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A Saturnian longitude system based on a variable kilometric radiation period

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[1] This paper describes a longitude system for Saturn which is locked to the period of Saturn kilometric radiation. Because the apparent radio emission period varies with time, the period used in the system is allowed to vary. The resulting system results in the 'diurnal' peak of the radio emission occurring when the subsolar longitude is 100°, as was the case during the Voyager epoch. The variable period used in this system is shown to be statistically the same as periodicities recently reported for residuals in Saturn's magnetic field. It is expected that this longitude system will be more useful for organizing magnetospheric phenomena and even spoke creation in the rings than the existing longitude system based on the fixed period determined from Voyager observations which is fully 1% shorter than the currently-measured period. **Citation:** Kurth, W. S., A. Lecacheux, T. F. Averkamp, J. B. Groene, and D. A. Gurnett (2007), A Saturnian longitude system based on a variable kilometric radiation period, *Geophys. Res. Lett.*, *34*, L02201, doi:10.1029/2006GL028336.

1. Introduction

[2] The International Astronomical Union (IAU) adopted a longitude system for Saturn [*Seidelmann et al.*, 2002] that was based on the Voyager determination of the period of Saturn kilometric radiation (SKR) [*Desch and Kaiser*, 1981] under the premise that the radio emissions were tied to the magnetic field and the concept that the emissions were 'triggered' when Saturn achieved a given rotation orientation with respect to the Sun. Since the magnetic field has its source in the deep interior of the planet, it was assumed that the period reflected the rotation period of the deep interior, hence, could be used as a basis for organizing various phenomena as has been done at other gas giant planets, for example, Jupiter. However, subsequent and ongoing observations by Ulysses, which can detect the most intense SKR emissions from its solar orbit, revealed substantial variations of the SKR period of order 1% on time scales of years [*Lecacheux et al.*, 1997; *Galopeau and Lecacheux*, 2000; A. Lecacheux, Saturn's variable radio period, manuscript in preparation, 2006]. Further, observations by Cassini on approach to Saturn and in orbit have confirmed the variations [*Gurnett et al.*, 2005; Lecacheux, manuscript in preparation, 2006]. With differences between the period used by the IAU and those observed by Ulysses and Cassini of order 1%, the official longitude system cannot be expected to be useful for comparing Cassini observations separated by more than a few weeks.

[3] The purpose of this paper is to propose a new longitude system for Saturn that organizes the Saturn kilometric radiation in the expectation that such a longitude system might also be useful for organizing other magnetospheric phenomena better than the current IAU system.

[4] The reason for the variation in the SKR period over time is not well understood. *Galopeau and Lecacheux* [2000] suggested an explanation which relies on a magnetic connection between the SKR source and the magnetopause at a point where a Kelvin-Helmholtz instability is initiated. Since the location of the Kelvin-Helmholtz instability initiation point is a function of solar wind speed, this point can move in time, as the speed varies. *Cecconi and Zarka* [2005] explained how non-random variations in the solar wind could result in an average period which deviates, significantly, from the underlying planetary rotation period. Other suggestions invoke differential rotation [*Dessler*, 1985], or some means of slippage of field lines relative to the deep interior [*Gurnett et al.*, 2005]. However, it is not the purpose of this paper to explore the reasons for the variable period.

[5] It should be noted that a fundamental finding based on the Voyager observations is that the SKR source does not appear to rotate with the planet, as is the case for most Jovian radio emissions [*Warwick et al.*, 1981]. Rather, the SKR appears to brighten periodically when a certain orientation of the planet with respect to the Sun is achieved. That is, given a longitude system with the correct period, the SKR is expected to peak when the subsolar longitude is at a fixed value. For the Voyager era, this particular longitude was 100°. Hence, we use the sub-solar longitude rather than the observer's (sub-spacecraft) longitude in the following analysis, although we derive a sub-spacecraft longitude, as well.

2. Analysis of SKR Phase

[6] Previous determinations of planetary rotation periods have focused primarily on the period of the emissions as one would find with a Fourier transform, for example. However, we note that an analysis of the phase of the SKR 'diurnal' peak offers a perhaps more accurate way to track the apparent variation in the period. Figure 1 represents the intensity of SKR for successive 'rotations' of Saturn, assuming a fixed period of 10 hours, 47 minutes, 6 seconds [*Giampieri et al.*, 2006]. In Figure 1 the ratio of the SKR intensity integrated from 20 to 500 kHz with respect to a 'rotation' average value is plotted as a function of phase throughout the 'rotation'. Over the two-plus year duration of this spectrogram, the peak in the SKR drifts in

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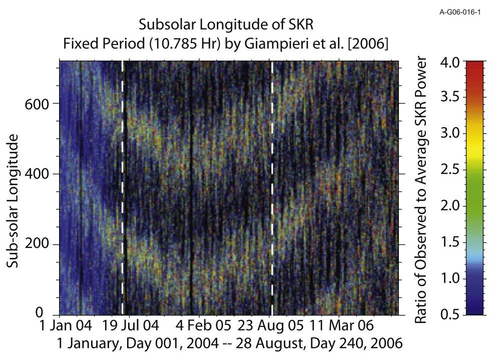

Figure 1. A plot of the intensity of SKR integrated from 20 to 500 kHz and normalized to the average over one rotation as a function of subsolar longitude and time using an assumed fixed period of 10.785 hours based on work by *Giampieri et al.* [2006] for the interval 1 January 2004 through 28 August 2006. Each rotation is plotted twice for clarity. The absolute phase is arbitrary. But, the fact that the SKR peak wanders with variable slope over the time interval means that a fixed period does not organize the SKR modulation well. It should be noted, however, that during the interval studied by Giampieri et al., indicated by the white dashed lines, the phase of the SKR drifts only minimally with a local minimum near the center of the interval.

phase. Further, the drift in phase, as seen by the slope of the SKR peak, varies with time, actually showing zero slope later in the interval, and a reversal in the slope, afterwards. Using a slightly different period (10 hours, 47 minutes, 34 seconds) chosen to minimize the phase drift over the more than 2.5 year interval, we have fit a sine wave to each rotation to determine the phase of the peak. Four successive rotations are used to determine an average phase. The resulting data set is the phase of the SKR peak as a function of day past an epoch of 1 January 2004 and is shown in

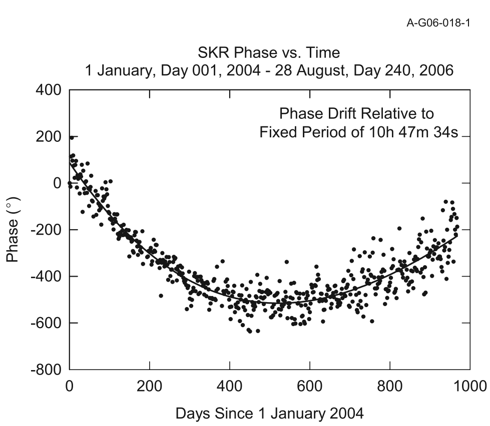

Figure 2. The dots are 4-rotation average determinations of the peak in the SKR intensity using an arbitrary fixed period of 0.4497 days. The phase was determined by fitting the ratio of the SKR intensity and a 1-rotation average intensity with a sine wave and determining the phase of the peak. The line is a third-order polynomial fit to the data using equation (1).

Figure 2. The 3rd-order polynomial in equation (1), below, is fit to this data set and is also shown in Figure 2. The polynomial, then, describes the variation of SKR phase relative to a fixed period as a function of time over the interval January 1, 2004, through August 28, 2006:

$$\phi(T) = C_1 + C_2 T + C_3 T^2 + C_4 T^3 \qquad (1)$$

[7] In equation (1), $\phi\ (T)$ is the drift of the phase of the SKR peak in degrees per day and T is the time in days from the epoch date (T_0 = 1 January 2004), corrected for one-way light time from Saturn to the spacecraft. The four constants, C_n, are from the fit to the SKR data and are 87.77 (±10.1)°, $-2.527(\pm 9.05 \times 10^{-2})\ ^\circ d^{-1}$, $3.041 \times 10^{-3}\ (\pm 2.17 \times 10^{-4})^\circ\ d^{-2}$, and $-7.913 \times 10^{-7}\ (\pm 1.47 \times 10^{-7})^\circ d^{-3}$, for n = 1, 2, 3, and 4, respectively. By subtracting this trend from the phase determined using a rather arbitrarily chosen fixed period of 0.4497 days (corresponding to 10 hours, 47 minutes, 34 seconds), the SKR phase variation can be removed, resulting in a plot of SKR phase versus time as shown in Figure 3. In essence, the variation in phase leads to a variable period. In this paper, we define a longitude system which uses this variable period. Note that the dependence of the system on the subsolar longitude implies that this system is based on a synodic period, not a sidereal period. The difference between the synodic and sidereal periods of Saturn is about 3 seconds.

[8] We note that the visibility of the SKR peak is degraded late in the analysis interval and that there is an increased spread in its occurrence in phase as can be seen in Figures 1–3. At present, it is not clear if this is a temporal effect (perhaps caused by variations in the solar wind) or a local time effect as Cassini's orbit evolves with its apoapsis moving into the tail.

3. Definition of the Longitude System

[9] The definition of the longitude system requires two steps. First, we define a system which places the rotational modulation peak of SKR at a fixed subsolar longitude. In order to allow this system to be used to compare with certain earlier studies, we will define the subsolar longitude at SKR peak as 100° as was the case during the Voyager epoch. Once this system has been defined it is straightfor-

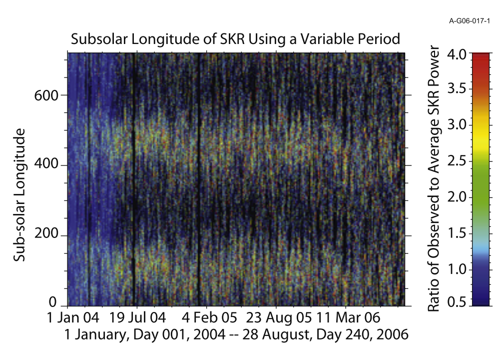

Figure 3. A plot similar to that in Figure 1, but using the subsolar longitude system developed herein based on a variable period. The peak of the SKR is centered at 100° in order to mimic the situation during the Voyager epoch.

```
IDL> owlt=8.69 ;Saturn-Cassini one-way light time in
seconds at time t chosen to be 00:00 on Jan. 1, 2006 for
this example
IDL> localtime=4.952 ; Local time of Cassini in hours at
time t
IDL> DeltaT=Julday(t)-Julday (1,1,2004,0,0,0)-owlt/86400.
IDL> phasedrift = poly ( DeltaT, [87.77, -2.527, 0.003041,
-0.0000007913])
IDL> lambdasun=360.*(1.0/0.4497)*DeltaT-phasedrift + 100.0
IDL> ;lambdasun is the subsolar longitude in degrees
IDL> lambdasun = lambdasun mod 360 + 360*(lambdasun lt 0)
IDL> print,lambdasun
      13.66
IDL> CassiniLongitude = (12.0-localtime)*15.+lamdasun
IDL> print,CassiniLongitude
      119.38
```

Figure 4. Sample IDL code to compute the subsolar and subspacecraft longitudes. It is assumed that the user has access to SPICE kernels and software which can be used to determine owlt in seconds from Saturn to Cassini and localtime in hours for the time of interest t = 00:00 on Jan. 1, 2006 for this example. Note that DeltaT is an absolute difference in time, hence, should not include leap seconds. However, the error introduced in using UTC vs. UT is negligible relative to the uncertainties in the fit parameters in equation (1).

ward to determine the longitude of another body in orbit about Saturn, such as Cassini, simply by taking into account the local time of the other body.

[10] For the usual case of a planet with a fixed rotation period, the rotation rate of the planet $\omega = d\lambda/dt$ is a constant, where λ is longitude. It follows, then, that $\lambda = C_0 + \omega(t - T_0)$ where the constant C_0 simply defines a specific phase of the longitude system at the beginning time of the epoch T_0 and t is the time of interest. But, since the period of SKR appears to vary, the drift in phase $\phi(T)$ determined above is used as a correction term so that $\lambda = C_0 + \omega_0 T - \phi(T)$. Here, ω_0 is an arbitrarily chosen fixed rotation rate and we've used

$$T = t - T_0 - R(t)/c \qquad (2)$$

In equation (2), t is the time of interest, $R(t)$ is the distance of the observer from Saturn, and c is the speed of light. This correction is necessary to determine the time at Saturn since observations and ephemeris information available are relative to the position of Cassini.

[11] Given the polynomial fit to the phase drift given in equation (1), one can define the subsolar longitude λ_{Sun} as

$$\lambda_{Sun} = C_0 + \omega_0 T - \phi(T) \qquad (3)$$

where $\omega_0 = 360°/P_0$ is the assumed rotation rate in °/d with a period of P_0 = 0.44970 days. The constant C_0 = 100° shifts the subsolar longitude such that SKR peaks at 100°, as was the case during the Voyager epoch. Once the subsolar longitude is known, then the longitude of another body, such as Cassini $\lambda_{s/c}$, can be determined directly from its local time:

$$\lambda_{s/c} = \lambda_{Sun} + \left(12 - LT_{s/c}\right)15° \qquad (4)$$

where $LT_{s/c}$ is the local time of the spacecraft. The local time of the spacecraft (or other bodies) can be determined from the SPICE kernels provided by the Cassini project http://naif.jpl.nasa.gov/naif/. Local time is defined as

$$LT_{s/c} = 12 - \frac{\left(\lambda'_{s/c} - \lambda'_{Sun}\right)}{15} \qquad (5)$$

where the λ's are the longitudes of the spacecraft and Sun in an equatorial system.

[12] Sample IDL code is provided in Figure 4 to compute λ_{Sun} and $\lambda_{s/c}$, given the one-way light time in seconds between Saturn and Cassini and Cassini's local time, in hours. It is assumed the user has software or other means (such as SPICE kernels) by which to determine these two values.

4. Discussion

[13] *Giampieri et al.* [2006] found that the magnetic field exhibits periodicities that are longer than the Voyager SKR period by about 1%. These authors suggested that the magnetic field period was both different from the SKR period and stable over a period of ~14 months. Herein we show that, in fact, the SKR period derived for the same time interval is statistically identical to the Giampieri et al. period and that the error bars in the period of the magnetic field can be explained by a continuing drift in the period over the 14 month interval of analysis. Figure 1 shows the SKR intensity integrated from 20 to 500 kHz and normalized by the average over one rotation period as a function of subsolar longitude using the Giampieri et al. period and time for the interval 1 January 2004 through 28 August 2006. The drift in the phase of SKR in Figure 1 shows that adopting the fixed 10.785 h period from Giampieri et al. does not organize the SKR peak well, although the phase drift during the interval of time analyzed by these authors (indicated by dashed lines) does show a local minimum centered during the interval. Figure 3, on the other hand shows the phase of the SKR peak using a variable period as described above.

[14] Figure 5 compares the variable period found above with that of *Giampieri et al.* [2006]. Note that the SKR period falls within the ±40-second error bars given by the analysis of the magnetometer data for virtually the entire 14-month interval analyzed. Hence we suggest that the SKR period is identical to the period exhibited by the magnetic field. Since the SKR is generated well above the cloud tops and the magnetic field observations are all obtained well above the planet, both measurement techniques measure the period of the external magnetic field. Since most would agree that the deep interior does not exhibit variations in its rotation period of the magnitudes and time scales reported from SKR observations due to conservation of angular momentum and energy arguments, the connection between the external and internal field must allow for some slippage or other variation.

[15] Evidence from both Ulysses and Cassini [*Galopeau and Lecacheux*, 2000; Lecacheux, manuscript in preparation, 2006] indicates that the period of SKR modulation, once thought to be the rotation period of the deep interior of the planet, varies by the order of 1% on time scales of a year to several years. The overlap of the SKR period with that determined for the magnetic field during the first 14 months

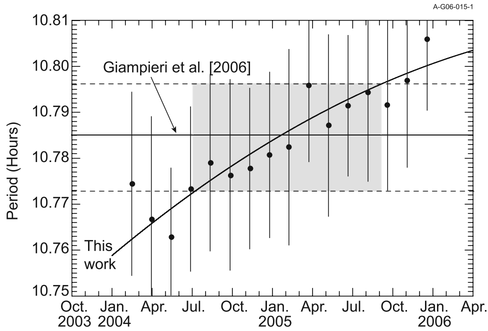

Figure 5. A plot of the variable period exhibited by Saturn Kilometric Radiation (SKR) compared to the fixed period in residuals of the magnetic field published by *Giampieri et al.* [2006]. The drifting solid line is the period of SKR as a function of time determined herein using an analysis of the drift of the phase of the SKR peak relative to an assumed fixed period of 0.4497 days. The dots represent periods determined using a Fourier transform of the SKR intensity data for successive intervals of 40 days; the error bars are from the width of the peak of the Fourier transform periodogram. Note that the Fourier transform results are not used in the analysis which produces the drifting period (solid line). The solid horizontal line is the fixed period of 10 hours, 47 minutes, and 6 seconds from *Giampieri et al.* [2006] and the dashed lines represent the ±40-second uncertainty from that study. The width of the gray shaded region represents the interval of time used in the *Giampieri et al.* [2006] study. Notice that the line representing the variable SKR period falls within the Giampieri et al. error bars for very nearly the same interval of time studied. The conclusion is that the SKR and magnetic field exhibit identical periods and that they drift at appreciable rates on time scales of a year or more.

of Cassini's orbital tour strongly implies that both the magnetic field measurements and the radio measurements provide the same period, that of the external magnetic field. The relationship between this period and that of the rotation of the deep interior of Saturn is not understood at this time.

[16] Using the variable period of SKR, we have defined a longitude system which fixes the 'rotationally' modulated peak of SKR to times when the subsolar longitude is 100°. Given the subsolar longitude and the local time of the spacecraft, the subspacecraft longitude can be determined by a simple relation.

[17] Since the external magnetic field and SKR both display the same period, it follows that the newly-defined longitude system may organize other phenomena in Saturn's system. One might immediately think of magnetospheric phenomena such as injection events [cf. *Hill et al.*, 2005] that might demonstrate some relationship with this system, but others may benefit from exploration using this system, as well. For example, *Porco and Danielson* [1982] showed that spoke formation in the main ring system occurred at a specified longitude based on the Saturn longitude system used for the Voyager flybys, hence, it is possible that a system based on SKR might also organize any Cassini-identified spokes. We expect that the identification of phenomena that are or are not organized by this new longitude system will shed light on the nature of the asymmetry which evidently controls the occurrence of SKR and accounts for the periodicities reported in the residuals of the magnetic field left after subtraction of an axisymmetric model such as those analyzed by *Giampieri et al.* [2006]. This information may lead to new models for the azimuthal asymmetry which, in turn, may shed light on the true period of the deep interior. It is also possible the internal period will remain masked.

[18] Since the SKR period continues to change with time, we anticipate the need to update the polynomial fit to the SKR phase drift in the future. However, the fact that the variation appears smooth on the more than two and one-half year time interval fit, so far, suggests that the present system can be used to predict the SKR-relative longitude for some time beyond 28 August 2006 without significant error.

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References

Cecconi, B., and P. Zarka (2005), Model of a variable radio period for Saturn, *J. Geophys. Res.*, *110*, A12203, doi:10.1029/2005JA011085.

Desch, M. D., and M. L. Kaiser (1981), Voyager measurements of the rotation period of Saturn's magnetic field, *Geophys. Res. Lett.*, *8*, 253–256.

Dessler, A. J. (1985), Differential rotation of the magnetic fields of gaseous planets, *Geophys. Res. Lett.*, *12*, 299–302.

Galopeau, P. H. M., and A. Lecacheux (2000), Variations of Saturn's radio rotation period measured at kilometer wavelengths, *J. Geophys. Res.*, *105*(A6), 13,089–13,102.

Giampieri, G., M. K. Dougherty, E. J. Smith, and C. T. Russell (2006), A regular period for Saturn's magnetic field that may track its internal rotation, *Nature*, *441*, 62–64, doi:10.1038/nature04750.

Gurnett, D. A., et al. (2005), Radio and plasma wave observations at Saturn from Cassini's approach and first orbit, *Science*, *307*, 1255–1259, doi:10.1126/science.1105356.

Hill, T. W., A. M. Rymer, J. L. Burch, F. J. Crary, D. T. Young, M. F. Thomsen, D. Delapp, N. André, A. J. Coates, and G. R. Lewis (2005), Evidence for rotationally driven plasma transport in Saturn's magnetosphere, *Geophys. Res. Lett.*, *32*, L14S10, doi:10.1029/2005GL022620.

Lecacheux, A., P. Galopeau, and M. Aubier (1997), Re-visiting Saturnian radiation with Ulysses/URAP, in *Planetary Radio Emissions IV*, edited by H. O. Rucker, S. J. Bauer, and A. Lecacheux, pp. 313–325, Austrian Acad. of Sci. Press, Vienna.

Porco, C. A., and G. E. Danielson (1982), The periodic variation of spokes in Saturn's rings, *Astron. J.*, *87*, 826–833.

Seidelmann, P. K., et al. (2002), Report of the IAU/IAG working group on cartographic coordinates and rotational elements of the planets and satellites: 2000, *Celestial Mech. Dyn. Astron.*, *82*, 83–110.

Warwick, J. W., et al. (1981), Planetary radio astronomy observations from Voyager 1 near Saturn, *Science*, *212*, 239–243.

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