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## The reversal of the rotational modulation rates of the north and south components of Saturn kilometric radiation near equinox

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[1] It has been known for many years 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 slowly on time scales of years. Recently it has been shown that the radio emission consists of two components that have different rotational modulation rates, one emitted from the northern auroral region and the other emitted from the southern auroral region. In this paper we show using radio measurements from the Cassini spacecraft that the rotational modulation rates of the northern and southern components reversed near Saturn's recent equinox, which occurred on 11 August 2009. We show that a similar reversal was also observed by the Ulysses spacecraft near the previous equinox, which occurred on 19 November 1995. The solar control implied by these reversals has important implications on how Saturn's rotation is coupled into the magnetosphere. **Citation:** Gurnett, D. A., J. B. Groene, A. M. Persoon, J. D. Menietti, S.-Y. Ye, W. S. Kurth, R. J. MacDowall, and A. Lecacheux (2010), The reversal of the rotational modulation rates of the north and south components of Saturn kilometric radiation near equinox, *Geophys. Res. Lett.*, 37, L24101, doi:10.1029/2010GL045796.

### 1. Introduction

[2] During the 1980–81 Voyager 1 and 2 flybys of Saturn, an intense radio emission was discovered originating from the high-latitude auroral regions of Saturn's magnetosphere at frequencies from about 50 to 500 kHz [Kaiser *et al.*, 1980; Kaiser and Desch, 1982; Lecacheux and Genova, 1983]. Since the wavelength of the radiation was in the kilometer range this radio emission is now called Saturn Kilometric Radiation (SKR). The Voyager observations also showed that the SKR had a clock-like rotational modulation with a period of 10.6567 h [Desch and Kaiser, 1981]. Because the rotation period of Saturn cannot be determined accurately from the motion of clouds, and because the source of the radiation was thought to be linked to the deep interior via the planetary magnetic field, this period was adopted as the internationally recognized rotation period of Saturn [Davies *et al.*, 1996]. However, soon afterwards radio observations by the Ulysses spacecraft showed that the modulation period varied by up to one percent on times scales of years

[Lecacheux *et al.*, 1997; Galopeau and Lecacheux, 2000]. The long-term variability was subsequently confirmed by radio observations from the Cassini spacecraft during the approach to Saturn in 2002 to 2004 [Gurnett *et al.*, 2005]. Further observations after Cassini was inserted into orbit around Saturn on 1 July 2004 revealed an even more puzzling feature, which is the presence of two distinct SKR modulation periods [Kurth *et al.*, 2008], one at about 10.6h that originates from the northern auroral region, and the other at about 10.8h that originates from the southern auroral region [Gurnett *et al.*, 2009]. In this paper we show using more recent Cassini observations that the rotational modulation rates of the northern and southern components have converged and reversed shortly after Saturn's equinox, which occurred on 11 August 2009. We also show that a similar reversal occurred in the Ulysses radio observations during the previous equinox, which was on 19 November 1995.

### 2. Cassini Observations

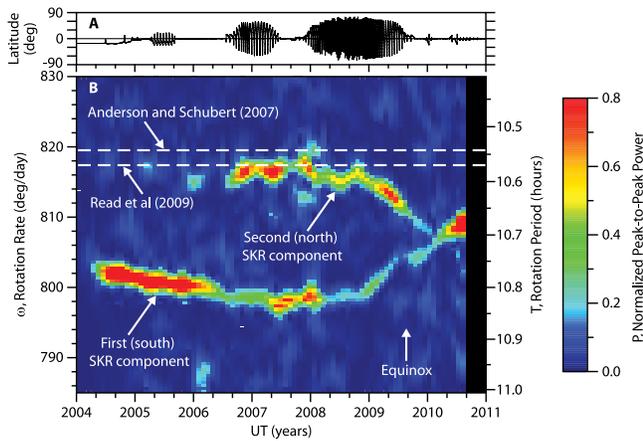
[3] A color-coded frequency-time spectrogram showing the rotational modulation rates of the two SKR components is shown in Figure 1. The spectrogram starts on 1 January 2004, shortly before Cassini was inserted into orbit around Saturn, and extends to the latest data processed, which was on 31 October 2010. The spectrum processing uses a 240-day Hanning weighting function to define the time window for the spectrum analysis. The center of the window is stepped forward in 30 day intervals to generate the time axis in the spectrogram. The color shows the normalized peak-to-peak power of the SKR modulation. Further information on the spectrum processing is given in the auxiliary material.<sup>1</sup> The band labeled "First SKR component" is the component first detected by Cassini during the approach to Saturn, and the component labeled "Second SKR component" is the component discovered by Kurth *et al.* [2008]. As shown by Gurnett *et al.* [2009] the first component originates from the southern hemisphere, and the second component originates from the northern hemisphere. The two dashed lines near the top of the spectrogram are the internal rotation rates of Saturn inferred by Anderson and Schubert [2007] based on gravity measurements of the oblateness of Saturn, and by Read *et al.* [2009] based on the stability of Saturn's zonal wind system.

[4] Figure 1 shows that prior to 2009 the rotational modulation of the two SKR components remained well separated in two slowly varying bands, around  $800 \pm 2$  deg/day for the first (south) component, and around  $816 \pm 2$  deg/day for the second (north) component. However, starting in late 2008

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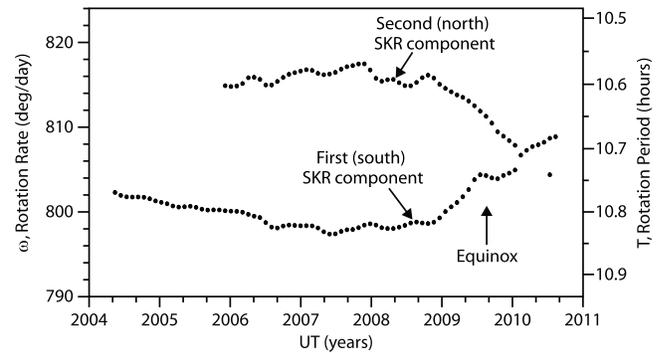
<sup>3</sup>LEISA, UMR 8109, Observatoire de Paris, CNRS, Meudon, France.



**Figure 1.** (a) The latitude of Cassini, and (b) a color-coded frequency-time spectrogram from the Cassini Radio and Plasma Wave Science (RPWS) instrument. The spectrogram shows the normalized peak-to-peak power of the SKR modulation as a function of Universal Time (UT) on the horizontal axis, the rotational modulation rate,  $\omega$ , on the left vertical axis, and the rotation period,  $T$ , on the right vertical axis. The white dashed horizontal lines are the internal rotation rates inferred by *Anderson and Schubert* [2007] and *Read et al.* [2009].

the modulation rates of the two components began to converge. Once this trend was established, the modulation rates followed relatively linear trends, with drift rates of about  $\pm 5$  deg/day per year, and crossed in early 2010, shortly after Saturn's equinox. As can be seen the intensity of the second (northern) component began to decrease after about mid-2009 and is now only marginally detectable near the crossing point. In contrast, the first (southern) component continued through the crossing point with easily detectable intensities, and has even intensified in the most recent data. Polarization measurements in this region of higher intensity (July to August 2010) show that the polarization is left-hand with respect to the wave vector, which is consistent with a southern source [*Kaiser and Desch*, 1982]. The diminished intensity of the northern component is almost certainly a visibility effect caused by the spacecraft orbit, which transitioned from high-latitude coverage to equatorial coverage around mid-2009. Most likely the low intensity of the northern source is due to a difference in the beaming pattern in the two hemispheres, which prevents the radiation from the northern source from easily reaching the equator. Note from Figure 1 that the northern source is either undetectable, or very weak, whenever the spacecraft is in a near-equatorial orbit, or south of the equator. This asymmetry is probably related to the  $0.038 R_S$  (Saturn radii) northward offset of Saturn's rotationally aligned dipole [*Connerney et al.*, 1984], which causes a corresponding poleward shift in the northern SKR source region [*Cecconi et al.*, 2009].

[5] To obtain an accurate determination of the time at which the two components crossed, parabolic fits were made to the two spectral peaks in each of the 30-day analysis intervals in order to accurately determine the two modulation rates. The results are shown in Figure 2. Based on this plot we estimate that the reversal occurred in late February 2010, approximately seven months after the

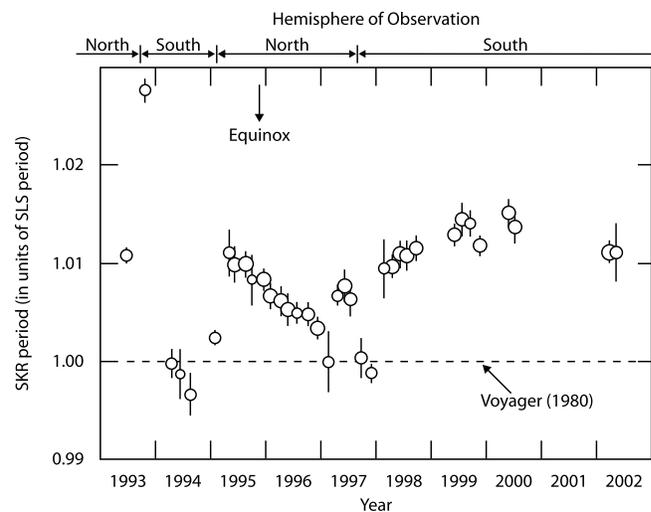


**Figure 2.** A plot of the rotational modulation rates of the two SKR bands at 30-day intervals from the spectrogram in Figure 1. Note that the modulation rates of the two components reversed about 7 months after the equinox.

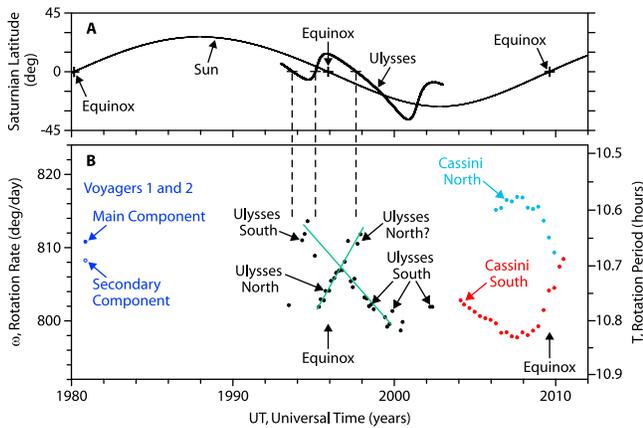
equinox. Another notable feature in Figure 2 is the near mirror symmetry of the two components about an average modulation rate of  $\sim 807$  deg/day.

### 3. Ulysses Observations

[6] Since the Cassini observations provided evidence of a reversal in the modulation rates of the north and south SKR components near equinox, it is interesting to see if a similar reversal could be found in the Ulysses radio measurements, which provided observations around the previous 19 November 1995 equinox. A plot of the SKR rotational modulation period detected by the Ulysses radio instrument around this time is shown in Figure 3. For the techniques used to process the Ulysses data see *Galopeau and Lecacheux* [2000]. As can be seen there is considerable scatter in the modulation rates, interspersed with intervals where no SKR could be detected. This is in part due to the considerable distance of Ulysses from Saturn (8 to 15 AU),



**Figure 3.** The rotational modulation period of SKR emissions detected by Ulysses around the time of the 19 November 1995 equinox, adapted from *Lecacheux* [2002]. The rotation period in the Saturn Longitude System (SLS) is 10.6567 h [*Davies et al.*, 1996]. The hemisphere of the observations, north or south, is indicated at the top of the plot.



**Figure 4.** (a) The Saturnian latitudes of the Sun and Ulysses, and (b) a plot of the SKR rotational modulation rates detected by Voyager 1 and 2, Ulysses, and Cassini as a function of time for one complete revolution of Saturn around the Sun. The equinoxes are marked by the square crosses. The vertical dashed lines mark Ulysses crossings of Saturn's equator.

which makes the signal very weak, much weaker than for the Cassini observations. Nevertheless, there is a clear organization of the data in some regions. In particular, there is a decreasing trend to the modulation period in the northern hemisphere from early 1995 to late 1997, and a somewhat similar increasing trend in the southern hemisphere from about mid-1997 to mid-2000.

[7] To see how the Ulysses observations might be related to the Cassini observations, we have converted the periods in Figure 3 to rotation rates in deg/day and plotted them, along with the recent Cassini measurements, in Figure 4b. The time scale includes one complete 29.5-year revolution of Saturn around the Sun. The equinoxes are marked by crosses in the top panel, which shows the Saturnian latitude of the Sun and of Ulysses. When plotted on this scale one can see that there are two well-defined linear features in the Ulysses measurements (indicated by the green lines) that intersect in August 1996, about nine months after the equinox. After labeling the points according to which hemisphere the observations were made, one can see that the modulation rates associated with the northern and southern branches reverse at the intersection of the green lines, very similar to the reversal that occurred in the Cassini data. Note that the modulation rate at the intersection,  $\sim 807$  deg/day, is almost exactly the same as for the Cassini observations. One can also see that after the reversal the lower (south) branch of the Ulysses observations links up smoothly with the lower (south) branch of the Cassini observations. Although the slopes of the linear features are somewhat less than the reversal observed by Cassini, the location of the intersection several months after the equinox, the similarity of the rotational modulation rate at the intersection, and the linkage of the declining southern branch of the Ulysses observations to the southern branch of the Cassini observations, provide a strong case that Ulysses detected a reversal of the northern and southern SKR modulation rates shortly after the 19 November 1995 equinox.

[8] It is also of interest to compare the Cassini and Ulysses observations to the SKR observations obtained

during the Voyagers 1 and 2 flybys of Saturn, which were on 12 November 1980 and 26 August 1981. It turns out that these flybys also occurred near an equinox, which was about a year earlier, on 3 March 1980. Measurements of the SKR modulation rate spectrum were obtained for a 267-day period around the two flybys. Two statistically significant peaks were found, one main peak at 810.76 deg/day, and a much weaker secondary peak at 808.23 deg/day [Desch and Kaiser, 1981]. As can be seen in Figure 4, these modulation rates are much closer to the 807 deg/day rate at the Ulysses and Cassini reversals than they are to the maximum and minimum rates (818 and 798 deg/day) in the regions well away from the reversals. Therefore, based on the trends in the Cassini and Ulysses data, the Voyager measurements appear to be consistent with what would be expected for a reversal about a year or so after the 3 March 1980 equinox. Further analysis of the Voyager data should be performed to determine if separate north and south modulation rates can be resolved, and if they are, how they relate to the Cassini and Ulysses observations.

#### 4. Conclusions

[9] We have shown that the rotational modulation rates of the northern and southern components of SKR detected by Cassini reversed about seven months after the 11 August 2009 equinox, and that a similar reversal occurred in the Ulysses SKR data about nine months after the 19 November 1995 equinox. The central question that needs to be addressed regarding these observations is what causes the complicated temporal variations. The problem is particularly vexing given the fact that Saturn's magnetic dipole axis is aligned almost exactly ( $< 1^\circ$ ) with its rotational axis [Smith *et al.*, 1980], which provides no obvious source for these variations.

[10] At present there are two competing theories for what causes these long-term variations: internal and external. The internal model postulates that instabilities in Saturn's internal magnetic dynamo produce rotating "magnetic anomalies" that, via their linkage to the magnetosphere, provide rotational control of radio emissions as well as other magnetospheric phenomena [Stevenson, 1983; Dessler, 1985]. The external model postulates that the magnetosphere slips with respect to the rotating axially aligned dipole, and that the slippage rate is controlled by field-aligned currents that couple the magnetosphere to the upper atmosphere of Saturn [Gurnett *et al.*, 2007; Goldreich and Farmer, 2007]. Although neither model has been conclusively established, the increasingly complex rotational modulation of the SKR has made the internal model seem less and less viable. For example, the existence of two rotational modulation rates, one in the north and one in the south, with differences as large as 18 deg/day, means that the internal magnetic field would have to wrap around by one rotation every 20 days. This short time scale is inconsistent with the time scales normally quoted for large electrically conducting bodies such as Jupiter and Saturn, which range from hundreds to tens of thousands of years [Levy, 1976; Hathaway and Dessler, 1986]. The evidence presented here of solar control, with large changes on time scales of only a few years, would appear to make the internal magnetic anomaly model totally implausible. Hubbard and Stevenson [1984] estimate that the time scale for the transport of energy

and momentum between Saturn's surface and the deep interior is on the order of  $10^9$  years. If such a transport is responsible for the observed changes, then it would have to be limited to a very shallow layer near the surface.

[11] On the other hand, rapid changes are not implausible for the magnetospheric slippage model, which mainly involves the upper levels of the atmosphere. As discussed by Gurnett *et al.* [2009] and Southwood and Kivelson [2009] the transfer of angular momentum from the atmosphere to the magnetosphere is controlled by two factors: (1) the conductivity of the upper atmosphere; and (2) the high altitude zonal winds. Both of these could be easily influenced by changes in the incident solar flux on relatively short time scales. We note that the onset of rapid changes in the rotational modulation rates in 2008 occurred at about the time that the northern auroral zone was transitioning from darkness to sunlight, and vice versa for the southern auroral zone. The resulting changes in solar flux likely have important effects on both the conductivity and the zonal winds in the two hemispheres. To decide which might be most important, note that for both the 2009 and 1995 equinoxes the reversals are delayed by a substantial fraction of a year, which implies that there is a significant time delay in the magnetospheric response. Since the time constant for changes in the atmospheric conductivity is expected to be very short, minutes to hours, this delay would seem to favor variations in the high altitude zonal winds, which are likely to have a much longer response time, probably months to years. Unfortunately, little is known about the zonal winds at the very high altitudes where the coupling to the magnetosphere occurs.

[12] **Acknowledgments.** The research at the University of Iowa was supported by NASA through contracts 1356500 and 959515 with the Jet Propulsion Laboratory, and the research at Observatoire de Paris was supported by the Centre National d'Etudes Spatiales.

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