

Spinning, Breathing, and Flapping: Periodicities in Saturn's Middle
Magnetosphere

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Key points

1. Equatorial plasma and field moments in the core region are modulated at the SKP period.
2. The peak phase of observed plasma properties depends on the location of measurement.
3. Periodic changes in the magnetosphere can be described as spinning, breathing, and flapping.

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Abstract

In Saturn's magnetosphere, ubiquitous fluctuations with a period of ~ 10.7 hours have been observed in Saturn Kilometric Radiation (SKR), auroral emissions, the magnetic field, the electron density, and energetic particle fluxes. Here we characterize previously unstudied periodicities in plasma properties inside of $15 R_S$ near the equatorial plane. Although periodically varying magnetic perturbations rotate relatively smoothly (*spinning*), plasma properties do not. The phase of the peak value of plasma density or pressure perturbations can change substantially across a few hours of local time or R_S . As a means of interpreting observations, we use a magnetohydrodynamic simulation that generates field-aligned currents centered at 70° invariant latitude in Saturn's southern ionosphere and rotating at the SKR period. The simulation reproduces many periodic features of the data including not only spinning perturbations but also global scale compression and expansion (*breathing*). Simulated plasma properties are also modulated by periodic large scale north-south motion (*flapping*) in regions beyond ~ 15 Saturn radii (R_S), which we do not analyze here. Inside of $15 R_S$, plasma responds to a superposition of spinning and breathing at the spin period, developing perturbations that peak at

different phases depending on what is measured and where. Strong compressional effects act impulsively over a limited range of rotation phase. Superposition of local and global scale variations produces phase jumps across short distances and can introduce multiple peaks in the variation of plasma properties within one rotation period, accounting for anomalies in the phase-dependence of periodic fluctuations identified in the sparse data available.

Index Terms and Keywords: Ionosphere: Ionosphere/magnetosphere interactions (2736), Magnetospheric Physics: Planetary magnetospheres (5443, 5737), Planetary Sciences: Solar System Objects: Saturn (6275)

1. Introduction

Periodicities in magnetic and plasma properties attributable to a tilt between the spin axis and magnetic dipole axis are observed at both Earth and Jupiter. Unlike Jupiter and Earth, Saturn has an internal magnetic field that is remarkably axisymmetric; the tilt of the dipole axis is no larger than 0.06° [Cao *et al.*, 2011]. Correspondingly, one might not expect Saturn's magnetosphere to exhibit diurnal periodicities. Strangely, periodicities near the planetary rotation period (varying between 10.6 and 10.8 hours) in the radio frequency power, the magnetic field, and plasma phenomena are evident throughout Saturn's magnetosphere [Carbary and Mitchell, 2013].

Periodicities in Saturn's Kilometric Radiation (SKR) were originally observed in the Voyager era [*Kaiser et al.*, 1980; *Desch and Kaiser*, 1981; *Warwick et al.*, 1981].

Voyager's measurement of the SKR showed an enhancement in power with an average period of 10h 39m 22 s, which was adopted by the IAU as Saturn's internal rotation period. However, measurements with Ulysses and, later, Cassini, showed that the SKR period was changing on the order of $\sim 1\%$ per year, shattering the notion that the oscillation was tied to the internal rotation of the planet [*Gurnett et al.*, 2005; *Kurth et al.*, 2007, 2008]. Even more puzzlingly, analysis shows that emissions from the northern and southern hemispheres are modulated at different periods [*Gurnett et al.*, 2009a].

Periodicities at the SKR frequency have also been observed in auroral hiss [*Gurnett et al.*, 2009b], ultraviolet (UV) auroral emissions [*Nichols et al.*, 2010a and b; *Provan et al.*, 2009b; *Carbary*, 2013], north-south displacement of the equatorial current sheet [*Khurana et al.*, 2009; *Arridge et al.*, 2011], commonly referred to as *flapping*, energetic electron and neutral atom fluxes [*Carbary et al.*, 2008, 2009; *Paranicas et al.*, 2005b], the location of the magnetopause [*Clarke et al.*, 2006, 2010a and b; *Pilkington*, 2015], and the plasma electron density [*Gurnett et al.*, 2007]. The changing location of the magnetopause is associated with periodic global scale compression and expansion, a feature that is well represented in the magnetohydrodynamic simulations of *Jia et al.* [2012] and *Jia and Kivelson* [2012]. We refer to this expansion and contraction of the

large portions of the magnetosphere as *breathing*, even though the term is inexact because the change of scale is not simultaneous throughout the system.

Perturbations in the magnetic field are also well organized by the SKR period [Southwood and Kivelson, 2007; Andrews, et al., 2008; Provan, et al., 2011; Provan, et al., 2012]. In the core magnetosphere (the dipolar and quasi-dipolar equatorial region inside of 12-15 R_S), the magnetic perturbations rotate almost rigidly, so we allude to their periodic variation as *spinning*. The azimuthal perturbations of the magnetic field lag the radial perturbations by 90° . When organized by the southern SKR period, the radial and colatitudinal perturbations exhibit an in-phase modulation. When organized by the northern SKR period, the radial and colatitudinal perturbations are out of phase [Andrews et al., 2008; Provan et al., 2009a]. Neither the azimuthal nor radial perturbations of the magnetic field vanish at the magnetic equator [Southwood and Kivelson, 2007].

Periodicities of ion plasma moments in the middle magnetosphere have not previously been reported. In this study we analyze plasma parameters in Saturn's ring current region using data obtained between October, 2005 and June, 2006 from 6 to 15 R_S and very close to the equator to determine if plasma pressure and ion density perturbations are organized by the SKR period, as are magnetic perturbations. We find that the equatorial plasma density and pressure vary periodically within 15 R_S but the perturbations do not remain at the same phase relative to the magnetic perturbations across all radial and local time locations. We use the simulation by Jia et al. [2012] to

help us interpret the observed periodicities in the middle magnetosphere, finding that they arise from a superposition of two types of periodic responses to a single driver, spinning and breathing. The combined responses produce wave forms that are periodic, but not sinusoidal, in some cases having multiple peaks and troughs over one 10.8 hour cycle.

In Section 2 we introduce the magnetic field and plasma data and the simulation. In Section 3, we show the results of our analysis, extracting averages of the periodic variations of measured plasma and field properties in selected radial (r) and, where appropriate, local time (LT) bins, comparing the structure of the periodic variations in different bins to each other and to periodicities found in the simulation. In Section 4, we use the simulation to understand the relationships observed in the data. Finally, we summarize our work and present the conclusions in Section 5.

2. Selection and Processing of Data

Our objective is to characterize and interpret periodicities of plasma properties near the equator in Saturn's middle magnetosphere. In this section, we briefly introduce the longitude system used in this study, then discuss the field and plasma instruments and how we obtain the parameters of interest. Next, we explain why we restrict our study to the quasi-dipolar equatorial region of Saturn's middle magnetosphere. Then, we acknowledge aliasing introduced by the spatial distribution of spacecraft orbits, discuss its implications for our analysis, and bin the data into radial bins. Finally, we use the simulation of *Jia et al.* [2012] to suggest how the periodic variations of plasma properties

are likely to vary with local time (LT). Breaking up the data in LT bins suggested by the simulation allows us to interpret some puzzling features of plasma pressure and density variations.

2.1 Phase System

Critical to our analysis is the local time-corrected SKR phase of each measurement. Several longitude systems have been developed based on the periodicity of SKR radiation. We use the Saturnian Longitude System 4 [Gurnett *et al.*, 2011], which has both northern (valid from April 5, 2006 to Jan 13, 2011) and southern (valid from September 12, 2004 to August 3, 2011) components. During the interval used in this study, the northern hemisphere SKR was modulated at approximately 10.6 hours; the southern hemisphere SKR, associated with magnetic perturbations roughly 3 times greater than those at the northern period [Provan, *et al.*, 2011], was modulated near 10.8 hours and was very stable. The lower-frequency (dominant) component of periodicity of SKR power between September 12, 2004 and October 15, 2009 was used to establish the SLS4-S longitude system, which we use to organize the plasma data. In the SLS4 system, the peak of SKR power occurs when the Sun is at a longitude of 100° . Other phase systems [Lamy, 2010; Provan *et al.*, 2009a; Andrews *et al.*, 2010a] define 0° as the direction towards which the magnetic perturbation vector points when the SKR power peaks. Therefore, there is a phase difference between the SLS4 phase system and that of Lamy, Provan, and Andrews. In analyzing the data, we use the Doppler-shifted SLS4 S

phase, which corrects the SLS4-S phase for the LT position of the Cassini Orbiter, as described in *Kurth et al.* [2008], with the acknowledgement that the northern signal adds jitter [*Provan et al.*, 2011]. The correction for the spacecraft LT is imposed because there is evidence that the magnetic perturbation is nearly fixed in a rotating system. We refer to this LT-corrected parameter as "rotation phase." Each data point described below was assigned a rotation phase based on the SLS4-S system [*Gurnett et al.*, 2011].

2.2 Data Selection

Our study uses data from plasma and field instruments aboard the Cassini spacecraft obtained when the spacecraft was in the equatorial region of Saturn's magnetosphere ($-0.5^\circ < \text{latitude} < 0.5^\circ$) between 6 and 15 Saturn radii (R_S). The plasma parameters are provided by two instruments: the Charge Energy Mass Spectrometer (CHEMS) sensor of the Magnetospheric Imaging Instrument (MIMI) [*Krimigis et al.*, 2004] and the ion mass spectrometer (IMS) part of the Cassini Plasma Spectrometer (CAPS) [*Young et al.*, 2004]. The CHEMS sensor measures energetic ions between 3 and 220 keV/e while the IMS instrument samples the thermal plasma properties between 1 eV/e and 50 keV/e. The energy ranges of the CAPS and MIMI ion sensors overlap between 3 and 50 keV, but the overestimation of the plasma pressures due to this overlap is $< 25\%$, well within the scatter in the data [*Sergis et al.*, 2007]. The CAPS moments were calculated based on numerical integration of the observed IMS singles count rates for times when the nominal plasma corotation flow direction was in the field of view of

the IMS [Thomsen *et al.*, 2010]. We included only verified data with no flags, thereby limiting our number of available measurements to 950 points. Hot ion density and pressure data at 5 min resolution for ≥ 3 keV protons (H+) and water group ions (W+) were derived from MIMI/CHEMS and LEMMS data by integration over the energy range from 3 keV to >200 keV [Krimigis *et al.*, 2004; Sergis *et al.*, 2007, 2009]. The densities of H+, He+, and water group ions (W+) were summed in order to obtain ion density. The contribution to the pressure from the thermal ions was calculated from temperature and density. Electron pressures in the inner equatorial magnetosphere are lower than ion pressures by a factor of ten [Sergis *et al.*, 2010] and well within the scatter in the ion observations. Consequently, electron pressures were not included in our analysis of the total pressure. Pressures derived from the CAPS and MIMI instruments are summed in order to determine total plasma pressure. We use one-minute-averaged magnetic field data from the fluxgate magnetometer on the MAG instrument [Dougherty *et al.*, 2004] in order to calculate magnetic pressure. All data were downloaded from the Planetary Data System (PDS).

2.3 Magnetic Pressure

Figure 1 shows the magnetic field data returned from a typical periapsis pass on one of the orbits analyzed. The top panel shows the theta component of the magnetic field in KRTP spherical polar coordinates. The KRTP coordinate system is a planet-centered spherical system referenced to Saturn's northern spin (also magnetic field) axis. The

second panel contains (dB_θ), the residual of the B_θ component of the magnetic field, i.e., the difference between the measured B_θ and the Cassini Saturn Orbit Insertion (SOI) magnetic field model [Dougherty, et al., 2005]. Inside of about 15 R_S , there is a depression in the residual magnetic field. The slowly varying negative perturbation of the averaged dB_θ near periapsis can be accounted for by a symmetric ring current. An eleven-hour running average of dB_θ is plotted in the same panel with a red line. The sinusoidal oscillation with a period near that of the SKR superposed on the ring current signature gives evidence of a rotating asymmetric ring current [Krimigis et al., 2007; Khurana et al., 2009; Provan et al., 2009b; Brandt et al., 2010]. This feature is seen clearly in the blue line, a four-hour running average of dB_θ . We define the difference between the eleven-hour running average and the four-hour running average, i.e. the sinusoidal perturbation associated with the asymmetric ring current, as δB_θ and plot it in the bottom panel.

Inside of 15 R_S , the magnetic field can be well approximated by the SOI model plus perturbations due to the symmetric and asymmetric ring currents:

$\mathbf{B} = \mathbf{B}_{SOI} + \mathbf{dB} + \delta\mathbf{B}$; $|\delta\mathbf{B}| \leq |\mathbf{dB}| \leq |\mathbf{B}_{SOI}|$. The periodic variation of $\delta\mathbf{B}$ has been examined extensively by Andrews et al. [2008; 2010a,b] and Provan et al. [2009a,b]. In comparing with plasma bulk properties, we focus on rotation-phase dependent variations of magnetic pressure, which, to lowest order in the near-equatorial regions, depend on

\mathcal{B}_θ as

$$\delta P_{mag} \approx B_{\theta} \cdot \delta B_{\theta} / \mu_o \quad (1)$$

Magnetic pressure perturbations associated with the asymmetric ring current were calculated for every measurement in our dataset.

2.4 Non-uniform Distribution of Plasma Data

In establishing the rotation phase-dependent variations of ion bulk parameters, we are constrained by non-uniform data coverage of which it is important to be aware. On many of the orbits used in this study, Cassini traversed similar spatial paths (radial distance vs. LT) through Saturn's magnetosphere. Coincidentally, the spacecraft repeatedly returned to the same radial position at almost the same SLS4S phase. In Figure 2, we show where (a) magnetic field and (b) plasma data were acquired in plots of local time vs. radial distance. Each point is colored by local-time-corrected SLS4-S phase (rotation phase). It is clear that large regions of local time are poorly covered in the dataset, especially near dawn and dusk. In addition, the aliasing in radius by rotation phase is easy to see, as the colors at the same radial distance repeat multiple times. For example, predominantly cyan and orange/blue curves indicate that almost all of the data at 6 R_S were acquired at phases between 120° and 240°. At 8 R_S , all of the data were acquired at phases less than 120° and greater than 240°.

Strong coupling between rotation phase and radius can produce misleading results when data that vary strongly in radius are plotted vs. phase. Figure 3 reveals that both the (a) ion density and (b) plasma pressure vary strongly (close to exponentially) with radial

distance over the range of interest so we remove the phase-averaged radial trend before investigating the variation of pressure with rotation phase. The phase-dependent aspects of radial gradients (if any) remain in the data. We obtain the radial trends by fitting second-order exponentials to the data and have plotted the fits over the data in Figures 3a and 3b. Figures 3c and 3d are plots of the differences between the data and the fits to their radial dependence for density and pressure, respectively. The ratios dn/n and dP/P change little with radial distance: the amplitude of the perturbations is roughly 10% of the background. In Section 3, we analyze the rotation phase dependence of these detrended perturbations.

2.5 NS Displacements of Current Sheet: Effects on Plasma Properties Inside of 15 R_S

A number of factors cause the current sheet to lie above the planetary equator during the interval used in this study, so we must justify the use of measurements acquired slightly off the magnetic equator to represent equatorial measurements. The planet's spin axis is aligned with its magnetic dipole axis, but the magnetic equivalent dipole is offset 0.04 R_S northward of the center of mass of Saturn [Smith *et al.*, 1980]. Furthermore, during southern summer, Saturn's axis of rotation is inclined to its orbital plane so that the solar wind velocity has a finite northward component, and as a result its current sheet is bowl-shaped [Arridge, *et al.*, 2008], lying northward of the magnetic equator at a height that increases with radial distance over the radial range of interest. Additional displacement of the equatorial plasma sheet may result from periodic flapping

of the tail current sheet. (During the interval of this study, the magnetic equator moved up and back periodically but rarely moved below the planetary equator [*Khurana et al.*, 2009].) We will show next that the plasma parameters inside of 15 R_S are little modified by these small north-south displacements of the magnetic equator, implying that the measured values are effectively equatorial values.

Plasma parameters near the equator have been shown to change slowly with north-south displacement from the magnetic equator. *Thomsen et al.* [2010] [see also *Perron et al.*, 2006] have used the form

$$n = n_0 e^{-\frac{z^2}{3H^2} \left(1 - \cos^6\left(\frac{z}{L}\right)\right)} \quad (2)$$

to organize the dependence of the plasma density (n) on distance along a dipole field line. Here, z is parallel to the spin axis, L is radial distance to the equatorial point on the field line and H is the scale height along a dipole field line, a function of radial distance. All are measured in R_S . Our data were acquired along parts of the Cassini orbit within 0.5° of the equatorial plane, or, equivalently, at $|z| \lesssim 0.13$ at 15 R_S , the outermost limit of our study. The density scale height, H for the dominant water group ions at the centers of the radial bins that we will examine is $\sim 3 R_S$ at 13.5 R_S , 2.2 at 10.5 R_S , and 1.5 at 7.5 R_S [*Thomsen et al.*, 2010], increasing to 3.5 R_S at 15 R_S . Energetic particle scale heights such as those investigated farther down the tail by *Sergis et al.* [2011] and *Arridge et al.* [2011] are expected to be larger. We use the simulation of *Jia et al.* [2012] (described in Section 2.7.1 below) to establish that flapping leads to a maximum displacement of the

current sheet of $0.8 R_S$ at $13.5 R_S$, the center of the outermost bin. The northward displacements (dipole offset, bowl-shaped distortion, northward flapping), if acting concurrently at a time when Cassini was at the lowest latitude used in our data set, would imply that the measurements could have been as far as $1 R_S$ from the center of the current sheet at $13.5 R_S$, which would change the plasma density by no more than 10%, a change that is small compared with the changes that we will show are organized by rotation phase. Hence we do not correct the plasma data for distance from the current sheet and we use near-equatorial measurements as representative of values at the magnetic equator. The temperature of the plasma changes little with small displacement from the center of the plasma sheet, so the analysis can also be applied to the change of thermal pressure.

2.6 Radial Binning

Low energy ions account for most of the plasma density in the magnetosphere. Pressure is provided by both dense, low-energy ions and tenuous, high-energy ions, but the contribution of ions of different energies to the total pressure varies with distance. *Sergis et al.* [2010] found that in the equatorial ring current between 6 and $9 R_S$, the thermal ion plasma is the major source of particle pressure. The contribution of the energetic particles to the pressure becomes comparable to that of the thermal ions outside of $9 R_S$ and becomes dominant beyond $12 R_S$. *Sergis et al.* report that the inertial body force and the radial pressure gradient force are comparable at 9–10 R_S , with the pressure gradient contributions becoming dominant outside of $11 R_S$. We

define our radial bins following the changing characteristics of the plasma environment, separating the data by radial cuts from 6 to 9 R_S , where thermal ion pressure dominates the energetic particle pressure and magnetic pressure; 9 to 12 R_S , the center of the ring current, where the ion plasma pressure and energetic particle pressure are nearly equal; and 12 to 15 R_S , where energetic particle pressure dominates the cold ion plasma. It is worth noting that even in regions where the energetic particles dominate the pressure, they contribute to density and average drift velocity at most at the few percent level.

2.7 Local Time Binning

Local time asymmetries of magnetospheric properties are known to be significant. Day-night asymmetries have been observed in moon micro-signatures [Roussos *et al.*, 2005; Paranicas *et al.*, 2005a], charged particle drift paths [Paranicas *et al.*, 2010], plasma flow [Wilson *et al.*, 2013], and plasma temperature and energy flux [Thomsen *et al.*, 2012] in Saturn's inner and middle magnetosphere. Furthermore, simulations by Jia *et al.* [2012] and Kivelson and Jia [2014] show periodic magnetopause displacements of $\sim 5 R_S$ associated with large scale expansions and contractions of the dayside magnetosphere that produce different effects at different LTs. For these reasons, it would be desirable to investigate the possibility of LT effects on the form of the perturbations. However, the limited data preclude analysis in multiple LT bins. We investigate whether

the wave forms are likely to vary greatly with LT by examining the local time variations of plasma responses in a magnetohydrodynamic (MHD) simulation.

2.7.1 MHD Simulation

In order to understand how periodic behavior is imposed on Saturn's magnetosphere, *Jia et al.* [2012] developed a magnetohydrodynamic simulation in which they impose vortical flow perturbations along the equipotentials of one cycle of the $m=1$, 15th spherical harmonic in the ionosphere centered at 70° latitude (dipole $L=8.5$) in the southern hemisphere. The vortical flows, which extend from $\sim 64^\circ$ (dipole $L=5.5$) to $\sim 76^\circ$ (dipole $L=15$) in latitude, drive a pattern of field-aligned currents into the magnetosphere and the northern ionosphere. The imposed currents (that vary sinusoidally) rotate about the spin axis with a period of 10.8 hours. Although it has been disputed whether the field-aligned currents are driven from the ionosphere or arise from processes elsewhere in the magnetosphere, there is no reason to question that at Saturn there is a system of field-aligned currents rotating at the SKR period and a quantitative model of the global response to a rotating current system helps us interpret the plasma periodicities observed. We have extracted information on the periodic responses of plasma parameters at different local times and radial distances.

In the simulation, the properties of the solar wind are held constant, so magnetospheric dynamics are driven by internal processes. The vortical flows in the equatorial plane of the magnetosphere are opposite in direction to what *Andrews et al.*

[2008] refer to as the core field inside the cam region. These flows are analogous to the magnetospheric vortices identified by *Gurnett et al.* [2007]. The simulation was allowed to run for 100 hours without the vortical flows to obtain the baseline magnetosphere. Then, the flow vortices were turned on and the simulation ran for another 50 hours to allow the magnetosphere to stabilize. All results we show will feature time steps taken later than 150 hours of simulation time.

Figure 4a illustrates streamlines of the flow imposed in the southern ionosphere at an arbitrary time step in the simulation, and Figure 4b shows schematically the corresponding pattern of flow in the equatorial plane of the magnetosphere. These patterns rotate at a prescribed rate as implied by the green arrows in the figures. The dotted circles in Figure 4b are $5 R_S$ apart. Equatorward flow perturbations in the ionosphere correspond to radially inward flow perturbations in the magnetosphere. Conversely, poleward flow perturbations correspond to radially outward flow perturbations in the magnetosphere. In this schematic, we would expect the pressure to increase between 5 and $10 R_S$ at the bottom of Figure 4b where the flows are converging and to increase in the same radial range at the top, where flows are diverging. This system of high and low pressure perturbations separated by 180° would rotate about the planet. The semi-rigid rotation of magnetic field fluctuations about Saturn has been well studied [*Andrews et al.*, 2010b] and, as previously noted, magnetic pressure $= B\delta B_\theta/\mu_0$ varies with rotation phase in the same way as does δB_θ . The simulation shows that a

localized source of compressional waves at low altitudes develops near the ~ 70 degree invariant latitude flux tube [Kivelson and Jia, 2014]. These compressional waves make their way relatively slowly ($\sim 6 R_S/\text{hr}$) through the equatorial regions of the large magnetosphere and decay in amplitude as they move away from their source, imposing perturbations throughout the middle magnetosphere. The fundamental wave speeds vary greatly over the simulation domain. In the equatorial region the Alfvén speed varies from about 400 km/s inside of $10 R_S$ to < 35 km/s beyond $10 R_S$ (minimum values of about 12 km/s in the 20-23 LT sector). Near the equator, the sound speed is less than 60 km/s inside of $\sim 8 R_S$ and rises to near 100 km/s beyond $\sim 8 R_S$ and inside of $\sim 15 R_S$. Propagation of fast perturbations along the background field occurs at much higher speeds. In the range of L-shells that we analyze, near the equator the speed is about 400 km/s and increases to 5000 km/s at high latitudes within a few R_S of the ionosphere.

As described in Kivelson and Jia [2014], the simulation reproduces the magnitude and variation of the periodic displacement of the magnetopause, an element of what we refer to as breathing, better than it represents the phases at which the excursions occur. The phase delay is interpreted by noting that the MHD simulation [Jia et al., 2012] does not incorporate the contributions of energetic particles and, correspondingly, the sound speed is underestimated outside of $\sim 9 R_S$ [Kivelson and Jia, 2014] where the thermal pressure of energetic particles becomes of order that of the bulk plasma [Sergis et al., 2010]. Near $15 R_S$, the energetic particle pressure is $\sim 3/2$ the pressure of the thermal

particles. Wave speeds are proportional to the square root of the pressure, so the wave speed in the simulation is roughly 0.6 of the actual value in the outermost bin (12-15 R_S) that we analyze. Fast mode waves, therefore, propagate too slowly outside of $\sim 9 R_S$ in the simulation, leading us to expect an offset in the peak phase of pressure perturbations between the simulation and the data.

One might ask whether the mean flow speed is also underestimated in a simulation that does not include the effects of energetic ions, which drift more rapidly than thermal particles. Our calculations show that at 10.5 R_S , energetic particles (50 keV), which make up only 3% of the plasma density in the middle radial bin, drift relative to the thermal plasma at about 12.5 km/s, and thus modify the bulk background of 70 km/s by only $\sim 1\%$. Therefore, energetic particles do not shift the phases of the periodic perturbations of plasma parameters significantly.

The simulation has been found to reproduce quantitative elements of perturbations in Saturn's magnetosphere, including the periodic motions of the magnetopause [*Clarke et al.*, 2010a, 2010b; *Kivelson and Jia*, 2014, *Pilkington et al.*, 2015], the flapping and phase-dependent variations in thickness of the magnetotail current sheet [*Khurana et al.*, 2009; *Arridge et al.*, 2011; *Provan et al.*, 2011; *Provan et al.*, 2012; *Jia and Kivelson*, 2012], variations of electron plasma density in the inner magnetosphere [*Gurnett et al.*, 2007; *Jia et al.*, 2012], and the noon-midnight electric field [*Thomsen, et al.*, 2012; *Jia and Kivelson*, 2016]. We expect it to give meaningful insight into the properties of the

periodic plasma responses, possibly with some delays in phase in the outer part of the region that we investigate. The amplitude of the oscillations may be reduced somewhat because of insufficiently small grid scales and/or more dissipation than in the real system.

We first consider the patterns of simulated plasma and field perturbations in the equatorial magnetosphere through a rotation period. Figure 5 shows plots of selected plasma and field properties in the equatorial plane of the simulation at time steps separated by three hours starting at 195 hours. The pink dots on the axes mark $5 R_S$ intervals. The green dots are magnetic field lines mapped to the equatorial plane from 70° latitude in the ionosphere at locations separated by 15° in longitude. Noon is towards the left and the location of the dayside magnetopause is marked with an orange line. The columns, from left to right, show density perturbations, plasma pressure perturbations, magnetic pressure perturbations, and total pressure perturbations: the sum of the magnetic and plasma pressures. Perturbations were extracted from the simulation by removing the average of the previous five 10.8 hour cycles for each pixel. The black arrows (unit vectors) show the orientation of magnetic field perturbations in the equatorial plane. It is readily apparent that the magnetic pressure perturbations inside of $\sim 12 R_S$ rotate almost rigidly as described by *Andrews et al.* [2008] and *Provan et al.* [2009b], corresponding to a very structured variation with rotation phase, but the other quantities plotted do not. Beyond $\sim 12 R_S$ none of the plotted quantities rotate without significant change in structure.

2.7.2 Defining LT Bins

In order to examine how various properties of interest vary with rotation phase at different radial distances and local times, we select points in the simulation corresponding to the centers of the radial bins used to analyze the data (e.g., for the 6-9 R_S bin, we sample at 7.5 R_S) every 3 hours of LT and plot the dependence of the perturbations on rotation phase. In Figure 6, we show how the magnetic pressure, ion density, and plasma pressure perturbations at different radial distances and different LTs vary with rotation phase in the simulation. To the upper right of the figure is a "clock" with hands whose colors identify the LTs at which the similarly colored curves in the other columns were extracted. It is evident from Figure 6 that the peak phase and shape of the wave forms extracted from the model are non-sinusoidal and change with local time. Where the forms of the simulated variations are similar over a range of LT, we assume that it is meaningful to group measured values of the corresponding properties over that range of LT and thereby improve the poor statistics in the data.

In the case of magnetic pressure perturbations in the 6-9 R_S range, the wave-forms vary little with LT (roughly the same amplitude and peak phase), other than near noon (magenta curves) where the wave form is considerably different than at other LTs, possibly due to the motion of the magnetopause. From 9-12 and 12-15 R_S , the LT bins from 12 to 21 LT display two peaks: one that coincides with the peak in the dawnside bins, and a second one that occurs later.

Our data set, however, lacks the coverage needed to examine the predicted local time dependence of the magnetic field perturbations. In Table 1, we show how many magnetic pressure data points were available within each LT and radial bin. There are few measurements in the post-noon sector in any radial bin. Therefore, it is not appropriate to separate the measurements into local time bins.

Like the magnetic pressure, the variation with rotation phase of the simulated ion density between 9 and 15 R_S changes little with LT, so there is no need to divide the measurements into separate LT bins. However, the density perturbations from 6-9 R_S differ significantly in different LT bins. On most of the day side (from 1030 to 1930 LT), the wave form peaks near 70° rotation phase but on the night side (1930 to 0730 LT) it peaks near 120° . The phase of the dayside peak corresponds closely to the phase of a local minimum in the night-side density variation. The wave form in the bin centered at 9 LT differs markedly from both of the structures identified in the innermost bin.

Insight from the simulation suggests that we should divide the 6-9 R_S bin into 3 local time bins: one from 1030-1930 LT, one from 1930-0430 LT, and one from 0730 to 1030 LT. However, there are no data in the bin centered at 0900 LT and few data in the 0730-1030 LT bin. The only LT bin with sufficient coverage in phase to analyze meaningfully is from late morning to past dusk (1030-1930 LT).

The peaks of the simulated plasma pressure wave forms from 6-9 and 9-12 R_S in the third column of Figure 6 are fairly close in phase at all LTs, but the troughs are long

and drawn out, with absolute minima falling between 120° and 240° , depending on the LT. Again, however, the distribution of the data favors the day side (see Table 2, which shows the distribution of plasma data in radial distance and local time) so dividing the data into different LT bins would not be meaningful. In the outermost range of our analysis (12-15 R_S), the wave forms of the plasma pressure perturbations vs. rotation phase vary dramatically with LT. On the dusk side (orange, gray, and gold) there is a clear minimum near 240° while on the dawn side (green, red) there is a clear minimum near 70° . There is an almost 180° shift in peak phase between the pre-midnight and post-midnight LT sectors. Guided by these findings, we divide our observations in the outermost radial range into two separate LT bins, one combining the bins centered at 0300 and 0600 LT and covering the LT range from 0130 to 0730 LT and one combining the bins centered at 1500, 1800, and 2100 and extending from 1330 to 2330 LT. After the data were divided into local time and radial bins, the points in each bin were plotted versus SLS4S phase. The results are shown in Figure 7 and discussed below.

3. Results

After processing the data as described in Section 2, we plotted the measured values of magnetic pressure, ion density, and ion pressure perturbations vs. rotation phase in designated radial bins over 2 complete cycles (Figure 7). Each row contains the data from all LT unless otherwise indicated. For each parameter in each bin, the data are grouped into 10 rotation phase bins with equal numbers of points, except for the plasma

pressure in the outermost bin where we use only 7 rotation phase bins due to a paucity of points. The red circles are the medians of both the analyzed parameter and its phase in each phase bin. The error bars extend plus/minus one standard error of the mean. A sinusoidal fit to the medians was performed and the result is plotted on each graph in black.

In order to determine the goodness of fit, we calculate the coefficient of determination, or $R^2 = 1 - SS_{\text{res}}/SS_{\text{tot}}$, which indicates how well the total variation of the bin medians are explained by the fit, with 1.0 meaning that there is perfect correlation between the data and the fit and 0 meaning that there is no correlation. Here, SS_{res} is the sum of squares of the residuals, and SS_{tot} is the total sum of squares of the data values. The values of R^2 , as well as the number of points in each radial bin, are noted on the graph, and the peak phases and amplitudes of the sinusoidal fits are noted in the titles of the graphs.

We find that magnetic pressure oscillations are well organized by SLS4S phase with peak at phases between 254° and 284° , increasing from 6 to 15 R_S . Perturbations in the magnetic pressure, $P_{\text{mag}} = B \cdot \delta B_\theta / \mu_0$, result from periodic variations of δB_θ whose behavior inside of 15 R_S has been analyzed previously [Andrews et al., 2008; Andrews et al., 2010b; Provan et al., 2009b; Provan et al., 2011]. Andrews et al. [2010b], using data from a longer time interval than that used in this study and taken within 5° of the dipole equator, established that δB_θ peaks at $250 \pm 20^\circ$ rotation phase between 6 and 9 R_S and

that the peak shifts by of order 30° out to $15 R_S$. The peak phase in our analysis is within the error of the observed peaks in δB_θ in *Andrews et al.* [2010b] and in the simulation (Figure 6).

Despite the sparse measurements of plasma parameters, Figure 7 shows that there is a periodic variation of total plasma pressure and density with rotation phase. However, some anomalies require explanation. For example, although the observed peak of the magnetic signature shifts by only $\sim 30^\circ$ between the 6-9 R_S bin and the 12-15 R_S bin, the observed peak of the density perturbations shifts by 185° between the 6-9 R_S bin and the 12-15 R_S bin. The observed peak of the total pressure perturbations shifts by 176° across the midnight meridian in the 12-15 R_S radial bin, although the sinusoidal fits are admittedly poorly constrained and, in both cases, the minima are identified by a single median point.

The phase relationships among the parameters are also of interest and call for interpretation. In the 6 to 9 R_S bin, magnetic pressure perturbations are in lagging quadrature with the thermal pressure perturbations and leading quadrature with the ion density perturbations. Within the error of the fits, density perturbations are in anti-phase with thermal pressure perturbations. In the 9 to 12 R_S bins, the magnetic pressure perturbations are in-phase with the density and plasma pressure perturbations. In the 12 to 15 R_S bin, the magnetic pressure and density perturbations are in-phase but the thermal pressure is again in quadrature; the magnetic pressure leads the thermal pressure on the

dawn side and lags on the dusk side. The challenge is to interpret these phase relations in terms of a superposition of the effects of the rotating field-aligned currents (FACs) and the expansion and contraction of large portions of the magnetosphere.

Kivelson and Jia [2014] have shown that the rotating field-aligned currents in the simulation launch waves that drive the large scale compressions and expansions of the magnetosphere. A fast mode compressional wave in a uniform system has magnetic pressure perturbations in phase with thermal pressure perturbations, but we find that the thermal and magnetic pressure perturbations are not everywhere in phase. *Kivelson and Jia* [2014], following *Southwood* [1977], point out that in a non-uniform system the fast and slow modes are coupled; centrifugal acceleration further complicates the relationships between perturbations of magnetic pressure and thermal pressure, and consequently the phase relations may differ from those expected for compressional waves propagating across the background field in a uniform, non-rotating system. Nonetheless, the total pressure perturbations develop and compressional waves propagate in outward spirals as seen in column 4 of Figure 5.

4. Interpretation

We have noted that the periodic signals, especially their phase relations, reflect the response of the field and plasma to the perturbations directly driven by the imposed rotating FACs and to the global scale variations driven by compressional waves launched near the source of the FACs. Magnetic pressure vs. rotation phase takes a simple form in

the simulation and appears to be dominated by currents driven directly from the source in the ionosphere. The field-aligned currents couple to perpendicular currents that drive vortical flow in the equatorial plane. The core field points towards the maximum in magnetic pressure perturbations ($\sim 250^\circ$) and rotates with a 10.8 hour period. Inward of the FACs, the flow converges near $\sim 250^\circ$ rotation phase (see Figure 4b), creating a maximum in magnetic pressure in the $\sim 64\text{--}70^\circ$ invariant latitude (λ) range (that maps roughly to our 6-12 R_E radial bins and slightly beyond), and diverges at higher invariant latitudes, where it reduces the magnetic pressure near $\sim 250^\circ$. The magnetic pressure in the 6-9 and 9-12 R_S bins peaks close to the expected phase. Outside of 12 R_S , especially near noon (see Figure 6), the variation is not as well organized in rotation phase, possibly because of the expected transition from converging flow to diverging flow.

Understanding the peak phases of the plasma parameters is more difficult, because the signals do not merely rotate. We turn to the simulation to gain insight into the jumps in phase found in the plasma data.

4.1 Responses to Compressional Waves

We have noted that the ionospheric vortices and associated flows serve as the source of large scale pressure perturbations that propagate outward from low altitudes. For example, in column 4 at hour 198.00, one can follow the leading edge of the pressure minimum (blue) from near 1800 LT to 1200 LT and estimate the radial velocity as ~ 60 km/s. The compressional waves produce perturbations that do not merely rotate; they

cause large portions of the magnetosphere to change shape and scale [Jia and Kivelson, 2012; Kivelson and Jia, 2014]. For example, the total pressure perturbations (magnetic + plasma) in Figure 5 show that the magnetopause (orange line) moves in and out as it responds to alternating fronts of high pressure and low pressure on the dayside. Similar fronts on the night side stretch and relax the field lines tied to 70° invariant latitude (follow the green dots down one of the columns in Figure 5 and note how they move down the tail and back). These are aspects of what we have called breathing of the magnetosphere. We put forward the hypothesis that in each cycle, the system experiences spinning, breathing, and flapping perturbations (the latter not pertinent to the core magnetosphere), all at the same period but not locked in relative phase and argue that this produces anomalies in the phases of peak perturbations of plasma properties in critical LT sectors. At a fixed radial distance, signal maxima of parameters dominated by the spinning response (e.g., δB and magnetic pressure) fall at nearly the same rotation phase at all local times, typically with peaks and troughs roughly 180° apart; they seem to be relatively little affected by breathing. However, the periodic changes in the size and shape of the magnetosphere resulting from propagating compressional waves affect plasma parameters near the equator at different rotation phases in different parts of the magnetosphere. In the data, we have identified two significant jumps in the phase of the peak of the sinusoidal fits: the plasma pressure perturbations remain within 50° of 360° except on the dawn side of the 12 to 15 R_S bin where the peak phase is close to 180° and

the phase of the peak in density perturbations changes by up to 139° across between the 6-9 R_S and the 9-12 R_S radial bins. These shifts are far larger than the phase delay of $12^\circ/R_S$ that *Cowley et al.* [2006] have identified as a propagation delay in the quasi-dipolar magnetosphere. We will find that the simulation shows that global expansion and contraction of the magnetosphere, i.e., the breathing response, affects the rotation phase dependence of density and plasma pressure and explains these jumps.

4.2 Breathing and the Distortion of Magnetic Shells

Distortions of the magnetospheric size and shape in the simulation can be described quantitatively by characterizing the distortion of shells of fixed invariant latitude as a function of rotation phase. In Figure 8 we show the points of intersection with the equator of constant invariant latitude shells traced from the ionosphere every 2 degrees of latitude from 65° to 72° every 2 hours LT from 195 h to 205 h of simulation time, close to a full cycle. Colors represent the invariant latitudes, and points emerging from the same LT are connected with black lines. A heavy black radial line marks 250° rotation phase. Supplement 1, a movie available online, provides a dynamic version of this figure. In Figure 8, it is immediately apparent that the size and shape of the invariant latitude shells in the middle magnetosphere change radically over one full cycle (note, for example, the expansion of the 70° invariant latitude shell previously represented in Figure 5). At hour 196 with the subsolar SLS4-S phase near 120° , the invariant shells bulge slightly near dusk. As this bulge rotates into the night side it is no longer confined

by the magnetopause and expands down tail. The bulge continues to stretch and rotate. Near dawn, the shells of invariant latitude become very stretched. When the stretched field lines enter the pre-noon sector, the shells suddenly relax to a more circular configuration, suggesting that a plasmoid has been released and the field lines have collapsed towards Saturn like a slingshot. The release of the plasmoid is responsible for the impulsive increase in density in the simulation near 100° rotation phase at 10.5 and 13.7 R_S , which we will discuss in more detail later. The pulse-like signature has been described previously in studies of the magnetic field by *Yates et al.* [2015].

In the supplementary material, Figure S1 expands the region shown in Figure 8 to reveal that the entire magnetosphere dramatically reconfigures itself once every cycle, changes that are reflected in the evolution of the middle magnetosphere described above. On the day side, the magnetopause, whose location closely follows the location of the 80° invariant latitude shell over one cycle, moves in and out cyclically. In turn, the dayside flux tubes in the middle magnetosphere (see Figure 8) compress and expand slightly. As plasma and magnetic flux tubes rotate around to dusk, at a critical rotation phase they begin to stretch rapidly down the tail. The plasmoid development is linked to the tangling of the outermost shell lines on the dawn side (see Figure S1 and Figures 8h-8j) and is associated with the extreme outward displacement of the shells at highest invariant latitude. In Figure 8k, the outermost shells are less distorted and in Figure 8l, the shells have become quasi-circular, much as in Figure 8a, as the dayside magnetosphere recovers

from the plasmoid release. The effects of the plasmoid release cause the magnetopause to move further outward on the dawn side than on the dusk side [Kivelson and Jia, 2014].

The strong coupling between the rotating bulge and the expansion and contraction of the magnetosphere corresponds to what we refer to as breathing.

In order to understand more about the consequences of magnetospheric breathing, we must link its action in the equatorial plane to rotation phase. If a bulge in the magnetic shells were rotating at a constant rate, its effects would appear at a fixed rotation phase at every LT, and would be indistinguishable from the effects of spinning, or semi-rigid rotation. Figure 8 shows that this extreme situation does not apply. For instance, in Figure 8e, the bulge is located just before midnight at hour 200. At hour 201 (Figure 8f), the bulge has rotated azimuthally, but the maximum stretching is still centered at midnight. From hour 202 to hour 204, the bulge barely moves. This progression, in which the region of peak stretching rotates more slowly than SLS phase through the nightside of the magnetosphere, shows that spinning and breathing are not tightly coupled. On the dayside, the compressional wave creating the bulge (see spiral-shaped pressure fronts in Figure 5) rotates faster than the SLS4 phase, likely due to the collapse of the tail. Between hours 204 and 207, the bulge rotates through the LTs from dawn to dusk: at hour 204 the expanded region is located near dawn and at 207 it is near dusk. Thus, the bulge has rotated through half a rotation in only a third of the 10.8 hour period. Signals that rotate more slowly than the SLS4 phase will appear at decreasing

SLS4 phase at increasing local time. Similarly, signals that rotate faster than SLS4 phase will appear at increasing SLS4 phase at increasing local time.

4.3 Breathing and Dayside Density

Scatter inherent in the data, arising from jitter [Provan *et al.*, 2011], solar wind variability, and injection events, make it difficult to identify details of the signatures of periodic variations of the magnetosphere in the data plots, but, using global-scale information from the simulation, we can interpret variations with rotation phase of the simulated parameters. The analysis of the distortion of magnetic shells can be used to interpret the simulated density perturbations from 12-15 R_S in the second row of Figure 6. The simulated densities exhibit abrupt increases and slower decreases in slope at slightly different rotation phases in different LT bins. The density perturbations at 21 LT (orange) increase sharply near 126° . The sharp increase appears at decreasing rotation phase with increasing LT between 21 LT and noon: at midnight (blue) the sharp increase begins at about 120° , at 3 LT (green) the rise begins near 115° , at 6 LT (red) near 100° , at 9 LT (cyan) near 90° . Correspondingly, in Figure 8 the magenta curve moves inside of $10 R_S$ at 21 LT at hour 202, at midnight at hour 203, at 0300 LT at hour 204, and at 0600 LT at 205, etc., i.e. the compression advances faster than rotation phase. Correspondingly, in Figure 8 the bulge moves more slowly than the rotation phase from noon to dusk but the compression moves faster than rotation phase. This varying effect implies that the responses of the field and plasma are not tightly locked to SLS phase.

The shifting phases of the key responses can be used to separate the effects of breathing from those of spinning.

Breathing is a global phenomenon that affects different parts of the magnetosphere differently. On the day side, it is particularly evident in the in-and-out motion of the magnetopause, which is so closely linked to the expansion and contraction of the dayside magnetosphere that the magnetopause position can be used to characterize dayside expansion and contraction. Figure 9a shows the standoff distance of the noon magnetopause vs. rotation phase from the simulation. Figures 9b-d are the plots of density perturbations from the simulation for the different radial bins. We have marked the phases of the maximum and minimum magnetopause standoff distances with vertical lines on each graph. Given that the compressional waves on the day side are propagating radially at about 70 km/s and that the typical outermost location of the magnetopause is near $28.5 R_S$ at noon at $\sim 250^\circ$, one would expect that the peak of the compressional wave causing the outward displacement at noon at $13.5 R_S$ would have passed about 3.6 hours earlier at a phase of $\sim 250^\circ - 120^\circ = 130^\circ$ and that its trough (corresponding to minimum magnetopause displacement) would have passed 4.8 hours earlier at $\sim 290^\circ$ rotation phase. We find no anomalies in the magenta curve (plotted for noon) in Figure 9d at 130° but there is a small but clear positive anomaly in the density near 290° phase. A similar bulge is seen at a slightly larger rotation phase in Figure 9c for the magenta curve representing

noon $10.5 R_S$. The compressional waves have little effect on density on flux tubes within the shells of the dominant FACs.

Having discussed expectations based on phase delays, it is initially puzzling to note that the maximum magnetopause standoff distance occurs at the same phase ($\sim 250^\circ$) as the minimum of the density oscillations in the 6-9 R_S radial bin (Figure 9b) at a phase when the density near noon in the 10.5 and 13.5 R_S bins is not far below its maximum value (Figure 9c and d, respectively). We can understand the large phase change in density across radial bins by examining Figures 9e and 9f, which are cuts showing the density in the noon-midnight meridian of the Jia and Kivelson [2012] simulation at the times at which the magnetopause is most expanded and most compressed. At $T=200$ h, the magnetosphere is most expanded (see Figure 9e) and the SLS4 phase at noon is $\sim 250^\circ$. Here the dayside field lines from 9 to 15 R_S are stretched and centrifugal forces have pushed plasma into the equatorial plane, creating an enhancement in plasma at the equator. Because centrifugal forces are not very important from 6 to 9 R_S , where rotation-related forces are relatively weak, there is no corresponding enhancement in the innermost bin and changes in plasma density result principally from the increased equatorial area of the flux tube associated with the development of a magnetodisk configuration [Achilleos *et al*, 2010]. The reconfiguration due to the expanded dayside magnetosphere produces a trough in the density perturbation at 250° rotation phase at noon in the 6-9 R_S bin. Conversely, when the dayside magnetosphere is compressed at

T=205 h (see Figure 9f), there is a maximum in density perturbations in the 6 to 9 R_S bin and a minimum in the 9 to 15 R_S bins. The reconfiguration of the dayside magnetosphere associated with breathing is the dominant source of perturbations observed in ion density on the day side.

4.4 Quantifying Breathing on the Night Side

The nightside perturbations in the regions inside of 15 R_S in the simulation can also be understood as partially controlled by magnetospheric breathing, i.e. the stretching and collapse of the magnetic flux tubes. In order to quantify the impact of breathing on the nightside magnetosphere, we must estimate the stretching of the flux tubes. The contribution of breathing to the rotation phase-dependence of measurements varies with radial distance because the expansion and contraction of invariant latitude shells become increasingly significant in the outer magnetosphere on the night side. Consequently, we concentrate on the region outside of 9 R_S , examining the periodic responses in the 9-12 R_S and 12-15 R_S bins in the simulation at pre-midnight, i.e. 21 LT, midnight, and post-midnight, 3 LT). Using the simulation we have calculated $dr/d\lambda$, which we refer to as the stretching parameter, a proxy for stretching of flux tubes, at 10.5 and 13.5 R_S and the selected LTs over one phase cycle. Here dr is the radial distance at the equator between two invariant latitude shells (Figure 8) and $d\lambda$ is the difference of their invariant latitudes. We plot invariant latitude vs. the dr values for each time step over a full cycle and fit the values with a spline fit.

To obtain the stretching parameter for each radial bin, we extract the slope of the spline fit ($dr/d\lambda$) at the invariant latitude corresponding to the desired radial distance.

The stretching parameter is plotted vs. rotation phase (blue dots) at radial distances of $10.5 R_S$ (column 1, Figure 10) and $13.5 R_S$ (column 1, Figure 11). The dashed black lines in those plots show the value of $dr/d\lambda$ for a dipole field. Gaps in the plots of the stretching parameter appear where the field has expanded too far down the tail to be evaluated or has run into the magnetopause.

The variation of the stretching parameter with rotation phase provides a way of quantifying the rotation phases at which magnetospheric expansion and contraction is significant at specific magnetospheric locations. Stretching is taken to start when the first upward change of $dr/d\lambda$ between consecutive points exceeds half the variance of $dr/d\lambda$ over one full cycle and to end at the maximum $dr/d\lambda$. Contraction begins at the maximum $dr/d\lambda$ and continues until the change of $dr/d\lambda$ between consecutive points falls below half the variance for at least 3 consecutive points without gaps. For example, at $3 LT$ at $10.5 R_S$ (Figure 10) a sharp change in slope of the $dr/d\lambda$ curve at about 90° indicates the onset of rapid stretching. The expansion peaks near 133° and the field collapses to roughly its initial configuration near 200° rotation phase. In contrast, in the same radial bin but at $21 LT$, the expansion begins at 290° rotation phase, peaks at 123° , and ends near 216° . In the plots, blue shading indicates the range of rotation phase in

which expansion is occurring locally, and red shading indicates where contraction is occurring.

At both 10.5 and 13.5 R_S , the field is stretched for a larger portion of a rotation period in the pre-midnight region than in the midnight or post-midnight region. Despite being stretched for a longer portion of a rotation period, the stretching parameter is considerably smaller pre-midnight than at midnight or post-midnight (e.g., at 10.5 R_S it reaches $\sim 9 R_S/\text{degree}$ of invariant latitude pre-midnight, $\sim 18 R_S/\text{degree}$ at midnight and $\sim 13 R_S/\text{degree}$ post-midnight). For the purposes of our analysis, we identify variations that occur inside of the colored shaded region as associated with both spinning and stretching, and variations outside of the shaded region as imposed by spinning alone.

4.5 Separating Spinning and Breathing on the Night Side

Having found a way to characterize magnetospheric stretching as a function of LT and radial distance in the simulation, we attempt to identify which changes arise from spinning and which are dominated by breathing. This can be done only approximately, but we believe that the approach we next describe is meaningful. We model variations arising from spinning as sinusoidal functions of rotation phase. The magnetic pressure appears to rotate almost rigidly in the equatorial cuts of the simulation magnetosphere so a sinusoid should provide a good fit to the variations. However, we know from *Andrews et al.* [2010] that the peak phase of the magnetic field changes between radial bins.

Therefore, we fit a sinusoid to the unstretched portion of the curve representing magnetic

pressure in each radial and LT bin to identify the phases of extrema of spinning perturbations. The extrema in the magnetic pressure perturbations fall between 235° and 256° and between 55° and 76° depending on the radial distance in question. We postulate that these spin phases approximate extrema of the spinning contribution to the other parameters that we are trying to interpret. (We consider extrema in order to allow responses in the plasma to be close to in-phase or out-of-phase with the magnetic perturbations.) The meridional flow in the simulated ionosphere peaks at 70° and 250° . Therefore, the extrema identified in the magnetic field occur within 30 minutes of the strongest radial flows imposed by the rotating current system. The Alfvén travel time from the ionosphere to the equator ranges between 20 and 30 minutes between 7.5 and 13.5 R_S [McAndrews *et al.*, 2009]. These travel times are short compared with the 10.8 hour period that we are analyzing, so the close links in phase between ionospheric and magnetospheric perturbations is plausible.

We next fit sinusoids with extrema fixed by the magnetic pressure to the spinning portion of each plasma parameter. At 21 LT, the range of phase not affected by stretching was too small to provide a meaningful estimate of the phases of extrema in magnetic pressure. Therefore, results in Figures 10 and 11 are shown at 0 LT, and 3 LT, for 10.5 R_S and 13.5 R_S , respectively. In these figures, blue and red shading have been overlaid on plots of the magnetic pressure, plasma pressure, and density fluctuations (solid blue lines) to identify intervals of expansion and compression inferred from the

rate of change of the stretching parameter. The black lines are sinusoidal fits to the simulated signal over the part of the rotation in which no significant expansion or contraction is present, with the phases of the extrema specified by the magnetic pressure, as described above; the lines are drawn solid in the range of rotation phase used to fit the data and dashed elsewhere. In both Figures 10 and 11, the red lines, which we will refer to as residual perturbations, are the differences between the curves from the simulation and the sinusoidal fit. In order to estimate the scale of fluctuations unrelated to either spinning or breathing we evaluate the RMS variations of the red curves in the spinning region. Portions of the red curves within 2 RMS of zero, shaded in dark gray in the plots, are regarded as insignificant because their variation is comparable with background fluctuations. We focus on the portions of the residual curves (red) that fall outside the shaded range which we believe are meaningfully related to breathing. We next interpret the results.

5. Discussion

We have previously remarked that periodic variations in magnetic pressure are dominated by the spinning response. At 10.5 (Figure 10), the sinusoids fit the spinning region very well and the residuals are of order the random fluctuations, indicating that the breathing response has little effect on the waveform of the magnetic pressure perturbations. At 13.5 R_S (Figure 11), the residuals meander beyond the shaded region both at midnight and 0300 LT at a rotation phase for which the tail is stretched but flux

tubes are compressed azimuthally. This analysis reveals that the breathing response can modify the wave form of the magnetic pressure in the outer part of the region we analyze.

Thus we confirm that the magnetic pressure perturbations on the night side inside of $12 R_S$ are primarily controlled by spinning, but outside of $12 R_S$, breathing alters the wave form as the field lines stretch and collapse.

Interpreting the role of the breathing response is more complicated for the plasma parameters. As the tail stretches, the plasma spreads radially, thereby reducing its density, but increasing stress due to rotation may compress plasma along the field lines towards the equatorial plane, an effect that increases the equatorial density. Changing field magnitude can heat or cool the plasma and thereby affect the thermal pressure.

Thus, during intervals of stretch and collapse, it is hard to predict whether density and plasma pressure will increase or decrease as a result of stretching at any given local time or radial distance. What is evident, however, is that, for the plasma parameters at both 10.5 and $13.5 R_S$, significant excursions of the residual perturbations outside of the gray shaded regions occur only during stretched times. At $10.5 R_S$, the residuals of the plasma pressure remain largely within the gray excluded region with excursions that are small compared to the size of the excluded range. Thus, although the range of uncertainty (gray shaded region) is a large fraction of the amplitude of the perturbation signature, we conclude that the plasma pressure perturbations at $10.5 R_S$ are imposed dominantly by spinning. At $13.5 R_S$, the residual perturbation of the plasma pressure comes outside the

excluded region inside of the stretched region at 3 LT. Although the size of the residual falling outside of the excluded region is small compared to the range of the excluded region, it is tempting to link this excursion to breathing because the decrease occurs when the tail is greatly stretched. Furthermore, the sinusoidal fits to the pressure at both midnight and 3 LT at $13.5 R_S$ are poor, suggesting that something is severely distorting the waveform from that related to pure spinning.

The wave forms of the residual density perturbations in all the LT and radial bins plotted display peaks that extend outside the gray region of uncertainty. In each case, the excursions fall inside of the stretched region, peaking at $10.5 R_S$ where stretching is maximum and at $13.5 R_S$ as the flux tubes are relaxing, strongly implying that the extended peak in density is due to the effects of breathing.

The simulation suggests how the stretching of the field lines may change the wave forms of the plasma and field parameters. The changes depend on which parameter is being considered and where the measurements are made. It is valuable then, to return to the data to determine whether our understanding applies to the real world.

The peak phase of the measured density perturbations, the bulk of which were taken on the dayside, was found to jump across some radial bins. We found similar behavior in the simulation and showed that periodic expansion and contraction of the magnetosphere can result in phase jumps across radial bins. Close to Saturn, the dominant effect of expansion is to increase the volume of flux tubes and decrease the

plasma density, but outside of $9 R_S$, as the plasma on stretched field lines moves further from the planet, centrifugal forces not only move the plasma out but also accelerate the plasma along flux tubes towards the equator. The net effect in the stretched state can be to enhance the density in the equatorial plane outside of $9 R_S$, but depress it inside of $9 R_S$. Thus, dayside breathing of the magnetosphere can account for the phase jump observed in the density data across radial bins.

In addition to creating phase shifts across radial bins, breathing can also cause phase shifts across local time bins. At $13.5 R_S$, the plasma pressure in the simulation shifted phase by almost 180° across midnight. By examining the simulation, we found an asymmetry in the effects of stretching between pre and post-midnight. In the pre-midnight region, the magnetosphere stretches little, although it remains stretched for a large part of a rotation cycle. However, at midnight and post-midnight, the magnetosphere stretches more, but over a shorter part of a rotation cycle. As a result, breathing imposes the peak phase of plasma pressure at midnight and post-midnight, but spinning seems to dominate breathing pre-midnight. Thus, the large shift in peak rotation phase for the plasma pressure from 12 to $15 R_S$, can be attributed to the breathing of the night side magnetosphere.

6. Summary and Conclusions

In this study, we set out to fit the ion plasma moments in the core magnetosphere inside of $15 R_S$ into the picture of the semi-rigidly rotating magnetosphere, a model that

describes the magnetic field perturbations very well. We found that, despite the scatter in the data, the measured equatorial plasma and field moments from 6 to 15 R_S from October 2005 to August 2006, during southern summer, could be fitted by sinusoids modulated at the southern SKR period. However, the phases of peaks in the sinusoidal fits to the density and the thermal pressure of the plasma shifted across radial and local time bins in a way that was inconsistent with simple rotation. We used an MHD simulation by *Jia et al.* [2012] to put the observations into a global context. The simulation displays three types of large scale periodic responses of the magnetosphere that we refer to as spinning, or rotating around the planet semi-rigidly, breathing, or compression and expansion of invariant latitude shells, and flapping, or the up and down motion of the current sheet. We found that the effects of flapping are negligible inside of 15 R_S . We used the radial displacement of the equatorial locations of invariant latitude magnetic shells in the simulation as a proxy for expansion and contraction of the magnetosphere and thereby identified the portion of the rotation period that was affected by breathing in different radial and local time bins. Breathing and spinning, both modulated at the southern SKR period, were found to act concurrently but breathing was found to impose perturbations with different peak amplitudes and phases at different locations in the magnetosphere. The superposition of the two periodic variations accounted for the highly structured wave forms observed for simulated field and plasma properties at different radial distances and local times. Although the scatter in plasma

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measurements organized by rotation phase was too great to allow meaningful comparison with details of the structure of the rotation-phase variations extracted from the simulation, their shifting maxima accounted for the shifting phases of maxima in the sinusoids fitted to measured plasma properties at different locations in the equatorial plane.

Our work shows that a single driver generating two different types of response at the same period can produce plasma perturbations that vary with rotation phase in ways that differ from the simple spinning that accounts for the variation of the magnetic perturbations in the core magnetosphere.

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FIGURE CAPTIONS

Figure 1. The magnetic field data in nT vs. UT (day of year and hour) from a typical periapsis pass by Cassini from Jan 15, 2006 to Jan 19, 2006. The top panel shows the θ component of the magnetic field (B_θ) in spherical polar. In the second panel the black line is the residual of B_θ , defined as the difference between the measured B_θ and the field of the Cassini SOI dipole [Dougherty, et al., 2005]; the red line is an 11 hour running average of the residual, labeled $\langle dB_\theta \rangle_{11\text{hrs}}$; the blue line is a four hour running average of

the B_θ residual, or $\langle \delta B_\theta \rangle_{4\text{hrs}}$. The curve in the bottom panel is the difference between the red line and the blue line, δB_θ .

Figure 2. Plots of LT (hours) vs. radius (R_S) of the positions of all available (a) MAG data and (b) CAPS data. Points are colored by rotation phase, i.e. the SLS4-S phase (degrees) corrected for the LT of the measurement.

Figure 3. (a) CAPS ion number density [$\#\text{-cm}^{-3}$] and (b) CAPS + MIMI total plasma pressure [pPa] vs. radius [R_S] from Oct 11, 2005 to May 24, 2006 vs. radial distance between 6 and 15 R_S . The black lines represent second order exponential least squares fits with the equations displayed in the figures. (c) The CAPS ion number density and (d) CAPS + MIMI total plasma pressure with the radial trends removed by subtracting the fits on the left from the data.

Figure 4. Schematics showing the assumed flows in the simulation of *Jia et al.* [2012]. (a) The vorticity imposed in the southern ionosphere in the *Jia et al.* [2012] simulation at an arbitrary step of the simulation. The vortices, which vary sinusoidally in azimuth, are centered at 70° latitude (dipole $L=8.5$), and extend in latitude from $\sim 64^\circ$ to $\sim 76^\circ$ (dipole $L=7.2$ to 17). The colors represent vorticity parallel to the local magnetic field while the dotted white arrows show the direction of flow in the ionosphere. The green arrow indicates that the entire pattern rotates at the period of southern SKR. (b) A sketch showing schematically the flows in the magnetosphere imposed by flows in the

ionosphere. Red arrows denote the direction of flow along the black lines. Dotted gray circles mark $5 R_S$ increments. As in (a), the green arrow indicates rotation of the pattern. The SLS2-S phase (left-handed) towards which the core field points is indicated in both images as per *Andrews et al.* [2010b].

Figure 5. Snapshots of plasma and field properties in the equatorial plane from the simulation by *Jia et al.* [2012]. The snapshots are extracted every 3 hours, starting at $t=195$ hours. The Sun is to the left and the orange curve follows the location of the dayside magnetopause. The background colors represent ion density perturbations in the first column, plasma pressure perturbations in the second column, magnetic pressure perturbations in the third column, and total pressure perturbations in the fourth column. The green dots mark the intersection with the equatorial plane of field lines emerging from latitude 70° S and separated azimuthally by 15° .

Figure 6. Local time variation of field and plasma perturbations in the equatorial plane from the simulation. The first row shows the magnetic pressure perturbation [pPa] over one full cycle sampled every three hours in local time at radial distances of $7.5 R_S$ in the first column, $10.5 R_S$ in the second column, and $13.5 R_S$ in the third column. The colors of the curves identify the LT to which they apply and correspond to the colors in the clock figure on the right. The second row follows the format of the first, but shows ion density perturbations [\#-cm^{-3}]. The third row shows the plasma pressure variations [pPa].

Figure 7. Field and plasma perturbations vs. rotation phase in degrees over two cycles. The top row shows the magnetic pressure perturbations [pPa]. The second and third rows contain the results of the analysis of ion density perturbations [$\# \cdot \text{cm}^{-3}$] and plasma pressure perturbations [pPa], respectively. The columns show results for radial bins from 6 to 9 R_S , 9 to 12 R_S , and 12 to 15 R_S . All plots include data (blue dots) from Cassini measurements at all LT unless otherwise noted. Red circles mark the median perturbations and phases in 10 bins with equal numbers of points, except for the plasma pressure between 12 and 15 R_S , which was split into 7 bins in order to improve statistics. The red bars about the medians represent one standard error of the mean above and below the median. A sinusoid, offset by the mean of the medians, with amplitude and phase as free parameters, was fit to the medians and is plotted in black. Points were weighted inversely by the standard error of the mean in each bin. The amplitude and peak phase of each sinusoid is marked in the title of each graph.

Figure 8. Changing size and shape of the middle magnetosphere. Colored dots mark the intersection with the equatorial plane inside of 15 R_S of field lines emerging from the southern ionosphere at every degree of latitude from 65° to 72° at increments of 15° in local time. Dots and lines of the same color emerge from a fixed latitude as indicated in

the upper right, and black lines connect dots originating at the same local time. Noon is towards the left. The plots start at hour 195 and continue every 2 hours over a full cycle.

The heavy black radial line marks 250° rotation phase.

Figure 9. The effect of magnetopause motion in the simulation by *Jia et al.* [2012]. (a)

The distance [R_S] of the nose of the magnetopause from Saturn over one cycle vs.

rotation phase [degrees] at noon. The ion density perturbations [$\#\text{-cm}^{-3}$] from the

simulation at (b) $7.5 R_S$, (c) $10.5 R_S$, and (d) $13.5 R_S$. Curves are colored by LT as in

Figure 6 (e) A noon-midnight meridian cut of the simulation at hour 200, when the

magnetopause is most expanded, and at (f) hour 205, when the magnetopause is most

compressed. The background is colored by density perturbation and $7.5 R_S$ and $13.5 R_S$

have been marked with black lines.

Figure 10. From left to right the columns display plots of $dr/d\lambda$, magnetic pressure [pPa],

plasma pressure [pPa], and density [$\#\text{-cm}^{-3}$] perturbations at $10.5 R_S$. Successive rows

apply at different LTs (2100, 0000, and 0300). In the first column, containing the

stretching proxy, stretching and relaxing regions (see text) are marked with blue and red

shading, respectively. The expanding region (blue) begins when $dr/d\lambda$ begins to increase

abruptly as a function of λ and ends at the maximum $dr/d\lambda$. The contracting region (red)

begins at the maximum $dr/d\lambda$ and ends when $dr/d\lambda$ vs. λ flattens. The shaded regions

have been copied to the plots of the magnetic pressure, plasma pressure, and density. In

these plots, the blue traces correspond to the waveform from the simulation at the specified LT and radial distance. The gray lines are sinusoidal fits to the unstretched region, with extrema specified by a fit to the magnetic pressure in each bin. The fit lines are solid in the unstretched region used for the fit and dashed otherwise. The heavy red line is the difference between the blue and gray curves. The width of the gray shaded region is twice the RMS of the difference between the fit and the simulation data in the unstretched region and provides an estimate of the range of fluctuations that is not significant.

Figure 11: As for Figure 10, but for $13.5 R_S$. At 3 LT, gaps appear in the dots of stretching parameter where field lines have reconnected or have hit the magnetopause. The unstretched region cannot contain gaps.

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TABLES

Table 1. Radial and LT distribution of magnetic measurements used in this study.

Entries indicate the number of measurements within each 3-hour LT bin centered at the LT specified in the first column.

	6-9 R_s	9-12 R_s	12-15 R_s
0 LT	1114	1801	947
3 LT	668	883	2248
6 LT	89	900	1287
9 LT	1455	1255	3459
12 LT	2989	2607	338
15 LT	873	0	0
18 LT	1621	892	25
21 LT	1356	1180	1861

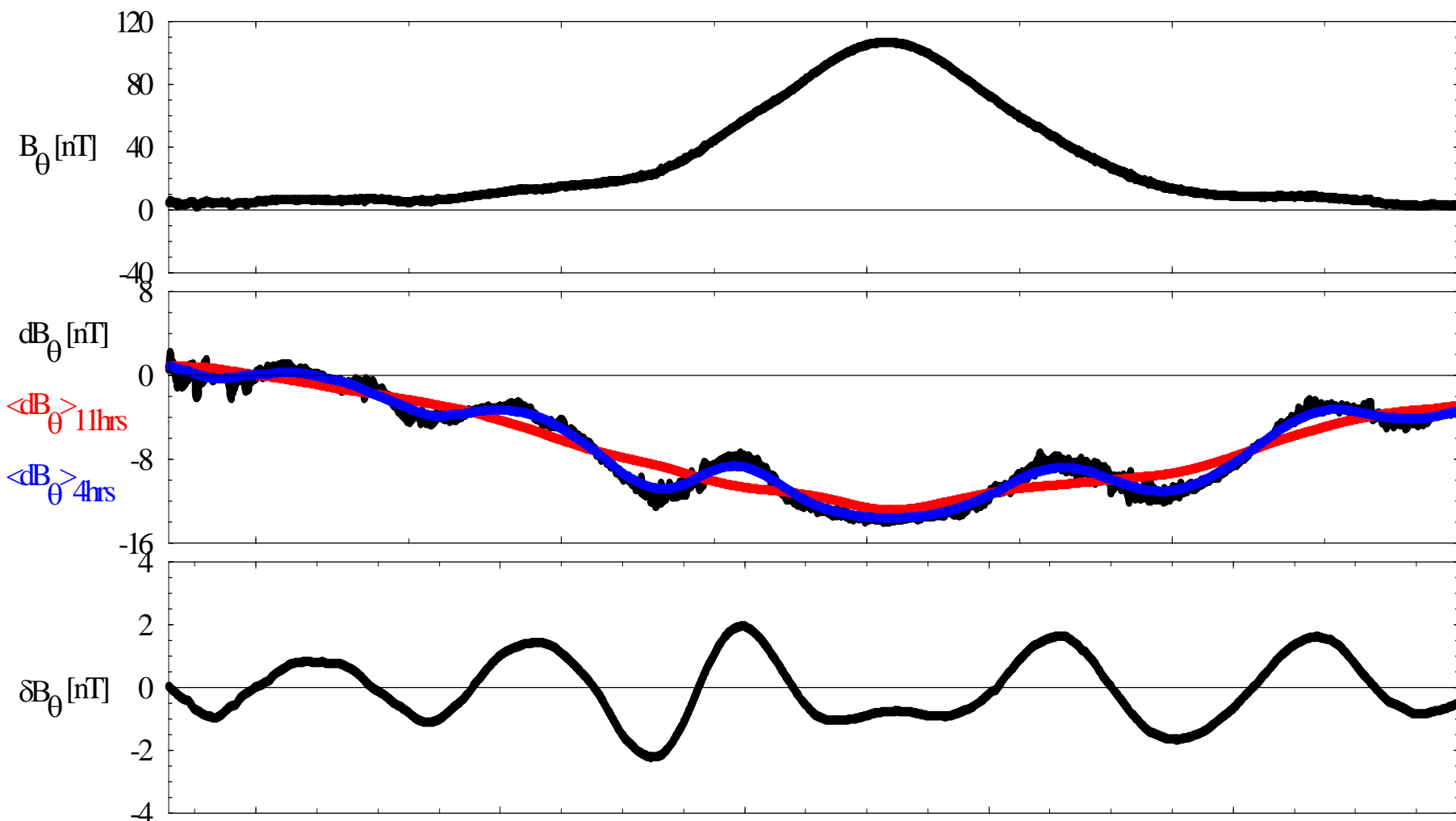
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Table 2. Radial and LT distribution of plasma measurements used in this study.

Entries indicate the number of measurements within each 3-hour LT bin centered at the LT specified in the first column.

	6-9 R_S	9-12 R_S	12-15 R_S
0 LT	12	8	29
3 LT	2	37	22
6 LT	0	57	23
9 LT	45	52	170
12 LT	105	164	4
15 LT	28	0	0
18 LT	79	21	0
21 LT	19	19	31

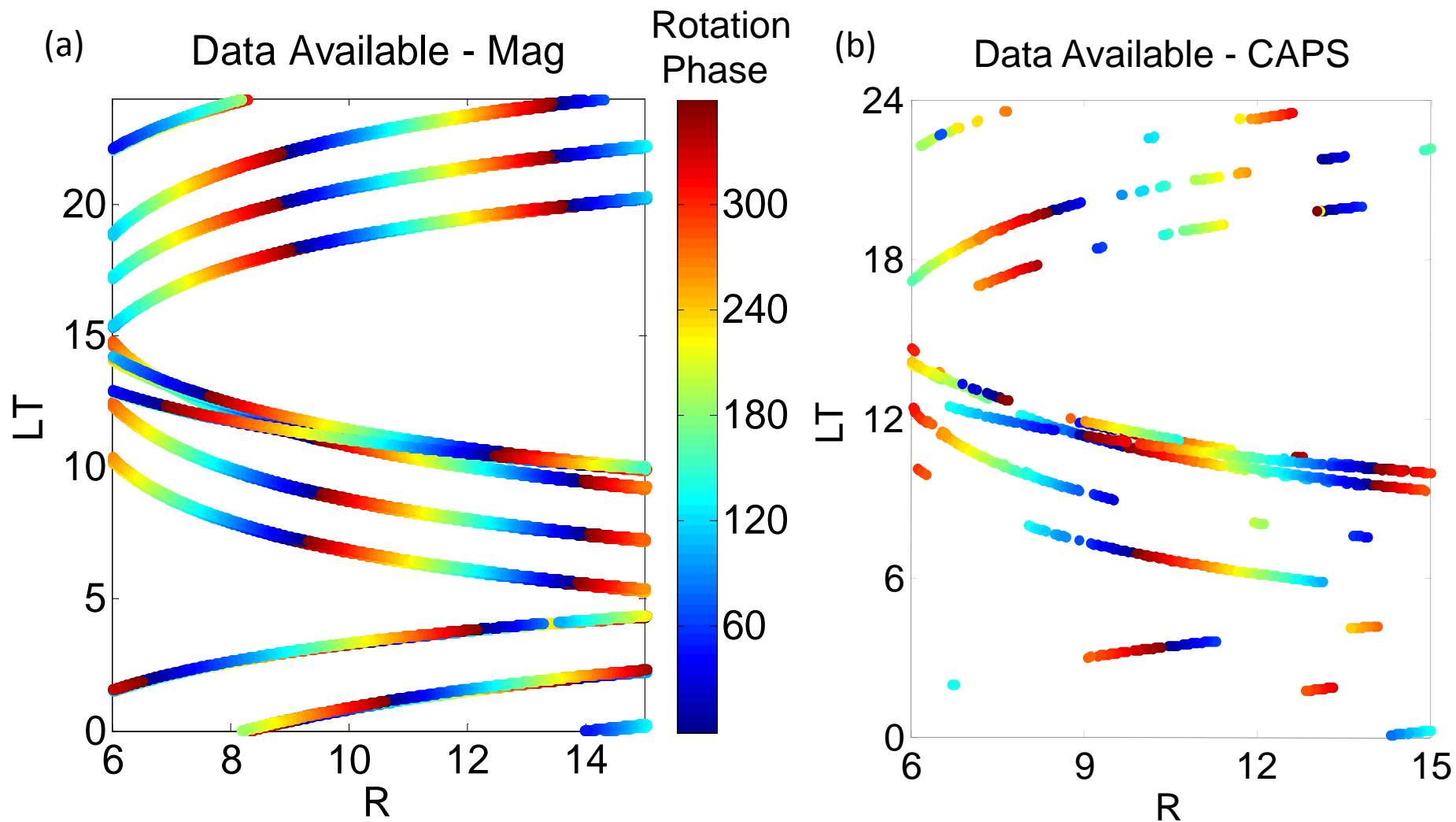
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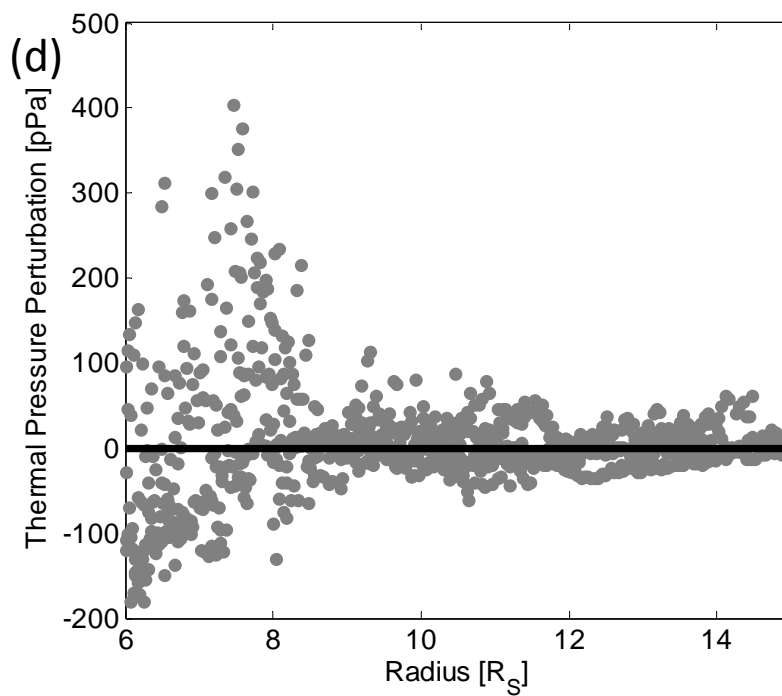
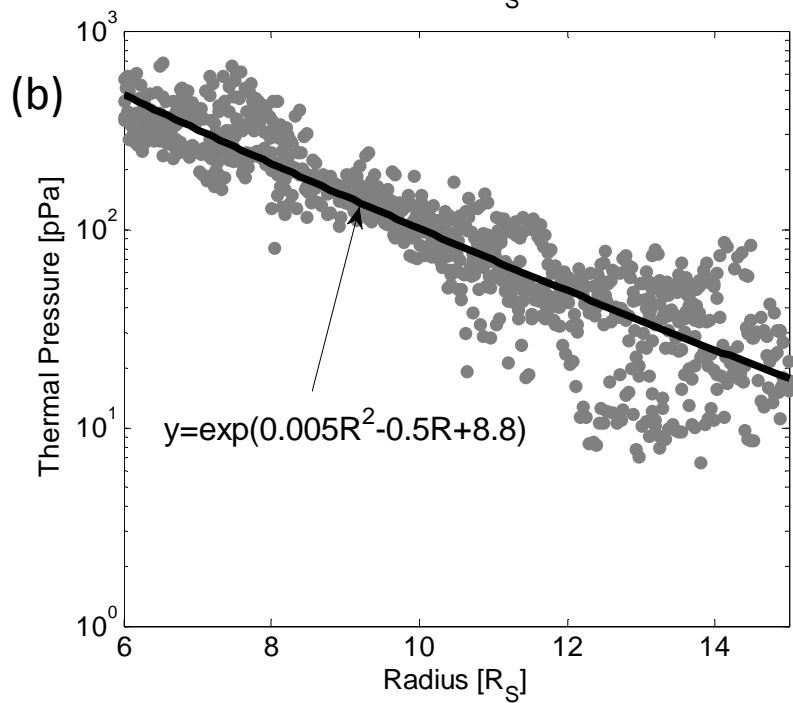
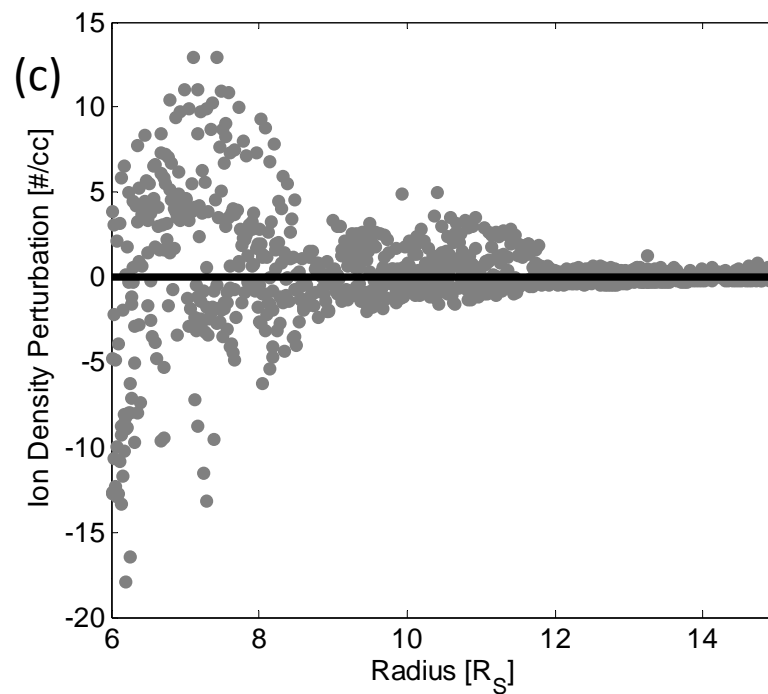
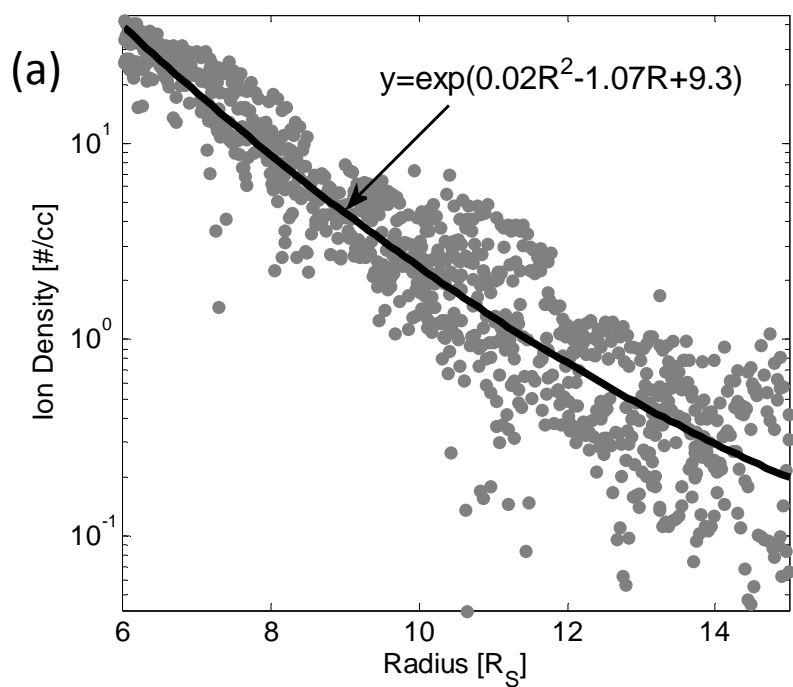


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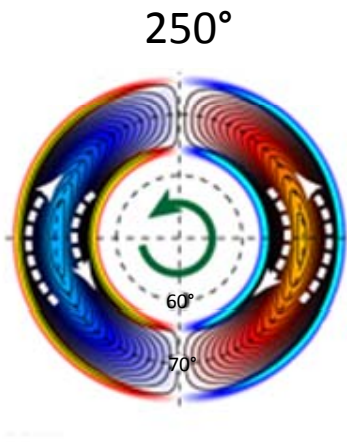
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$R[R_s]$	15.95	11.41	6.86	6.29	10.64
Latitude	-0.39°	-0.41°	-0.31°	0.30°	0.41°
LT [hrs]	9.08	10.31	13.31	19.46	22.88





(a)



(b)

