used to determine the dominant or governing magnetic period. The magnetic oscillations are in phase with integral multiples of southern...
Figure 6. Magnetic field time series in KRTP coordinates from the first periapsis of 2006. The field magnitude is represented by the black lines while the $r$, $\theta$, and $\phi$ components are indicated by the blue, red, and green lines, respectively. (a) The magnetic field vectors as a function of southern AP phase. (b) The magnetic field vectors as a function of northern AP phase (360$^\circ$ ≡ one cycle). The vertical dashed lines indicate an integer cycle.

AP phase while they drift with respect to the northern AP phase thus indicating that the magnetic field oscillations are governed by the southern AP phase and therefore the southern period.

4. Magnetic Phase Structure

We now present our results concerning the phase and structure of Saturn’s magnetic field. We separate our results into preequinox and postequinox sections in order to highlight the differences that occur with season and which magnetic period is dominant.

4.1. Preequinox

Figure 7 shows how the residual magnetic field components vary as a function of southern AP phase for each outbound pass in interval A (2006). Figures 7a–7c show the $r$, $\theta$, and $\phi$ components of the residual field, respectively. The pass numbers are indicated in Figure 7a. As described before, the residual magnetic field, $d\mathbf{B}$, is obtained by subtracting the Kronian internal field model [Dougherty et al., 2005] $\mathbf{B}_{\text{int}}$ from the 1 min magnetometer observations, $\mathbf{B}$:

$$d\mathbf{B} = \mathbf{B} - \mathbf{B}_{\text{int}}.$$  \hspace{1cm} (9)

For presentation purposes we apply a 1 h phase-conserving low-pass elliptical filter to the data attenuating variations with a frequency higher than 1 h$^{-1}$. We also add a 3 nT offset to each consecutive pass. This in no way affects the conclusions reached in this study. Figure 7d shows the phase of the first current sheet crossing (or approach when the current sheet was not crossed) of the normalized $d\mathbf{B}$ component as a function of southern AP phase. Phases for some cycles are missing as it was not possible to determine a current sheet crossing with a suitable level of confidence due to gaps in the data. It is worth noting that individual measurement error bars are difficult to quantify, but the mean standard deviation of the determined phases is shown in Figure 7d.

Inspection of Figure 7 shows the sinusoidal nature of the field components up to AP phase cycle 3 corresponding approximately to an equatorial radial distance of $\sim 12 R_S$. Beyond AP phase cycle 5 the field is no longer represented by a sinusoid but by periodic “pulse-like” excursions from a steady field. A transition region between sinusoidal behavior and pulse-like behavior is evident between AP phase cycles 3 and 5. Consecutive passes in Figure 7 show very similar magnetic field structure and phase; in particular, the “pulse-like” excursions consistently occur at integral multiples of southern AP phase. These pulses in the magnetic field were found to coincide with increases in plasma density and have been interpreted as Saturn's current sheet traversing the spacecraft once per southern cycle [Arridge et al., 2011]. Such current sheet oscillations or “flapping” have also been observed in Carbary et al. [2008], Provan et al. [2012], and in
Figure 7. Perturbation magnetic field components as a function of southern AP phase from the 2006 outbound passes in interval A. The (a) r, (b) θ, and (c) φ components of the perturbation magnetic. (d) The phase of the first current sheet crossing (or approach when the current sheet was not crossed) of the normalized dB, component along with the mean standard deviation of the determined phases. Data gaps or encounters of low confidence are omitted from the plot. The vertical dashed-lines indicate a unit cycle. The colors indicate the pass number in the selected time period.

the MHD models of Jia et al. [2012] and Jia and Kivelson [2012] where the 10.7 h oscillations are a response to rotating vortices in the neutral atmosphere. The observed flapping is found to be asymmetric about the equatorial plane, i.e., the current sheet moves from its solar wind flow-aligned position [Arridge et al., 2008] to Saturn's equatorial plane once per cycle [Khurana et al., 2009; Arridge et al., 2011; Provan et al., 2012]. This asymmetry doubtlessly results from the presence of rotational periodicity in the Kronian system, but the origin is still under debate. We propose that the distinct change in the time signature form of the signals in the inner and middle magnetosphere could not simply be due to say an atmospherically imposed signal but that there is also likely to be some form of periodic magnetospheric stress release occurring in the magnetotail, which collapses the current sheet to Saturn's equatorial plane. The mechanism for this shall be the focus of a future study.

We observe a small phase lag in the final pass of interval A compared to the previous passes (see magenta line in Figure 7d). We attribute this lag to the fact that this outbound pass traveled deep into the distant magnetotail (60 + Rs) before crossing midnight. The distances traversed by the spacecraft would require us to take into account how the radial propagation delay of the magnetic oscillations affect phase, which according to Provan et al. [2012] and Arridge et al. [2011] ranges between ~2 and 7° Rs^{-1}. The magnetic phases employed herein do not take into account this radial propagation and as such is likely to be the cause of the discussed discrepancies. This radial propagation delay is also manifested in the increase in phase with southern AP cycles of each current sheet crossing (see Figure 7d), if this delay was to be taken into account one would expect that the phase would be fairly constant for each pass with a significant decrease in the mean standard deviation presented. The employed AP phases were determined for Saturn's inner magnetosphere (<12 Rs) where the radial propagation delay is thought to be negligible [Andrews et al., 2012].

Figure 7 shows that there is minimal drift between the consecutive outbound passes in interval A, which suggests that, in this interval, the magnetic field oscillations are governed solely by Saturn's southern magnetic period. This is consistent with the works of Andrews et al. [2012] and Provan et al. [2013] who show
Figure 8. Perturbation magnetic field components as a function of mean AP phase from the 2010–2011 inbound passes (interval B). The (a) $r$, (b) $\theta$, and (c) $\phi$ components of the perturbation magnetic. The vertical dashed lines indicate a unit cycle. The colors indicate the pass number in the selected time period. The black arrow highlights the drift direction.

that for this period of interest the dominant magnetic oscillation period is that of the southern hemisphere. Such observations exemplify the long-term phase coherence between the magnetic field components and the southern magnetic oscillation phase.

4.2. Postequinox

The post-equinox observations are separated into two intervals. Interval B (DOY 182 in 2010 to DOY 018 in 2011), which encompasses a period where Provan et al. [2013] finds that the amplitude ratio $k$ between the northern and southern oscillations is approximately one, indicating there is no favored dominance between either magnetic oscillation. Interval C (DOY 045–229 in 2011) is a period that Provan et al. [2013] identifies as being governed by the southern oscillations with $k \sim 0.3$. Intervals B and C are shaded gray in Figure 1.

Given the equal amplitudes of both oscillations in interval B, one would expect that the magnetic oscillations would be governed by the mean frequency or period. Figure 8 shows the perturbation magnetic field components for inbound passes during interval B as a function of mean AP phase. The format of the figure is as in Figure 7 (without Figure 7d) except that phase cycles are now negative, indicating inbound data. In section 3 we defined zero AP phase as the first integer phase after periapsis; here for inbound observations, zero AP phase is taken as the first integer cycle before periapsis. These observations clearly show a different field structure to that presented in Figure 7 for interval A; magnetic field oscillations are periodic and sinusoidal for a greater range of phase and there are no clear “pulse-like” signatures evident. Focusing on Figure 8a, showing $dB_r$, a significant and systematic drift (toward the right or backward in phase as highlighted by the black arrow) in magnetic oscillations is evident with each consecutive pass. The direction of the slope (see arrows in the figure) indicates that the dominant frequency is lower than that of the mean frequency, indicating that the magnetic oscillations are not governed by this signal.

Having showed above that the magnetic oscillations are not governed by the mean period, we now present the same data set as a function of the northern AP phase followed by the southern AP phase. Figure 9 shows the same data set as Figure 8 but now as a function of northern AP phase. Similarly to the mean AP phase, the northern phase leads to a systematic drift toward the right but with a larger slope compared
Figure 9. Perturbation magnetic field components as a function of northern AP phase from the 2010–2011 inbound passes (interval B). The (a) $r$, (b) $\theta$, and (c) $\phi$ components of the perturbation magnetic. The vertical dashed lines indicate a unit cycle. The colors indicate the pass number in the selected time period. The black arrow highlights the drift direction.

to the mean frequency. The residual magnetic field components are presented in Figure 10 as a function of apparent southern AP phase (now including Figure 7d). The field oscillations now show a consistent field structure and minimal, if any, drift with each consecutive pass, suggesting that the magnetic field oscillations are well organized and governed by the southern magnetic AP phase. This is in contrast with the equal or no hemispherical dominance determined in Provan et al. [2013].

Upon further inspection of the interval B observations in Figure 10 (plotted versus apparent southern AP phase) one will notice that the oscillations within the first six passes are in phase, while the eighth pass is in antiphase with the rest as clearly indicated by the black arrow in Figure 10a or the phases of the current sheet crossings in Figure 10d. The seventh pass also has relatively small amplitude to its oscillations. This 180° phase jump either side of a “minimal amplitude” pass is characteristic of the beating signals discussed in section 2.1. The key factor being that the 180° phase jump discussed above only occurs when the mean frequency is used. The singular/pure signals propagate throughout the beat cycle without a sudden flip in phase. This 180° phase jump is seen in all three figures pertaining to interval B suggesting that the apparent southern and northern AP phases used herein and determined by Andrews and Provan interfere with each other. It is worth noting that in typical Cassini magnetometer time series there is little visual evidence of a modulating envelope resulting from the beating of the northern and southern oscillations. This is likely due to the variation in amplitudes of the northern and southern magnetic oscillations as seen in Andrews et al. [2012] and Provan et al. [2013], making it difficult to obtain an easily observable modulation. The “phase jitter” described in Provan et al. [2011] and the 180° phase jumps presented herein are the only evidence of beating between the northern and southern magnetic signals to date.

If, as the observations suggest, the southern AP phase in interval B is actually more representative of the “mean” AP phase and we assume that the northern AP phase is correct and free from southern interference, we can estimate a “refined” southern phase which should show a systematic phase drift in the opposite direction to that of the northern and mean AP phases (leftward in figures or forward in phase). This refined southern phase, given by $T_{m} = (T_{N} T_{M}) / (2 T_{N} - T_{M})$, is used in Figure 11, which shows the same
Figure 10. Perturbation magnetic field components as a function of southern AP phase from the 2010-2011 inbound passes (interval B). The (a) \( r \), (b) \( \theta \), and (c) \( \phi \) components of the perturbation magnetic respectively. (d) The phase of the first current sheet crossing (or approach when the current sheet was not crossed) of the normalized \( dB \) component along with the mean standard deviation of the determined phases. Data gaps or encounters of low confidence are omitted from the plot. The arrow and black dashed ellipse highlight the phase jump to be discussed. The vertical dashed lines indicate a unit cycle. The colors indicate the pass number in the selected time period.

Perturbation magnetic field observations as in Figure 8. The predicted, systematic leftward drift in the magnetic field components can clearly be seen. The corresponding refined southern period used in this calculation is 10.71 ± 0.02 h, ∼1.5 min larger than the average southern period determined by Provan et al. [2013] for this interval. Note that the error on this refined value is based on the standard deviation of the magnetic periods in interval B.

Let us now consider the interval C, where the amplitude ratio determined in Provan et al. [2013] suggests that the magnetic field oscillations are governed by the southern period (\( k \sim 0.32 \)). Figures 12a–12c show how the perturbation magnetic field components vary with southern AP phase for interval C (in 2011). The figure format is as in Figure 10 except that in Figure 12d the phase of the current sheet crossing is determined using the normalized \( dB_\phi \) component as it was the clearest one. The field structure of these observations are well organized by the apparent southern AP phase but there are also two 180° phase jumps (indicated by the arrows) and one minimal-amplitude pass. This is once again reminiscent of a mean frequency signal beating suggesting that the apparent southern magnetic AP phase employed here contains interference from the northern oscillations. The implication of these findings will be discussed in section 6.

We have observed three 180° phase jumps: one in interval B and two in interval C. The beat period determined for interval B is ∼180 days which is comparable with the length of this interval and as such one would expect at least one beat node to be evident. For interval C, the beat period has decreased to ∼70 days, suggesting that we would expect at least two beat nodes with 180° phase jumps during this interval. The phase jump in interval B, however, is coincident with a reported increase in amplitude ratio \( k \) from ∼1.05 to ∼1.33 [Provan et al., 2013] indicating a small transition to northern-governed field oscillations. Assuming that such a transition did in fact occur, it could result in the observed phase jump in this interval. While the above explanation may be plausible for interval B, it is unlikely to apply during interval C where we observe two 180° phase jumps despite Provan et al. [2013] (and Figure 1) clearly showing strong (\( k \sim 0.32 \)) southern
Figure 11. Perturbation magnetic field components as a function of refined southern AP phase from the 2010-2011 inbound passes (interval B). The (a) r, (b) \( \theta \), and (c) \( \phi \) components of the perturbation magnetic. The vertical dashed lines indicate a unit cycle. The colors indicate the pass number in the selected time period. The black arrow highlights the drift direction.

dominance for the entire interval. Another explanation which could result in the discussed drifts is that the AP phases (or frequencies) determined for the drifting passes are incorrect (as in not consisting of a pure or superpositioned frequency). However, if these AP phases are incorrect it is unlikely that we would consistently observe 180° jumps. We are therefore still left with the interpretation that these phase jumps result from a beating signal formed from the superposition of the northern and southern oscillations.

4.3. Seasonal Differences in the Magnetic Field Observations

During intervals A–C the Cassini spacecraft was located in Saturn’s equatorial plane and, for the outbound and inbound passes selected, at similar local times (at least within 20 \( R_S \)). Despite this fact, there are considerable differences in the magnetic field observations as evident in Figure 5. We attribute these differences, in part, to the position of Saturn’s magnetic equator relative to its rotational equator where the spacecraft was located and the nature of the orbits themselves.

In 2006, closest approach occurred around midafternoon (~1500 LT) after which the spacecraft proceeded into Saturn’s magnetotail before crossing midnight. The spacecraft was located below Saturn’s tilted current sheet throughout this interval and spent a significant period of time within the magnetotail region. This means that the spacecraft encountered three distinct magnetospheric regimes: (i) the inner dipolar region with sinusoidal behavior, (ii) the radially extended magnetotail with pulse-like behavior, and (iii) a transition region between the inner region and the magnetotail with some combination of both. The pulse-like behavior is interpreted as the current sheet moving down onto the spacecraft once per Kronian rotation. On the other hand, the inbound passes of 2011 originated at apoapsis in the dusk and late afternoon sector and ended at periapsis in the early morning sector (~0400–0600 LT). At these local times and radial distances, Saturn’s magnetosphere was not radially extended but instead compressed by the solar wind dynamic pressure that kept it, at the very least, in a quasi-dipolar state. The nature of the 2011 orbits combined with the fact that Saturn’s current sheet was located in the ecliptic plane after equinox means that after exiting the inner region, Cassini never really entered the magnetotail proper and thus did not see any pulse-like
magnetic field behavior. The behavior observed by the spacecraft was instead periodic and quasi-sinusoidal with a large amount of high-frequency fluctuations from the multiple current sheet crossings.

5. Applicability of the AP Method

Plotting magnetometer observations against magnetic oscillation phase for the postequinox intervals suggests that the AP method is approaching the limits of its applicability. The method performs very well preequinox where as Figure 7 shows, the coherence between the magnetic field components and southern AP phase lasts over 180 days. During interval A the magnetic periods are well separated (∼12 min) with ΔΩ/Ω ∼1/50—meaning that after ∼50 cycles there is a one-cycle difference between the northern and southern signals. This is considerably shorter than Cassini’s orbital period of ∼40 days (∼80–90 cycles), which in combination with (i) the SKR phases being well defined and used as guides and (ii) the field structure within the core region being, to first-order, sinusoidal means that the approach used by Andrews and Provan could be used to reliably infer the phases of the magnetic oscillations.

The published postequinox SKR phase data set is limited and still being debated as to whether the two signals coalesced together or crossed each other and therefore cannot be used as guide phases. The magnetic field structure is also complicated by the amount of time the spacecraft spends traversing the current sheet. As seen in the postequinox figures (Figures 5, 10, and 12), the field structure in the core region is not always as sinusoidal in intervals B and C as it is in interval A. Therefore, the 5–20 h band-pass filtering employed in the AP analysis may significantly alter the magnetic field observations before they are used in their fitting procedures. Without prior knowledge of the form of a signal (e.g., its coherence length) or the form of the power spectrum (e.g., power law or Gaussian) or some other dependence, there is an inherent uncertainty (or ambiguity) in defining frequency depending on the time scale on which the signal is observed. Moreover, if there are gaps in the data some assumption about the persistence of phase must
Figure 13. Effect of filtering on two 10.7 h waves. (a) The effect on a square wave and (b) the effect on a sine wave. The black line indicates the original waveform while the red and blue lines represent 5–20 h and 1–30 h band-pass filtered waveforms.

be made. The Lomb-Scargle technique for example works with high persistence of phase (high coherence length). Techniques like wavelet analysis work in the opposite limit. The Andrews work belongs in the first category where the frequency itself is assumed to vary on a slow timescale compared with the instantaneous period. It cannot be ruled out that there are sudden changes in phase but the filtering used inherently limits their detectability. Our use of phase eliminates some of the doubt by allowing for departures from sinusoidal behavior, but our use of the AP work to give our background phases itself means we are tied to the notion of dual period signals. However, we regard the clear ordering of the data by our procedure as evidence that the slowly varying dual period model is a sound starting point. We next demonstrate the effects of filtering to illustrate what can and cannot be done.

Figure 13 shows the effect of the filtering employed in the Andrews and Provan analysis on two extreme examples: (a) a 10.7 h square wave and (b) a 10.7 h sine wave. The black line shows the base waveform, while the red and blue lines show the waveforms after being band-pass filtered by 5–20 h and 1–30 h, respectively. The smoothing of the waveform caused by the 5–20 h filter is clearly visible, as both the square and sine waves now appear sinusoidal. This filter had no significant effect on the amplitude of the sine wave but decreased the amplitude of the square wave by \( \sim 20\% \). Nonetheless, phase is conserved and this would not happen if the signals were asymmetric with a cycle. The 1–30 h filtering, just shown for comparison, has a more modest effect on the square wave—preserving its pulse-like structure. However, the amplitude of the square and sine waveforms increased by \( \sim 45\% \) (positive portion only) and \( \sim 15\% \), respectively, due to the 1–30 h filter. The 5–20 h band-pass filter thus removes key information from the square wave. Such extreme filtering applied to magnetic field observations after equinox and outside the core region will, in turn, reduce the reliability of any fitting routines subsequently applied to the data.

The postequinox separation period between the northern and southern magnetic oscillations decreased to \( \sim 3.5 \) min resulting in \( \Delta \Omega/\Omega \sim 1/200 \). The two signals, thus, only become separable after \( \sim 200 \) cycles of observations. This coupled with the reduced reliability caused by the extreme filtering employed by Andrews and Provan imply that the orbit-to-orbit (\( \sim 20 \) day or \( \sim 45 \) cycles) changes discussed in Provan et al. [2013] are unlikely to be detectable or, at the very least, not attributable to actual phase changes in the magnetic oscillations.
6. Concluding Remarks

In this paper we have examined Cassini magnetometer data by ordering the data against various forms of magnetic rotation phase. In particular, we have used the frequency determinations of Andrews et al and Provan et al (AP) and the resultant northern and southern rotation phases to examine the magnetic field behavior as a function of respective phase. We have also introduced the use of the mean phase in a similar way.

We selected intervals where Cassini makes long sequences of nightside passes in 2006 before equinox (in mid-2009) and 2010 and 2011 after equinox. Although the northern and southern signals are believed to have separate northern and southern sources and to be pure in the polar caps, one expects the signals to be mixed on the passes chosen which lie in Saturn’s equatorial plane.

We have shown that over extended periods of time the signals are well ordered by one of the magnetic rotation phases whether or not the signals are close to sinusoidal. However, in the postequinox data intervals, AP indicate that the northern and southern periods are close and it is here that we see effects characteristic of being near the limits of determinability. In particular, we have used stacked plots to illustrate that signals can remain in phase for long periods but sudden 1/2-cycle phase changes then occur. Such changes are characteristic of wave beating where signals have similar amplitudes (in practice, the amplitude ratio, $k > 0.6$). Stable phase followed by a sudden shift would be expected only when the mean phase is being used as the basis. Global MHD modeling presented in Jia and Kivelson [2012] also shows 1/2-cycle phase jumps in the perturbation magnetic field components associated with the beating between the northern and southern oscillating signals. These jumps were evident with respect to the mean oscillating frequency (taken to be 10.7 h in their simulation). If other base phases were to be used, there would be a slow drift, whose speed depends on the difference of the base frequency to the mean. Accordingly, the anomalous phase behavior means that more work with our approach should allow refinement of the time variation in both periods and amplitudes of the northern and southern signals. This could involve treating the AP phases as “guide phases” and applying a correction (phase shift) to each pass, in order to ensure or preserve phase coherence over the desired interval. It would then be possible to determine a corresponding period and comparing this to magnetic field observations using our approach and to recent postequinox SKR periodicities [Fischer et al., 2014]. This refinement of the magnetic periods is the aim of a future study.

The discovery that Cassini’s magnetic field data are well organized by magnetic rotation phase is in itself important. The base periods (and thus phases) have been derived by AP using a relatively narrow band filtering, and any other method to getting base phases is difficult to envisage. However, we show that the magnetic field signals do not always appear to be sinusoidal, particularly in the nightside 2006 passes. The regularity of the behavior revealed by the ordering can be used to deduce spatial structure assuming a particular magnetodisc model [e.g., Khurana and Schwarzl, 2005; Arridge et al., 2011; Carbary, 2013]. For example, phase coherence (using AP southern phase) is maintained for more than 6 months of orbits in 2006; during which the apoapsis of the orbit rotated through ~4 h. This regularity means that a large part of what is observed is a rotating feature and thus would be a stationary spatial feature in the rotating frame. There is an important implication from the very nonsinusoidal form of the repetitive signal once the spacecraft is outside the dipolar field region of the magnetosphere. The signature is not consistent with the current sheet at the center of the tail simply flapping up and down, symmetrically about the equatorial plane. In 2006, Saturn was in southern summer. The spacecraft was in the equatorial plane of the planet and so in the deep tail one expects the mean current sheet to be above (north of) the spacecraft [Arridge et al., 2008; Khurana et al., 2009]. Therefore, one would not expect the radial component of the field to fully reverse as might be expected if the current sheet were flapping symmetrically about the equatorial plane.

The dynamical reason for expecting the spacecraft to be below the current sheet is that, far from the planet, the solar wind dynamic pressure causes the tail to align parallel to the antisolar direction. Near the planet, where the forces associated with the planetary field are dominant, the current sheet should align with the equatorial plane (where the spacecraft is located) due to centrifugal forces [Arridge et al., 2008]. The pulses occurring once per rotation change the magnetic field orientation indicating that there is a change in the direction of the stress. The solar wind-dominated stress is replaced by a stress corresponding to forces in the radial direction. This takes place over a small fraction of a cycle as shown in Figure 5a, where the magnetic field structure is typical of this interval. It is very difficult to see how such a local stress reconfiguration could be maintained statically in the rotational frame. Were the multiple current sheet encounters in 2006...
due to a warping associated with a standing Alfvén wave (similar to the “balletina skirt” structure of the heliospheric current sheet) the observations would suggest a rapid growth in oscillation amplitude with distance down tail. In this interval the spacecraft appears to skim the current sheet even at equatorial radial distances of ~30–40 $R_S$ (see Figure 5a where the radial distance increases from 5.59 $R_S$ at periapsis to ~46 $R_S$ on DOY 24). If, for example, the current sheet were hinged at ~25 $R_S$ [Arridge et al., 2008] with the magnetospheric tilt being ~20°, as was the case in 2006, the displacement amplitude for current sheet encounters at 30 $R_S$ would be of the order 2–3 $R_S$ during this interval. Therefore, at 40 $R_S$, a similar encounter would require an increase in the displacement amplitude by a factor of 3 giving amplitudes of 6–9 $R_S$. It seems more likely that the short displacements of the current sheet, in each cycle, from the Arridge-warped sheet position to the equatorial plane are associated with a cyclic dynamic effect. The hinging point is where solar wind stress starts to dominate the centrifugal forces associated with the planet. A cyclic “flip” or collapse of the current sheet into or near the equatorial plane suggests a cyclic enhancement of the centrifugal planetary stress. As such, the structure is likely to be due to a dynamic effect. A possible explanation is that the spacecraft is encountering in every cycle a region where material in the distant tail is escaping (plasma and energetic particle observations are needed to test this). Escaping material would imply eventual breaking or reconnection of the flux tubes. However, one should note that for the centrifugal effect to be significant the material must still be magnetically connected to the planet. Reconnection is not occurring near the spacecraft.

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