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Key Points:
- Current systems for the 10.7 h Saturnian magnetic signals are given
- Signal sources are in the polar caps, i.e., open field line regions
- The energy source is a dynamo process driven in each polar ionosphere

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The origin of Saturn's magnetic periodicities: Northern and southern current systems

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Abstract The recent survey by Andrews et al. (2012) of the separate northern and southern ~10.7 h periodic magnetic signals in Saturn's magnetosphere limits very much their governing current systems. The existence of signals with pure or close to pure northern or southern periods in respective polar caps taken with the relatively narrow bandwidth of the signals indicates that the actual periodicities are imposed independently from northern and southern polar regions, i.e., the open field line regions. Field-aligned currents must flow on the boundaries of these regions to exclude signals from the other hemisphere. Equatorward of the polar cap, on closed magnetic shells, there are distinct north and south "cam" source currents, the distinction being made clear by a difference in polarization. We outline the consequences for the governing current systems and the implications for sustaining the energy and power dissipation in the system.

1. Introduction

Almost everywhere in Saturn's magnetosphere there are magnetic oscillations seen with periods close to 10.7 h. In fact, the signals appear to share the periodicity evident in the Saturn kilometric radio emission [*Gurnett et al.*, 2007] and like those emissions to consist of signals with two distinct periods whose sources seem to be in opposite hemispheres [*Gurnett et al.*, 2009; *Andrews et al.*, 2010b; *Southwood*, 2011]. When first detected, the two periods were close to 10.6 h in the south and 10.8 h in the north. As Saturn approached equinox in August 2009, the periods came closer to each other. We shall refer to the magnetic signals as ~10.7 h oscillations.

Using results from a survey of northern and southern signals throughout the Cassini epoch [*Andrews et al.*, 2012], we propose a global current system. The signals are almost certainly in the magnetohydrodynamic (MHD) regime, and in MHD, the magnetic field is a fundamental means for transmission of stress in the medium. However, identifying the global current structure, in particular the field-aligned current location and their closure, is a way to identify the transmission of energy.

Several theories have proposed partial or complete electrical current systems. In 2007, *Southwood and Kivelson* [2007] proposed a system of rotating field-aligned currents as the source of the transverse magnetic signals seen in the equatorial regions of the closed field regions of Saturn's magnetosphere marked in Figure 1. The currents flow near the outer edge of the dipolar field lines and have an $m = 1$ axial symmetry about Saturn's rotation/magnetic axis. They emphasized that the field perturbations on which basis the current was deduced do not have a null at the equator. Accordingly, the currents flow along the field through the equatorial region. They cannot be simply due to ionospheric-magnetospheric coupling but must almost certainly represent coupling between northern and southern ionospheres as well.

The theory of *Southwood and Kivelson* [2007] was incomplete in not describing the manner in which the currents closed. Thus, although an interhemispheric field-aligned current might well explain the magnetic signals seen, as the manner in which the current system ultimately closed was unspecified, it could not explain their dynamical significance. Subsequent to *Southwood and Kivelson*'s [2007] attempt to place limits on the nature of the current sources, some very important new observations have emerged. In particular, it is now clear that there are northern and southern signals at slightly different frequencies and with different polarization. This led *Andrews et al.* [2010b] to propose a different model current system which recognizes both the presence of two frequencies and the north-south polarization difference; this is based on a previous discussion of the southern system currents by *Andrews et al.* [2010a]. This work gives a synthesis of the two models.

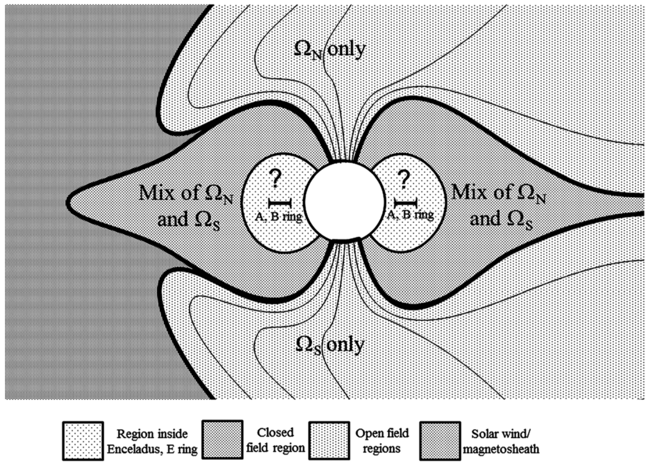

Figure 1. Graphic summary of the results of *Andrews et al.* [2012] on the distribution of northern and southern period signals in Saturn's magnetosphere. Pristine signals are seen in the two polar caps, while mixed signals are seen on closed field lines at lower invariant latitudes. There is doubt as to what happens in the inner dipolar regions which thread the A and B rings, as indicated by the question marks. For simplicity, the sketch is shown for equinox, and so the planetary dipole which aligns with the planetary rotation axis is at right angles to the solar wind flow. The Sun is on the left.

The recent survey work of *Andrews et al.* [2010a, 2010b, 2012] on the polarization and spatial location of the pervasive ~10.7 h magnetic signals using Cassini spacecraft measurements in the Saturnian magnetosphere now provides enough information for a fairly categorical description of the currents that underlie the system. The basic idea of the rotating *Southwood and Kivelson* [2007] system is retained. We first introduce a system which simply adds to their model by separating northern and southern current systems and propose closure routes through the ionosphere and inner magnetosphere. We then analyze the implications of significant compressional components in the signals and suggest that Southwood and Kivelson's assumption of no closure through transverse currents in the magnetosphere is wrong. There must be some transverse current flow in the regions where there is significant plasma density. We further look at the implications of the different polarization and localization of the northern and southern signals in regard to the transfer of stress between hemispheres.

2. Background

The magnetic signal was identified originally by *Espinosa and Dougherty* [2000] and *Espinosa et al.* [2003a, 2003b] and called the cam signal. The cam idea is a basic feature of the Saturn kilometric radiation (SKR) modulation mechanism proposed by *Southwood and Kivelson* [2009]. They proposed that the modulation is due to a once per cycle interaction between the rotating *Southwood and Kivelson* [2007] system and a higher-latitude system of field-aligned currents fixed in local time (i.e., with respect to the Sun). *Southwood and Kivelson* [2009] describe the magnetic field of the LT-dependent high-latitude pattern (associated thus with solar wind interaction) in terms of the field being swept back (on the morningside) and swept forward in the afternoon. A cyclical intensification of field-aligned currents gives rise to the modulation of the SKR radio signals and occurs in conjunction with the passage through the morning magnetosphere of the swept forward sector of the perturbation field. The morningside magnetosphere is singled out as the magnetopause compresses the rotating plasma coming from the nightside, and the high-latitude field is most strongly distended there so that intense field-aligned currents will flow from the equatorial plane to both northern and southern ionospheres. We shall not refer to this aspect of the system further in this paper. Rather, we concentrate on the likely form of the overall ~10.7 h oscillatory current system.

Southwood and Kivelson [2007, 2009] did not foresee that the signals are made up of magnetic oscillations with two separate periods. The frequency splitting was first detected in the allied radio signals [*Gurnett et al.*, 2009]. The magnetic signals are similarly separated in period [*Southwood*, 2011; *Andrews et al.*, 2010b]. The tracking of two signals with close periods is not a simple task. Most importantly, both signals, the northern and southern, exhibit different phase relations between field components, i.e., exhibit different polarization [*Provan et al.*, 2011, 2013; *Andrews et al.*, 2012]. This aids their tracking over time. Also useful is the fact that both northern and southern signals exhibit a simple sinusoidal variation with azimuth [*Southwood and Kivelson*, 2007]. This is commonly referred to as their having an angular wave number, $m = 1$. Another way to picture this is that each component of the field appears to be rotating about the planetary axis at their respective period. In the central tail, the signal departs from sinusoidal thus either higher order odd m numbers would be included or the nonsinusoidality could come from the time domain.

As the northern and southern systems of currents have slightly different periods, they must form two separate systems. Moreover, *Andrews et al.*'s [2012] delineation of regions of the magnetosphere where purely northern or purely southern signals are seen to provide critical clues to the location of the currents in the signals. This is inherently important as that also leads to isolating possible source regions. After identifying the geometry of the currents behind the signals, we speculate on the implications for their source.

3. The Signal Regimes

The first indication of the mixing of northern and southern signals in the closed field regimes was by *Provan et al*. [2011]. By tracking the northern and southern period signals effectively over most of the epoch where Cassini has been in orbit about Saturn, the following work of *Andrews et al*. [2012] and *Provan et al*. [2013] has delimited the separate overlapping regimes of the northern and southern signals. *Andrews et al*. [2012] also shows that while at middle- and low-invariant latitudes the signals appear to be a generally comparable mix of northern and southern periods, in the northern and southern polar caps the signals exhibit only northern and southern periods, respectively, within a ~10% limit of measurement uncertainty.

Identifying the northern and southern current systems is helped by recognizing that the signals are magnetohydrodynamic and thus organized by the magnetic field. We can use this to extrapolate from the Cassini data to what must occur in the full magnetospheric volume as signals can be expected to map along the magnetic field. Using the idea of MHD mapping, *Andrews et al.*'s [2012] results concerning signal localization can thus be extended to a global field pattern as in the sketch in Figure 1 which shows the Saturn magnetosphere with volumes marked where mixed or single frequency signals are seen. The identification of volumes is based on mapping along the field. Question marks appear in the vicinity of the rings where there is insufficient information. For simplicity, the sketch is shown for equinox, and so the planetary dipole which aligns with the planetary rotation axis is at right angles to the solar wind flow.

On the open field lines of the polar cap, the only detectable signal is that of the respective hemisphere, whereas in the closed field region both periods are detected. The thick lines delimit the regimes where signal properties change.

4. Interpretation

A signal can only be contained within a finite volume if sheet currents flow in the boundary of the volume. It follows that the thick curves in Figure 1 represent surfaces where sheet currents flow on the outer boundary of the open polar cap flux tubes to exclude the mixed signals in the closed field regions and to contain the monofrequency signal of each polar cap. They occur in the vicinity of the interface between the open and closed field lines. The boundary is unlikely to be a vanishingly thin sheet. It is likely to extend over several degrees of latitude. Indeed, strong field-aligned currents are seen between invariant latitudes $\Lambda = \sim 69–74°$. Similarly, the curves bounding the closed field line region represent surfaces on which currents with mixed frequency occur. In the equatorial regions these can be identified as the *Southwood and Kivelson* [2007] currents. The surfaces bounding the closed and open field lines merge as they approach the planet near $\Lambda = \sim 69–74°$. *Talboys et al*. [2009, 2011] have examined high-inclination orbits of Cassini during 2007–2008 and report current intensities of order a few *MA* per radian of azimuth in that region, certainly adequate to feed other current systems of the Saturnian system such as the ring current. However, the currents occur in thin sheets, and Cassini passes through the field perturbations in less than an hour. Part of the current is steady, and part is oscillating, namely, the part we are explaining here. The only published study so far which categorically separates the oscillatory and nonoscillatory components is that of *Southwood and Kivelson* [2009] which uses data from the earliest Cassini-inclined orbits. Their work organizes the data from late 2006 and separates that the component associated with the ~10.7 h oscillations. The amplitude is approximately half of the total current. As *Talboys et al*. [2011] indicate, a full analysis of the high latitude of intense dependence has yet to be done.

The symmetry of the magnetospheric magnetic signals means that at any time there must be paired field-aligned currents going into and out of the ionosphere on opposite sides of the planet. This corresponds to the so-called $m = 1$ azimuthal symmetry of the signals. Ionospheric currents must be present to close these magnetospheric field-aligned currents.

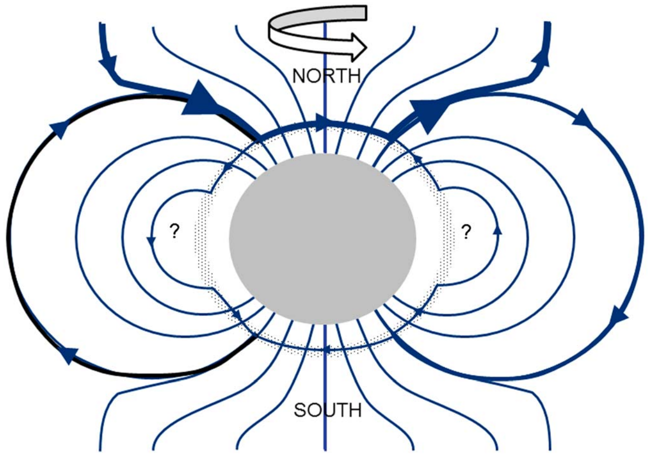

Figure 2. Proposed current configuration for the northern period field oscillations based on the transverse signals. The system of currents rotates about the planetary rotation/magnetic axis at the northern period.

We need to consider two current systems, the northern and southern. The field-aligned currents directly create signals transverse to the background field. Before coming to discuss the significance of the compressional component of the field perturbations (i.e., the component along the background field), let us consider the transverse field perturbations on their own. In Figure 2 we show a sketch of a modified *Southwood and Kivelson* [2007] system shown for the northern signal. This pattern of current rotates about the planet at the northern period. The additional currents are those flowing at the boundary of the polar cap into (eventually) interplanetary space on the open field lines and the closure currents across the polar cap ionosphere and in the ionosphere at lower latitudes. Southwood and Kivelson did not consider the high-latitude signals and so had no way of predicting the presence of the polar cap currents.

The inner edge of the system on flux tubes whose equator is in the vicinity of the rings is not entirely clear. We mark a doubt by question marks and suggest in the sketch that the closed field volume is closed outside the A and B rings and probably on the field lines that thread the innermost conducting plasma of Enceladus origin. However, *Andrews et al.* [2010a] showed direct evidence for the inner field-aligned current system shown in Figure 2, seen through detection of a reduction in the quasi-uniform transverse fields observed in the inner system. However, they report that the magnitude of the field-aligned currents was only ~1 *MA*, compared with ~6 *MA* for the main field-aligned currents at larger distances.

As indicated above, since field-aligned currents must make up part of the current, closure currents will flow in the ionosphere at the feet of the field lines in each polar cap. These are sketched in Figure 3 for the northern system in the northern polar ionosphere. Something analogous will apply for the southern system in the southern polar ionosphere.

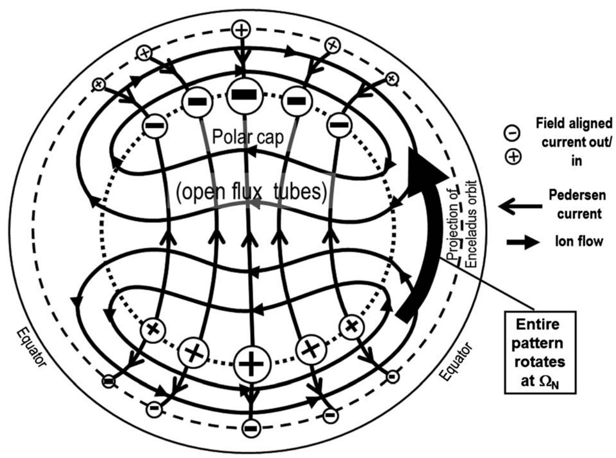

Figure 3. Schematic of current flow in the northern ionosphere for the northern oscillation as shown in Figure 2. Field-aligned currents flow in/out (plus/minus) of the ionosphere on the boundary of the polar cap. The sketch is made in an inertial frame (nonrotating). Accordingly, the flow pattern rotates at the northern frequency, Ω_N, and accordingly is not steady in the frame. The flow system is assumed to penetrate only to the Enceladus orbit and so the projection of the magnetic shell of the orbit into the ionosphere is shown. Also shown are the instantaneous streamlines for the perturbation in the ionospheric flow associated with the current system (a twin vortex).

In Figure 2, no northern currents are shown in the southern polar ionosphere. This is an extreme assumption; the Andrews et al. result only places an upper limit on the penetration of either signal into the opposite cap. If the boundary of the cap is rigid, this would be true. In practice, how much the signal penetrates into the cap depends on the compressibility of the ionospheric medium and the conductivity of the ionosphere on the field lines in question, and we shall return to this question subsequently.

The field-aligned currents at the northern period enter the southern ionosphere near the equatorward edge of the southern field-aligned current region. As there are two distinct frequencies present, there are two different systems, and on the field

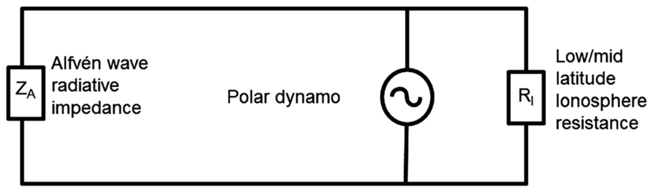

Figure 4. A simple circuit analogy for the fitting of an energy source to the current system in Figure 2, where the energy source is placed in the polar ionosphere.

lines that map to the open-closed field line boundary there will be two systems of current adjacent to each other, if not collocated.

5. The Open Field Lines

The behavior of the ~10.7 h period signals will be different on open field lines from what is expected in the closed field region. Provided that there is no solar wind reconnection on the rotation time scale, the magnetic flux tubes in the polar cap region should rotate with the ions of the ionosphere. Thus, in the polar caps, the rotating signal, being likely to be associated with the rotation of the planet or its polar atmosphere, should be imposed from below, from the ionosphere, on the magnetosphere above. As the field is open, the wave will not reflect and equilibrate. The signal travels upward as a wave and eventually will enter interplanetary space. There is no feedback from above to modify the rotation imposed at the ionosphere and, in particular, no interference from the other hemisphere. The signal going upward and outward would be a large-scale hydromagnetic wave, an Alfvén mode embedded in the rotating plasma. In the ionosphere there will be horizontal current associated with motion. Field-aligned currents will flow on the boundary of the open field region as part of the closure of the ionospheric currents. Then transverse volume currents in the Alfvén wave itself complete the circuit.

6. The emf (Driving Voltage)

The currents shown in Figure 2 fit the pattern reported by *Andrews et al.* [2012] for the magnetic signals well. If that were the only motive for identifying the currents, it would not be a very useful exercise. All that is done is to encapsulate the already known magnetic observations. However, a second issue can be addressed once the current pattern is established. Current systems, such as are shown, represent the transfer of electromagnetic energy within the system. Schematically, one can regard the field-aligned currents as analogous to an electronic circuit. Energy is dissipated in the resistive components and potentially stored in reactive components. However, there must also be voltage sources or an emf in the circuit where energy originates.

The pattern in Figure 2 is remarkably similar to the basic pattern found for solar wind-magnetosphere-ionosphere coupling at Earth. However, the emf in the terrestrial case is imposed across both polar caps, and the pattern of current is fixed with respect to the Sun whereas this one rotates. At Earth there is no doubt that the emf is in the solar wind. However, the fast rotation of Saturn means that this is not possible for the Saturn system.

The circuit loops in the closed field area and on the open field lines are in parallel, and both close through the polar ionosphere. If we take the very simple system of Figure 2, we are drawn to identify the energy source in the polar ionosphere. An equivalent circuit would look something like that in Figure 4. The low- and middle-latitude ionosphere on closed field lines are resistive elements, and the radiation of Alfvén waves into the polar cap renders that element resistive too, as long as no energy is reflected back. The absence of current in the opposite polar cap means that closure for both elements is through the polar cap ionosphere. In the sketch in Figure 4 this element is shown as an alternating current source. In practice, the neutral atmosphere's rotation imposed on the ionospheric ions imposes the periodicity and the currents rotate about the pole rather than oscillate.

A means to get the correct symmetry is to postulate an appropriate rotating structure in the neutral atmosphere [*Jia et al.*, 2012; *Jia and Kivelson*, 2012]. This would consist of a pair of oppositely directed vortices centered where the oppositely directed field-aligned currents are. However, the proposal of the neutral atmosphere as a source is not unique. Vortices could be set up by, for example, convection in the ionized medium itself. Indeed, the location of the currents in the vicinity of the boundary between the very different plasma regimes represented by the open and closed field lines in both hemispheres could be seen to suggest a plasma source.

7. Motion of the Polar Caps

The travel time for signals through the planetary atmosphere is likely to be much less than the 10.7 h period. Accordingly, within the planetary ionosphere, the signal should be quasi-static. It follows that the horizontal ionospheric electric field would be described by a potential.

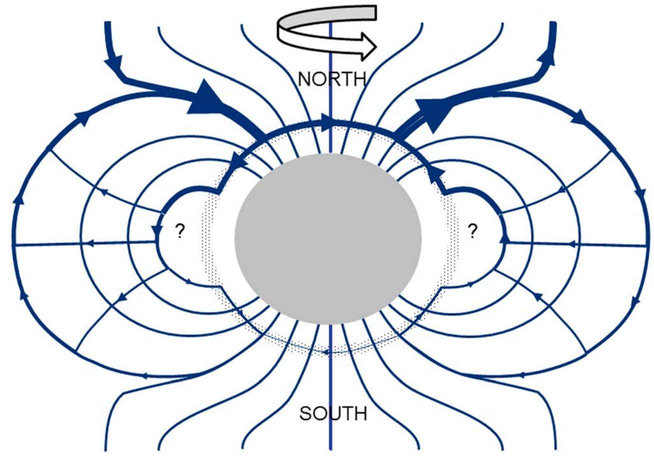

Figure 5. Sketch of the northern current system with allowance made for (i) transverse current flow in the region where there is a plasma ring current of Enceladus origin and (ii) a leakage current across the polar cap opposite to the source ionosphere.

If the signals from one hemisphere do not penetrate the opposite polar cap at all, the electric field for the corresponding signal would go to zero at the boundary of the polar cap in the hemisphere opposite to the source. In the source hemisphere, the observed $m = 1$ (longitudinal wave number) nature of the Saturn signals [*Southwood and Kivelson*, 2007] means that the potential must vary around the source polar cap boundary and the electric field cannot be zero there. A consequence is that the electric rotating disturbance moves the polar cap boundary north and south. At any instant, there should be poleward motion in one (planetary) longitude sector and equatorward in the other. It would produce a distortion in the boundary of the polar cap in which there is an equatorward bulge on one side and a depression or poleward displacement on the other. The auroral zone, in fact, does rock like a cam in just this way [*Nichols et al*., 2008, 2010].

As the cam-like polar cap structure rotates in the ionosphere, the large-scale Alfvén wave it excites would set up a helical motion on the polar cap field lines above in the magnetosphere. In the absence of any reflecting boundary above, the signals would be carried off eventually into interplanetary space. Outward motion has been detected in the ~10.7 h signals on the polar cap field lines. *Provan et al*. [2012] have reported that the ~10.7 h signals deep in the magnetotail show a phase delay of roughly 2.7° per Saturn radius, corresponding to a phase motion away from the planet at a speed of about 2.4×10^2 km s^{-1} [see also *Arridge et al*., 2011a]. Such a speed is quite consistent with an outward propagating magnetohydrodynamic wave. The net effect of the displacement in the polar cap boundary is that the total field in the polar cap cones around a mean direction with a ~10.7 h period.

8. Plasma Motion Outside the Source Polar Cap

A full understanding of the system we propose here will require a full analysis of the magnetohydrodynamics of the system. However, there are two issues that suggest that the ideal model illustrated in Figure 2 needs to be adjusted as a consequence of considering that the currents are actually carried in conducting fluids.

First, let us consider the exclusion of the flow from the polar cap opposite to the source. In Figure 2 we assumed that the electric field and horizontal currents were excluded from the cap in question and noted that this implied that the boundary would need to be rigid for this to be so. However, the rigidity of the polar cap boundary depends on the ionospheric conductivity near the boundary. In practice, the conductivity should be enhanced due to the auroral precipitation in the vicinity of the polar cap boundary. Accordingly, although the cap is unlikely to be perfectly shielded, some vestige of the motion of the boundary experienced in the source hemisphere will appear in the other hemisphere. *Andrews et al*.'s [2012] result does not preclude some leakage as they indicate only that the amplitudes differ by more than a factor of 10 in the polar caps. Figure 5 is a revision of Figure 2 and includes a leakage current crossing the opposite cap.

Figure 5 shows a second modification to Figure 2. Closure currents are sketched on the closed field lines. These are volume currents and are carried by the Saturnian magnetospheric plasma from Enceladus and its vicinity.

This plasma is trapped and slowly being transported outward. The process is spontaneous because ionized material from Enceladus cannot just build up and remain trapped on closed flux tubes. The inward gradient of ionized material will act as an internal source of energy for flux tubes to start an overturning motion. Plasma interchange instability will occur [*Southwood and Kivelson*, 1989]. In a situation with a steady source of ionized material from Enceladus, a spontaneous overturning interchange motion results. Energy is released by denser flux tubes moving outward and adiabatically losing energy as the flux tube volume increases; less dense tubes move inward gaining less energy than released on the overdense tubes. Plasma overturning thus carries material from Enceladus' vicinity to eventual loss (mainly down the tail) from the closed field lines into interplanetary space. The scale of the overturning cells depends on boundary conditions.

Thus, in addition to planetary rotation, there is a second source of energy inside the Saturn system. Indeed, *Goldreich and Farmer* [2007] and *Gurnett et al*. [2007] have separately proposed this as the source of the ~10.7 h oscillations.

If the plasma on the closed field lines were rotating at the same rate as the polar caps, as was assumed in the works of *Goldreich and Farmer* [2007] and *Gurnett et al*. [2007], this energy source would contribute in maintaining the current system we are discussing here. However, the plasma on closed field lines is found not to corotate but rather to be moving around the planet at a rate roughly one half of the planetary rate, corresponding to a period in the range 20–22 h [*Wilson et al*., 2009; *Thomsen et al*., 2010; *Arridge et al*., 2011b]. In such circumstances, because the northern and southern polar oscillation signals feed across both polar cap boundaries, they can modulate plasma behavior at lower latitudes where the overturning is occurring. However, the difference in rotation rates of the polar cap and subauroral low-latitude plasma means that it is difficult for the net release of energy by the interchange motion of the low-latitude plasma to contribute coherently to the maintenance of the 10.7 h signals. Certainly, it could not be a linear process. Accordingly, we suggest that the root source of energy for the ~10.7 h signals is the dynamo process in the caps proposed in section 6.

Nonetheless, current flow transverse to the field will occur in the ring current region. In the subcorotating region the ~10.7 h rotation of the polar cap causes a reversible passive modulation of the plasma pressure which must be counterbalanced by a compression/decompression of the magnetic field pressure, thus requiring transverse currents. Indeed there is a ~10.7 h compressional signal [see for instance, *Andrews et al*., 2010a, 2010b]. Figure 5 thus also indicates that distributed transverse current flow in the closed field region of the magnetosphere and will modify the system sketched in Figure 2. The transverse currents flow in parallel to the ionospheric currents at the feet of the closed field lines. Thus, part of the current closure from the polar cap source is through distributed transverse currents flowing through the plasma in the closed field line region. The transverse currents and the associated compressional field component in the signal can be regarded as a rotating partial ring current. However, this can be a misleading usage; in this case the term ring current does not mean there is a physically distinct group of plasma particles rotating with either the northern or southern ~10.7 h period.

9. The Andrews et al. Model

One further model deserves discussion. *Andrews et al*. [2010b] proposed model current systems which recognize both the presence of two frequencies and the north-south polarization difference of the field oscillations. Their model follows an earlier discussion of the currents associated with the southern signals by *Andrews et al*. [2010a]. *Southwood and Kivelson* [2007, 2009] had paid primary attention to explaining the transverse part of the signals. As we have discussed in the previous section there is a compressional signal, and *Andrews et al*. [2010b] emphasize this. The sketches in Figure 6 are adapted from *Andrews et al*. [2010b, Figure 9]. Figure 6a shows the important elements of the currents in the system for the northern signal. The currents and field rotate. If we take the sketch as the prime meridian, Figure 6b shows the corresponding northern meridional perturbation fields in a plane $\pi/2$ ahead in phase. The field line sketch well encapsulates the observed signal polarization. The proposed associated currents in Figure 6a have essential features in common with our sketch in Figure 5 but do not include bounding currents on the polar field lines, distributed transverse currents in the equatorial plasma, and an extension of the field-aligned currents into the opposite hemisphere as required by the continuity of the transverse signals across the equatorial region. The perturbation field in Figure 6b is solenoidal and indicates the presence of polar currents directed out of the page at the instant shown, with geometry representing the condition for SKR maximum when the Sun is to the right. Overall, the current system proposed here in Figure 5 may be viewed as combining features of those proposed previously by *Southwood and Kivelson* [2007] and *Andrews et al*. [2010a, 2010b].

The southern currents and field pattern are exactly like those illustrated but inverted about the equator. The sketch of the perturbation field lines in Figure 6, based directly on data, do show in a simple manner the difference in northern and southern polarization, with spherical polar perturbation fields ΔB_r and ΔB_θ being in

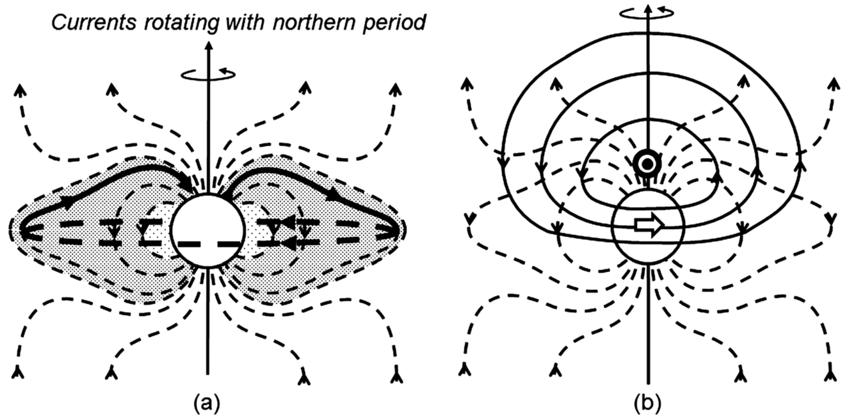

Figure 6. Sketches of proposed (a) currents and (b) perturbation fields adapted from *Andrews et al.* [2010b], for the northern system. The corresponding southern system is a simple inversion of the currents and perturbation fields in each plot. The proposed current system is shown by the thick continuous lines in Figure 6a. Essential correspondences for the northern system between Figures 6a and 5 are evident. The continuous lines in Figure 6b indicate the rotating perturbation magnetic fields in the principal meridian, with the sense of the current flow out of the page at the instants shown indicated by the circled dot.

phase for the southern system shown on the left, and in antiphase for the northern system shown on the right (ΔB_r and ΔB_ϕ are in quadrature for both). However, the rotating compressional magnetic field component (ΔB_θ near the equatorial plane) has the opposite phase relation to the transverse meridional component (ΔB_r near the equatorial plane) for northern and southern signals. Recalling that all of the Maxwell off-diagonal magnetic stress components have the form

$$P_{xy} = -\frac{\delta B_x \delta B_y}{\mu_0},$$

(where x and y are any mutually perpendicular coordinate directions), that ΔB_r and ΔB_θ are in phase or strict antiphase for southern and northern signals, respectively, implies momentum transfer is opposite for northern and southern signals. This is not surprising but once again points to a high-latitude source for the current system as a whole.

10. Conclusions

Using the results of *Andrews et al.* [2012] on the distribution of the separate northern and southern periodic magnetic signals in Saturn's magnetosphere, we have proposed a global current system for each hemisphere. We have deduced that the emf or voltage generating the signals originates in the respective polar caps, i.e., the open field line regions. In particular, we propose that the source has to be an ionospheric dynamo ultimately driven by the neutral atmospheric rotation.

In the source region in the polar cap ionosphere the transverse ionospheric currents satisfy $\boldsymbol{j}.\boldsymbol{E} < 0$ in the frame of the ions. The dynamo action produces horizontal currents which emerge as hemispherically unbalanced field-aligned currents rather like those proposed by *Southwood and Kivelson* [2007] on the boundaries separating closed and open field in each hemisphere and then are closed through distributed currents flowing across the field in the open and closed field regions. In the open field polar cap transverse volume currents in Alfvén waves complete the circuit. On the closed field lines, transverse currents will be carried through the plasma trapped there and also through horizontal currents at the field line feet in the ionosphere in the closed field line region. In these regions $<\boldsymbol{j}.\boldsymbol{E}>$ is positive.

We have also achieved a synergy between the earlier *Southwood and Kivelson* [2007] and the models of northern and southern fields and currents put forward by *Andrews et al.* [2010a].

Our model of current flow is consistent with the idea of rotating neutral atmospheric vortices with azimuthal wave number 1 in each hemisphere as proposed by *Jia et al.* [2012] and *Jia and Kivelson* [2012] as long as the vortices are centered on the open-closed field line boundary in each hemisphere. However, that model which roots not only the rotation but also the vortices in the neutral atmosphere is not unique. The location of the center of the disturbances within the boundary between open and closed magnetic flux suggests to us it is likely that the location of the disturbances is rooted in a plasma effect in the ionized atmosphere. It is intended to discuss this option in a future paper.

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