Spin-period effects in magnetospheres with no axial tilt

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[1] A magnetic axis that is tilted with respect to the spin axis causes waves that generate spin-periodic effects in a planet’s outer magnetosphere. Saturn’s magnetic axis is aligned with its spin axis, and yet its outer magnetosphere exhibits spin-periodicities in all species of charged particles, just as expected from a wavy magnetodisk. In a spin-aligned geometry, however, a rotating anomaly (or “cam”) in the inner magnetosphere can also generate spin-periodic waves by shaking the plasma sheet of the outer magnetosphere. Like a wobbling magnetodisk, this model predicts oscillations of the plasma sheet at distances beyond ~20 Rs (1 Rs = 60268 km). When viewed from a moving spacecraft, these oscillations cause charged particle periodicities near the spin period of the planet. The phase and polarity of these periodicities change systematically with local time, and spin-periodic effects should appear along the magnetopause. Citation: Carbary, J. F., D. G. Mitchell, S. M. Krimigis, D. C. Hamilton, and N. Krupp (2007), Spin-period effects in magnetospheres with no axial tilt, Geophys. Res. Lett., 34, L18107, doi:10.1029/2007GL030483.

1. Introduction

[2] Most planets with an intrinsic magnetic field have a magnetic axis significantly tilted with respect to the spin axis. The Earth’s magnetic axis tilts 11° relative to its spin axis, while Uranus and Neptune have extreme tilts exceeding 45° [Bagenal, 1992]. Magnetospheric periodicities arise because the magnetic axis sweeps around the spin axis once per planetary rotation, which effectively perturbs the magnetosphere once per rotation. The periodic perturbations are manifest as wave motions in the plasma sheet that travel from the inner to the outer magnetosphere [e.g., Eviatar and Ershkovich, 1976; Carbary, 1980]. At Earth, substorm activity obscures these perturbations, while at Jupiter, a rotating, tilted magnetic field in the inner magnetosphere causes wave motion in the outer magnetosphere. The regularity of these waves at Jupiter has allowed detailed global models to be developed [Khurana and Schwarzl, 2005].

[3] This model of spin periodicity cannot apply to Saturn because its magnetic axis is closely aligned with its spin axis. Magnetometer measurements from all spacecraft visiting Saturn agree that its magnetic dipole axis tilts less than 1° relative to its spin axis [Smith et al., 1980; Connerney et al., 1982; Davis and Smith, 1990; Dougherty et al., 2005]. Such a small tilt cannot cause periodicities of the same kind as observed at Jupiter. Nevertheless, Saturn’s inner and outer magnetospheres both exhibit strong periodicities at or near the nominal rotation frequency of the planet. Like Jupiter, Saturn’s spin-periodicities include those of the planetary radio emissions [Desch and Kaiser, 1981; Gurnett et al., 2005], magnetic field [Espinosa et al., 2003a; Giampieri et al., 2006], of plasma density [Gurnett et al., 2007], and of the charged particles and their spectra [Carbary and Krimigis, 1982; Krimigis et al., 2005; Carbary et al., 2007]. Furthermore, whereas Jupiter’s radio period remains stable over many years, Saturn’s radio period changes slowly [Galopeau and Lecacheux, 2000; Gurnett et al., 2005]. The spin-alignment and the radio period drift suggest that Saturn’s periodicities differ fundamentally from those of Jupiter.

[4] The anomaly model may explain Saturn’s periodicities, even though the idea originated as an attempt to describe certain aspects of the magnetospheric periodicities at Jupiter [Dessler and Hill, 1975; Dessler and Vasyliunas, 1979; Vasyliunas and Dessler, 1981]. Basically, the model proposes a longitudinal asymmetry (originally considered to be a magnetic anomaly) that rotates with the planet and generates spin-periodicities in the magnetosphere. More recently, Espinosa et al. [2003a, 2003b] proposed that a rotating anomaly, equivalent to a longitudinal pressure asymmetry, might transform rotary motion into reciprocating motion and launch periodic waves into Saturn’s magnetosphere. This incarnation of the anomaly model is referred to as the “cam” model because of its resemblance to a mechanical cam.

[5] The cam or anomaly can also induce waves in Saturn’s outer magnetosphere. Tilted ~20° relative to the solar wind flow, the compression/expansion action of the cam in the inner magnetosphere effectively “shakes” the outer magnetosphere and produces tailward-moving transverse waves in synchrony with the rotation of the inner magnetosphere. These waves travel outward and cause the observed periodicities in plasma sheet electrons and ions. The model also predicts similar waves on the flanks of the magnetotail and on the dayside magnetopause.

2. Charged Particle Observations at Saturn

[6] Virtually all phenomena observed in Saturn’s magnetosphere exhibit a periodicity close to the nominal SKR (Saturn kilometric radiation) period of 10 h 46 m (or 10.8 hr). Figure 1 reveals three of the various periodicities prominent in Saturn's magnetosphere: periodicities in electrons, protons, and oxygen ions. These data are from the particle detectors of the Magnetospheric Imaging Instrument on Cassini [Krimigis et al., 2004]. Figure 1 shows both unsmoothed (green) and smoothed (red) count rate profiles at 30-minute time resolution. The data were
obtained on days 201–221 (July 20–August 8), 2006, when Cassini made nearly a complete orbit around Saturn. Cassini sampled the midnight sector of the magnetotail and remained close to the plasma sheet, which permitted an opportunity to observe periodic waves in the plasma sheet. Periodicities are not clearly observed during the inbound part of the pass (before day 205), but strong periodicities slightly longer than the SKR period are observed on the outbound pass outside 20 Rₜₗₜₑₜ [Carbary et al., 2007]. The principle variations in Figure 1 are all near this period and can be interpreted in terms of encounters with a regularly oscillating plasma sheet. Although double or multiple sheet encounters may be glimpsed in the unsmoothed (green) traces, the present analysis concentrates on the main oscillations apparent in the smoothed (red) traces.

3. Model

[7] Consider an azimuthal enhancement in the plasma density that rotates with Saturn. Plasma density could be modulated by a feature at a fixed longitude in Saturn’s ionosphere, or by sporadic injections from Enceladus, a prolific source of ions for the magnetosphere [e.g., Tokar et al., 2006], or by a corotating convection pattern [Hill et al., 1981]. Whatever the source, mounting evidence suggests that such a rotational anomaly exists in the 3–5 Rₜₗₜₑₜ range [Gurnett et al., 2007].

Figure 1. Characteristic observations of electrons (28–102 keV), protons (2.8–78 keV), and oxygen ions (8.7–236 keV) for days 201–221, 2006, when the Cassini spacecraft made a nearly complete orbit around Saturn at very low latitudes near the plasma sheet. Half hour averages are shown; vertical dotted lines indicate radial distances. Seven-point smoothed data (red) clarifies periodicities in the unsmoothed data (green), but does not alter them.

[s] Figure 2 depicts a sequence of the rotating anomaly viewed from the north pole. One ~90° sector of longitude preferentially fills with plasma. The rotating plasma centrifugally loads that sector and causes a corresponding outward bulge in the magnetic field. The solar wind pressure confines the bulge on the dayside (x > 0 in the sequence), but lower confining pressure on the nightside (x < 0) allows the anomaly to oscillate inward and outward with larger amplitude in the midnight sector. Such oscillations are manifest at the cam “boundary” at ~20 Rₜₗₜₑₜ, which is considered the “hinge point” of the magnetosphere [Dougerty et al., 2006]. If the boundary is modeled as an eccentric circle centered on Saturn, the cam radius would be:

\[ r(\phi, t) = A + \delta A \cos(\phi - \omega t - \phi_0) \]  

where \( A \approx 20 \text{ R}_\text{S} \) is the hinge location, \( \delta A \approx 1 \text{ R}_\text{S} \) is the eccentricity offset, \( \phi \) is the local time, \( t \) is the time, \( \omega \) is the angular frequency of corotation, and \( \phi_0 \) is an arbitrary phase angle. For \( \omega \), a period of 10.793 hours is assumed [Kurth et al., 2007].

[9] There is no equation per se for the plasma sheet surface. This surface is calculated numerically by launching plasma sheet “particles” from the outer cam boundary. The outer cam boundary in Saturn’s equatorial (tilted) coordinates is represented by equation (1). The rectangular version
of (1) is \( \mathbf{r}(t) = [r(\varphi, t) \cos \varphi, r(\varphi, t) \sin \varphi, 0] \) where \( \varphi \) is a local time angle measured counter-clockwise from noon. This vector is transformed to Sun-Saturn orbit (SSO) coordinates:

\[
\mathbf{r}_o(t) = [x_o(t), y_o(t), z_o(t)] = \mathbf{M} \cdot \mathbf{r}(t)
\]

where \( \mathbf{M} \) is the transformation matrix. For \( \mathbf{M} \), the model uses a tilt of 21.7° (colatitude) and a phase of 131° (counterclockwise from noon) as measured in the SSO frame. Derived from Cassini navigation data, these angles define Saturn’s spin axis during the sample period of interest (days 201–220, 2006).

Once launched, the particles travel anti-sunward with the Alfvén speed of \( v = 3 \text{ RS/hr} \) in the minus-x direction [Cowley et al., 2006]. The equation of motion for the particles is then:

\[
\mathbf{r}_p(t) = [x_o - v \cdot t, y_o(t), z_o(t)]
\]

The locus of these points for multiple times represents the time-dependent surface of the center of the plasma sheet. The numerical calculation assumes a time step of 0.5 hours at a local time resolution of 2°. The surfaces are shown in Figure 3. If \( \mathbf{r}_I(t) \) is the spacecraft position, then the “z” distance between the plasma sheet and the spacecraft is \( |(\mathbf{r}_p(t) - \mathbf{r}_I(t))_z| \).

If there were no tilt of the magnetic axis relative to the solar wind flow, the cam would produce merely compressional waves that propagate outward from Saturn, as originally discussed by Espinosa et al. [2003a, 2003b]. However, the tilt of the Saturn’s spin axis in the SSO frame causes the planet’s plasma disk to bend in response to solar wind flow, apparently around ~20 RS down the tail [Dougherty et al., 2006; Khurana et al., 2006]. Because magnetotail field lines attach to the cam boundary at ~20 RS, the oscillation of the anomaly’s boundary causes tail field lines to also oscillate.

**ROTATING ANOMALY MODEL**

**PERIOD = 11.00 HRS**

**Figure 2.** Time sequence of the rotating anomaly, viewed from the north pole with the Sun at the right, in which one ~90° sector of longitude preferentially fills with plasma. The rotating plasma (or anomaly) centrifugally loads that sector and causes a corresponding radial “bulge” or “cam.” An outward arrow indicates the density maximum of this anomaly. Solar wind pressure confines the bulge on the dayside (x > 0 in the pictures), but lack of confining pressure on the nightside (x < 0) allows the bulge to press tailward and accentuates the compression/expansion action. The red dashed lines crudely approximate the magnetotail flanks, while the circle denotes the cam-like anomaly “boundary” at ~20 RS. This boundary is modeled as an eccentric circle whose rotational center is Saturn.

**Figure 3.** Surface of the simulated plasma sheet observed in Sun-Saturn orbit coordinates with the Sun at right. (top) The XY projection of the sheet and (bottom) the XZ projection. The black elliptical path shows the Cassini orbit from which the data of Figure 1 were taken. The parameters of the model were optimized using the electron data in Figure 1.
inward and outward. Outside of the ~20 Rs “hinge” distance, this inward-outward motion also produces up-and-down motion that launches transverse (Alfvén) waves. These waves propagate tailward in exactly the same manner as waves launched by a tilted, spinning magnetodisk. Figure 3 shows the resulting wave patterns in the plasma sheet. During the orbit discussed above, Cassini moved very close to the plasma sheet represented by this model and periodically encountered the sheet as a result of its wavy motion. (Animations S1 and S2 of the auxiliary material show this process dynamically.)

4. Optimization of Model

[12] To simulate what Cassini would see if cruising along such a plasma sheet, assume the count rates of charged particles falls off exponentially in range r from Saturn and as a Gaussian in distance z from the plasma sheet:

\[ C(r, z) = C_0 \cdot \exp\left(\frac{-r}{a}\right) \cdot \exp\left(\frac{-(z/b)^2}{2}\right) \]  

(4)

The surface of the plasma sheet is calculated numerically by launching “particles” from the cam boundary as explained above. r and z are measured in the SSO frame of Saturn.

[13] The parameters of the model are a, b, and \( C_0 \) in equation (4) and \( A, \delta A, \) and \( \phi_0 \) in equation (1). \( C_0 \) is merely a normalization factor computed by ratioing the sum of the observed rates and the sum of the model rates over the interval of interest; the remaining five parameters were optimized by minimizing the chi-square (in log space) between the model and the electron data of Figure 1. This minimization involved a brute-force search through five-dimensional parameter space. The results of this minimization appear in Table 1. The optimization indicates a hinge radius of 20 Rs, in good agreement with its presumed location, and a hinge offset of 2.8 Rs. This offset represents a significant eccentricity for the cam. Also, the minimization suggests a rather thin plasma sheet with thickness of about ~1 Rs. A formal uncertainty analysis of this optimization lies beyond the scope of this paper, but the fitted parameters are probably accurate to within ~30% in the context of the model. The mean relative deviation (observed count rate minus model count rate divided by model rate) of the fit is 0.26 in log space.

Table 1. Optimized Model Parameters

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_0 )</td>
<td>1062 counts/s</td>
</tr>
<tr>
<td>a</td>
<td>10.0 Rs</td>
</tr>
<tr>
<td>b</td>
<td>1.2 Rs</td>
</tr>
<tr>
<td>A</td>
<td>20.0 Rs</td>
</tr>
<tr>
<td>( \delta A )</td>
<td>2.8 Rs</td>
</tr>
<tr>
<td>( \phi_0 )</td>
<td>90°</td>
</tr>
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[14] Figure 4 compares the observed count rate profile with the optimized profile that Cassini detectors would observe for the same trajectory as in Figure 1. (The model is not valid inside 20 Rs, and this region is shown merely with an exponential dependence in r.) The simulated rates exhibit periodicities similar to those seen in Figure 1, with strong modulation at ~11 hours beyond ~20 Rs. The modulation diminishes as the spacecraft approaches the sheet more closely between day 214 and day 217. A similar reduction in modulation appears in the observations.

[15] The model exhibits several interesting features. First, transverse waves would be observed in the plasma sheet throughout the magnetotail (as opposed to compression waves). Second, the waves’ polarity changes ~90° between the flanks and the center of the tail. Third, waves interior to the tail would have a sawtooth shape while those on the flanks would have a sinusoidal shape. Fourth, the phase of the waves would change systematically with local time.

5. Conclusions

[16] Even without a tilted magnetic axis, strong spin-periodicitites can be induced in an outer magnetosphere by a rotating longitudinal anomaly, which generates a sort of mechanical “cam” at the edge of a corotating inner magnetosphere. The inward and outward cam motion combined with tilt of the magnetic axis relative to the solar wind flow launches transverse waves in the plasma sheet that propagate down the tail of the magnetosphere and also along its flanks. A related modulation might also be predicted at the dayside magnetopause.

[17] The anomaly-cam predicts periodicities in Saturn’s magnetotail that are quite similar to those actually observed in charged particles by Cassini. Assuming reasonable plasma sheet scales and wave speeds for the wavy plasma sheet, the model naturally leads to charged particle periodicities very similar to the ~11 hour periods actually observed. The model further suggests that the radial distance of ~20 Rs represents a critical point in Saturn’s magnetosphere where solar wind pressure begins to warp the magnetodisk along the direction of solar wind flow.

Figure 4. Count rates simulated using the offset cam model (red) compared to observed electron data (green) of Figure 1. The model was optimized using the electron data outside of ~20 Rs (dashed vertical line). Parameters of the model appear in Table 1.
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References