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Discovery of a north-south asymmetry in Saturn's radio rotation period

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[1] For many years it has been known that Saturn emits intense radio emissions at kilometer wavelengths and that this radiation is modulated by the rotation of the planet at a rate that varies by up to one percent on a time scale of years. Recent radio observations from the Cassini spacecraft have revealed the appearance of a second component, with a rotation period of about 10.6 hours, significantly less than the period of the previously known component, which is currently about 10.8 hours. In this paper we show that the first component originates from the southern auroral region, and that the second component originates from the northern auroral region. This north-south asymmetry in the rotation period has potentially important implications on how angular momentum is transferred from the interior to the magnetosphere. **Citation:** Gurnett, D. A., A. Lecacheux, W. S. Kurth, A. M. Persoon, J. B. Groene, L. Lamy, P. Zarka, and J. F. Carbary (2009), Discovery of a north-south asymmetry in Saturn's radio rotation period, *Geophys. Res. Lett.*, *36*, L16102, doi:10.1029/2009GL039621.

1. Introduction

[2] An intense radio emission from Saturn at kilometric wavelengths, now called Saturn Kilometric Radiation (SKR), was discovered in 1980–81 during the Voyager 1 and 2 flybys of Saturn [*Kaiser et al.*, 1980]. Extended observations by the Voyager spacecraft while in the vicinity of Saturn showed that the SKR displayed a clock-like rotational modulation with a period of 10h 39 m 24 ± 7s [*Desch and Kaiser*, 1981], close to the rotation period obtained from observations of clouds. This period was later adopted as the internationally accepted rotation period of Saturn [*Davies et al.*, 1995]. The rationale for this decision was based on the belief that the motion of the magnetospheric particles responsible for the radiation was controlled by the planetary magnetic field, which is linked to the deep interior. However, this belief was cast into doubt in 1997 when radio observations from the solar orbiting Ulysses spacecraft revealed the presence of small, approximately one percent, long-term variations in the period [*Galopeau and Lecacheux*, 2000]. Such variations, although small, are not possible for a large rapidly rotating planet such as Saturn. The existence of these small variations was subsequently confirmed by radio measurements from the Cassini spacecraft [*Gurnett et al.*, 2005], which during the approach to Saturn from 2002 to 2004 showed that the period had shifted to about 10.76 h. Even more puzzling, recently *Kurth et al.* [2008], using data from Cassini in orbit around Saturn, discovered the appearance of a second component, at times as strong as the first, with a period of about 10.6 h. The purpose of this paper is to further investigate the characteristics of these two components.

2. Rotational Modulation Analysis

[3] Before discussing the results it is useful to discuss how the Cassini radio measurements are analyzed to reveal the rotational modulation of SKR. Since the SKR spectrum is generally most intense in the frequency range from about 20 to 500 kHz [*Kaiser et al.*, 1981], the first step is to integrate the received power spectral density over this frequency range to obtain a quantity we call the intensity, in Watts/m^2. Because Cassini is in a highly eccentric orbit around Saturn, there are periodic variations in the intensity caused by the $1/R^2$ dependence on the radial distance, R, from the planet. To correct for these variations, the intensities are normalized by dividing by the average intensity over one rotation of the planet. The next step is to convert the normalized intensities to a frequency-time spectrogram, such as shown in Figure 1. To limit the spectrum analysis to a specific time interval the normalized intensities are multiplied by a Hanning weighting function [*Priestly*, 1981], where the duration of the window has been chosen to be 240 days. In order to generate the temporal variations shown in the spectrogram the center of the window is advanced in 30 day steps. To compute the frequency spectrum within each time window the intensities are sorted and averaged in 1 degree longitude bins for a series of assumed rotation rates, ω. For each ω the resulting averages are fit to a sinusoidal function of longitude, Asin $(2\pi\lambda_{\mathrm{Sun}}/360^\circ)$, in order to determine the amplitude, A, of whatever modulation may be present. The modulated power at this specific rotation rate and time is taken to be proportional to the square of the peak-to-peak amplitude of the sine wave fit. It is this quantity, $P = (2A)^2$, called the normalized peak-to-peak power, that is represented by the color in the spectrogram.

[4] In Figure 1 the spectral line labeled "first SKR component," is the component first detected in 2004 by Cassini during the approach to Saturn [*Gurnett et al.*, 2005]. This component is seen to have a rotational modulation rate that varies from about 797 to 803 deg/day. Because of the variable period, and the long time since the Voyager 1 and 2

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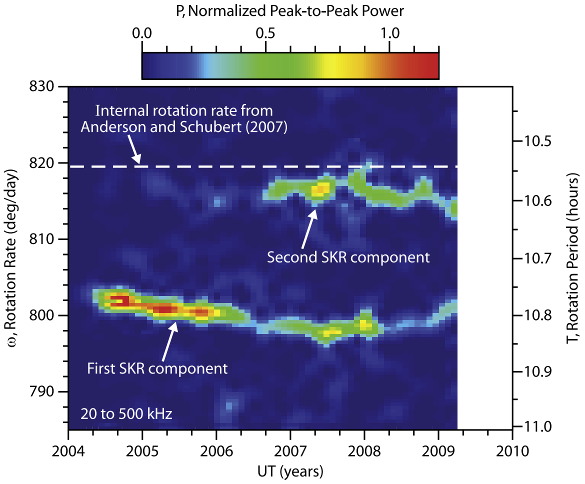

Figure 1. A color-coded frequency-time spectrogram that shows the normalized peak-to-peak power of the SKR modulation as a function of Universal Time (UT) on the horizontal axis, and the rotation rate, ω, on the left vertical axis and the period, T, on the right. The horizontal dashed line shows the internal rotation rate of Saturn inferred by *Anderson and Schubert* [2007] from gravity measurements of the oblateness of the planet.

observations, we do not know if this is the same component that was first detected by Voyager, or how it relates to the variable component detected several years later by Ulysses. The spectral line labeled "second SKR component," which was first detected by *Kurth et al.* [2008] starting in late 2006, is seen to have a rotational modulation rate that varies from about 814 to 818 deg/day. It is useful to compare these radio modulation rates to the measurement of the internal rotation rate by *Anderson and Schubert* [2007], which is based on gravity measurements of the oblateness of Saturn. The inferred internal rotation period that they obtained, 10 h 32 m 35 ± 13s, corresponds to a rotation rate in our units of 819.48 ± 0.25 deg/day. This rotation rate is shown by the horizontal dashed line in Figure 1.

[5] In an effort to illuminate the origin of the two SKR components we decided to investigate the possibility of a north-south asymmetry. Initially, we thought that such an asymmetry was unlikely. In particular, the magneto-hydrodynamic (MHD) model that is widely used to describe the motions of magnetospheric plasmas predicts that the plasma, to a first approximation, should be "frozen" to the rotating magnetic field lines [*Cowling*, 1957]. This implies that the northern and southern regions of the magnetosphere should rotate at the same rate. Nevertheless, we decided to proceed. To carry out the search for a north-south asymmetry the data were divided into two sets, one for latitudes greater than 10°, and the other for latitudes less than −10°. The latitudinal band near the equator, between ±10°, was excluded to reduce the simultaneous detection of radiation from both the northern and southern SKR sources, which previous studies have shown to be located at high latitudes along the auroral field lines on the pre-noon side of the magnetosphere [*Kaiser and Desch*, 1982; *Lamy et al.*, 2008]. Using the same software used to produce Figure 1, two spectrograms were produced, one for the northern hemisphere, and the other for the southern hemisphere. To our surprise, the resulting spectrograms, which are shown in Figure 2, clearly revealed that the first component originates from the southern hemisphere, and the second component originates from the northern hemisphere. The black areas in the spectrograms are from regions where there were either no data (when the spacecraft was not within the specified latitude limits), or not enough data to give reliable spectrums. The discrimination between the northern and southern hemisphere SKR sources is made strikingly clear if the spectrums are averaged over the most recent data, from 29 Feb. 2008 to 19 May 2009, where the spacecraft made an extended series of excursions to very high northerly and southerly latitudes. These spectrums are shown in Figure 3. Similar spectrums are obtained if the equatorial exclusion threshold is changed from ±10° to ±20°, or to ±30°.

[6] Compared to other rotation rate measurements these results show that (a) the rotation rate of the northern SKR source lags the internal rotation rate given by *Anderson and Schubert* [2007] by about 2 deg/day; (b) the rotation rate of southern SKR source lags the internal rate by about 19 deg/day; and (c) the rotation rate of the southern SKR source is very close to the rotation rates of the equatorial magnetic fields, plasmas and energetic particles reported by *Southwood and Kivelson* [2007], *Gurnett et al.* [2007], *Carbary et al.* [2007], *Burch et al.* [2008], *Andrews et al.* [2008], *Provan et al.* [2009] and others.

3. Discussion

[7] Based on observations of a similar type of radio emission at Earth it is widely believed that SKR is produced by precipitating auroral electrons via the electron cyclotron maser instability [*Wu and Lee*, 1979; *Galopeau et al.*, 1989; *Zarka*, 1998]. Just what causes the SKR to blink on and off

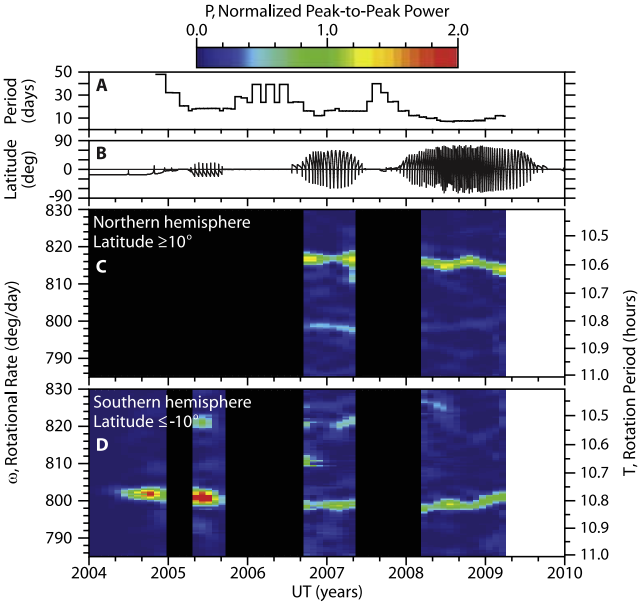

Figure 2. (a) Period and (b) latitude of Cassini's orbit. Spectrograms comparable to Figure 1 in which the data have been restricted (c) to the northern hemisphere at latitudes greater than 10° and (d) to the southern hemisphere at latitudes less than −10°. The black areas are regions where there is either no data available due to the ±10° equatorial exclusion, or too little data to give a reliable spectrum.

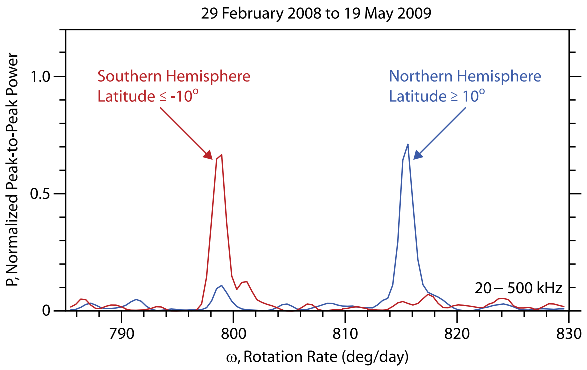

Figure 3. Rotational modulation spectrums averaged over the interval from 29 Feb. 2008 to 19 May 2009 where the spacecraft had a unusually long series of excursions to high northerly and high southerly latitudes.

with near clock-like precision is not known precisely, but is almost certainly related to the rotation of plasma and magnetic fields in Saturn's magnetosphere, sometimes called the "cam" [*Southwood and Kivelson*, 2007; *Gurnett et al.*, 2007; *Carbary et al.*, 2007; *Burch et al.*, 2008; *Andrews et al.*, 2008; *Provan et al.*, 2009]. What is surprising is that the plasma features responsible for the radio emission rotate at different rates in the two hemispheres. If the northern and southern auroras are on the same closed magnetic field lines, then according to the frozen field theorem the plasma features responsible for the radio emissions in the two hemispheres should be locked together at the same rotation rate. The frozen field problem can be avoided if the two features are on adjacent magnetic L-shells, which would allow them to pass by each other. Such a mechanism has already been suggested by *Dessler* [1985], who proposed that latitude dependent zonal winds could drive different rotation rates on different L-shells. However, Dessler's mechanism does not explain why the radio emission on one such L-shell would be preferentially produced in only one hemisphere, and not the other.

[8] To investigate the problem further it is useful to discuss the mechanism by which the internal rotation of Saturn is transferred to the magnetospheric plasma. Due to Saturn's large rotation rate and strong magnetic field the magnetospheric plasma, which tends to move along the magnetic field lines, is drawn outward by the centrifugal force and accumulates near the equatorial plane in the form of a disk (or torus). In such a system the rotation of the planet is transferred to the disk by field-aligned currents, $J_{\|}$, that link the conducting upper regions of the atmosphere to the plasma disk [*Hill*, 1979; *Cowley and Bunce*, 2003]. Since plasma is being continually added to the disk by Saturn's moon Enceladus [*Kivelson*, 2006] and lost by the interaction with the solar wind, in steady state a torque must be applied to the disk in order to maintain its rotation rate, which from energy considerations must be slower than Saturn's internal rotation rate. This torque is produced by the $\mathbf{J}_{\perp} \times \mathbf{B}$ force that arises from the closure of the field-aligned currents within the plasma disk. An equal but opposite torque is applied to the upper atmosphere at the foot of the magnetic field lines by the closure of the field-aligned currents through the conducting layers of the upper atmosphere.

[9] An unusual feature of Saturn is that its magnetic moment is aligned almost exactly (<1°) along its rotational axis [*Connerney et al.*, 1984]. If the rotating system described above is completely symmetric, with the same atmospheric conductivities in both hemispheres, then the field-aligned current system would have north-south symmetry, and there would be no reason to expect different rotation rates in the two hemispheres. However, the Saturnian system does have several north-south asymmetries that need to be considered. Due to the tilt of its rotational axis relative to the ecliptic plane, there is (a) an asymmetry caused by the difference in the solar illumination in the two hemispheres, and (b) an asymmetry caused by the non-zero incidence angle of the solar wind relative to the magnetic equator [*Khurana et al.*, 2009]. Also, there is (c) an asymmetry caused by the small (0.04 R_S) northward shift of the magnetic dipole along Saturn's rotational axis [*Connerney et al.*, 1984].

[10] To illustrate the possible effects these asymmetries might cause we first focus on the north-south difference in the solar illumination. During the first ~5 years of Cassini's orbital tour the southern polar region has been sunlit, whereas the northern polar region has been in darkness. Due to ultraviolet ionization in the upper atmosphere this difference in solar illumination increases the cross-field conductivity, called the Pedersen conductivity [*Parks*, 2004], of the southern polar region relative to the northern one. The higher conductivity has the effect of increasing the field-aligned currents in the southern hemisphere, thereby increasing the coupling to the plasma disk. The opposite effect occurs in the northern hemisphere. If the frozen-field condition is satisfied, i.e., $E_{\|} = 0$, this difference in coupling would not cause a difference in the rotation rate of the auroral plasmas in the two hemispheres. However, if there are nonzero parallel electric fields, $E_{\|} \neq 0$, which is known to be the case in Earth's auroral regions [*Mozer and Kletzing*, 1998], then significant north-south differences in the rotation rate can occur on the same L-shell. During the recent era, with the southern polar region in sunlight, the predicted effect would be for a smaller slippage of the auroral plasma relative to the equatorial plasma in the southern hemisphere (due to the better coupling), and a larger slippage in the northern hemisphere.

[11] Qualitatively, the predictions of the solar illumination model are consistent with the observed differences in the rotation rates summarized earlier. In both cases the direction of the slippage (planet rotating faster than the plasma disk) is consistent with the expected direction of angular momentum transfer, from the planet to the plasma disk. Because of the strong coupling in the southern hemisphere this slippage would involve a large retrograde transfer of angular momentum to the atmosphere in the southern polar cap region, and a much smaller transfer in the northern hemisphere. A specific prediction of the solar illumination model is that the strength of the coupling to the northern and southern polar regions should reverse at Saturn's equinox (on 10 August 2009), which would cause a reversal of the SKR rotation rates in the two hemispheres. Of the two remaining asymmetries, we note that the small northward shift in Saturn's magnetic moment would tend to increase the Pedersen conductivity in the southern hemisphere due to the weaker magnetic field strength. This effect

would increase the coupling in the southern hemisphere, but would not reverse at the equinox. The north-south distortion of the magnetosphere caused by the non-zero incidence angle of the solar wind relative to the magnetic equator is more difficult to analyze, but would also reverse at the equinox. Obviously, further analyses need to be performed to determine which, if any, of these asymmetries play a role in controlling the two SKR rotation rates.

4. Conclusion

[12] Although the north-south asymmetries discussed above have the potential to be important factors in explaining the hemispherical difference in the SKR rotation rates, there are other more complex effects that also need to be considered. For example, high altitude zonal winds can affect the field-aligned current systems via V × B (dynamo) electric fields generated in the conducting upper layer of the atmosphere. Hemispherical differences in the zonal wind speeds could easily cause significant north-south differences in the field-aligned current systems. It would take a difference of only about 50 m/s in the zonal winds in the two auroral regions to account for the difference in the two rotation rates. Finally, there is the possibility that the asymmetry may be due to some internal process associated with the generation of Saturn's magnetic field. At present there is no theoretical or experimental evidence that the internally generated magnetic field could vary on such short time scales.

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