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Evidence for spiral pattern in Saturn's magnetosphere using the new SKR longitudes

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[1] The periodicities in electrons observed in Saturn's magnetosphere are examined using the new longitude system based on a drifting signal of Saturn kilometric radiation (SKR). When averaged into longitude and range bins over 50-day time periods, 28–48 keV electron intensities clearly evidence patterns that peak at successively increasing longitudes with increasing radial distance from Saturn. That is, the electrons form a spiral pattern in the quasi-corotational frame of SKR longitude. The spiral has only one "arm" that extends from $\sim$10 R_S to as far as $\sim$60 R_S from the planet (where 1 R_S = 60268 km); the "arm" migrates an average of $\sim$3.4° in longitude for every R_S of radial distance. The spiral does not remain fixed in SKR longitude, but changes its relative position on time scales of $\sim$50 days. The "base" of one spiral appears connected with a postulated convection outflow at $\sim$330° longitude. **Citation:** Carbary, J. F., D. G. Mitchell, S. M. Krimigis, and N. Krupp (2007), Evidence for spiral pattern in Saturn's magnetosphere using the new SKR longitudes, *Geophys. Res. Lett.*, *34*, L13105, doi:10.1029/2007GL030167.

1. Introduction

[2] A variety of phenomena evidence periodicities at Saturn, including charged particles [*Carbary and Krimigis*, 1982], energetic neutral particles [*Paranicas et al.*, 2005], magnetic fields [*Espinosa and Dougherty*, 2000], and even spokes in the rings [*Porco and Danielson*, 1982]. However, the Saturn kilometric radiation (SKR) is the best-known periodic phenomenon at Saturn [e.g., *Desch and Kaiser*, 1981]. An SKR period close to that measured by Voyager instruments (10h 39m 24s) was until recently considered the rotation period of the planet [e.g., *Sanchez-Lavega*, 2005]. The SKR period of Saturn has, in fact, served to define the System III longitude systems for the planet [*Davies et al.*, 1996; *Seidelmann et al.*, 2002].

[3] SKR measurements subsequent to Voyager, however, have revealed a slowly changing radio period. The radio wave instrument on Ulysses measured a period of 10h 42m 34.2s and suggested the period was slowly changing [*Galopeau and Lecacheux*, 2000]. Observations by the radio wave and plasma science (RPWS) instrument on Cassini confirmed a change in period to 10h 45m 45s [*Gurnett et al.*, 2005]. From 14 months of observations within Saturn's magnetosphere, the Cassini magnetometer arrived at a period of 10h 47m 6s for periodicity of the perturbation magnetic field [*Giampieri et al.*, 2006]. Analysis of RPWS data from 2004 to 2006 showed a systematically varying period that could be fit to a third-order polynomial. This polynomial formed the basis for a "variable-period" SKR longitude system [*Kurth et al.*, 2007].

[4] This paper organizes the periodicities of 28–48 keV electrons in the variable-period longitude system. This new SKR system is applied to electron data from the first 300 days of 2006, a period selected because of spacecraft proximity to the equator and because of the validity range of the new SKR system. When averaged into range and longitude bins, the 28–48 keV electrons evidence statistical patterns reminiscent of "one-armed" spirals, at least for 200 days of the 300-day sample period.

2. Instrument and Data Set

[5] This paper uses data from the Low Energy Magnetospheric Measurement System (LEMMS), which is part of the Magnetospheric Imaging Instrument (MIMI) on the Cassini spacecraft orbiting Saturn. The solid state detectors of LEMMS measure ions and electrons from $\sim$20 keV up into the MeV range [*Krimigis et al.*, 2004]. Magnetospheric periodicities of about 11 hours are readily apparent in the electron channels of this instrument [e.g., *Krupp et al.*, 2005; *Carbary et al.*, 2007]. This investigation concentrates on the C1 electron channel (28–48 keV), which offers good statistics throughout Saturn's magnetosphere. The effects of Sun contamination, maneuvers, spurious counts, etc. were removed from the C1 data before processing.

[6] LEMMS has observed electrons in Saturn's magnetosphere since shortly before Cassini orbit insertion on day 183, 2004. After that time, the spacecraft orbit became less elliptical and began moving from southern to equatorial latitudes. During 2006, the Cassini orbital plane had moved close to Saturn's equatorial plane, which favored observation of charged particle periodicities associated with the plasma sheet. The strongest periodicities in charged particles occur at low latitudes near the center of the nominal plasma sheet [e.g., *Krupp et al.*, 2005; *Carbary et al.*, 2007]. Consequently, this investigation will concentrate on C1 electrons observed during 2006 when Cassini was close to the equatorial plane. During this time, Cassini predominately sampled the midnight-to-dawn sector of the magnetosphere from $\sim$10 R_S to as far as $\sim$60 R_S in radial distance.

[7] *Kurth et al.* [2007] have described an SKR "variable-period" longitude system. The system uses a polynomial fit to correct for apparent azimuthal drift in the SKR signal. The fit is strictly valid from orbit insertion through day 240,

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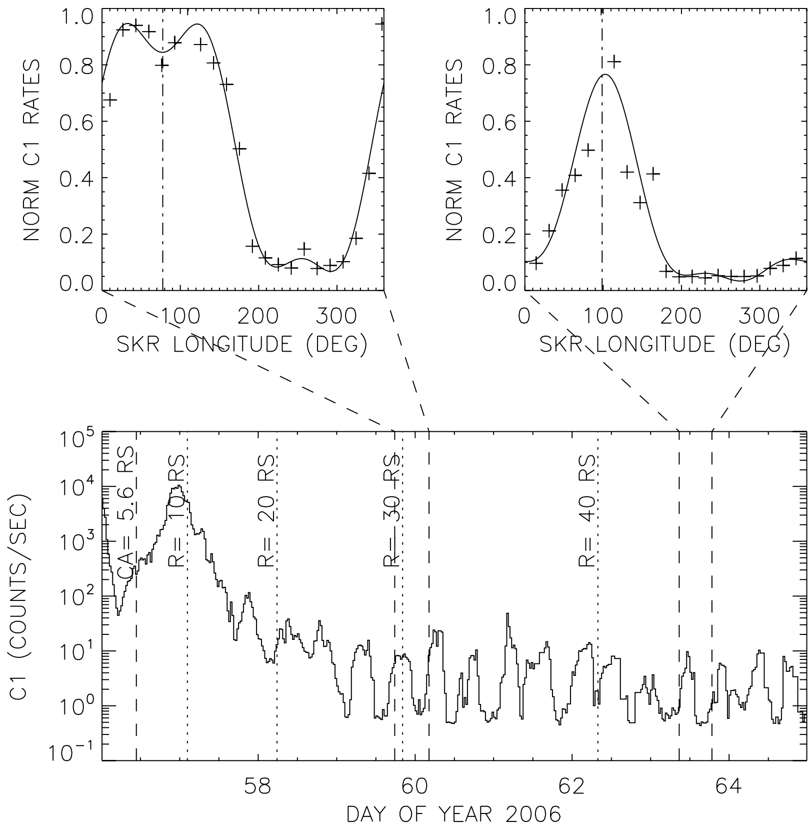

Figure 1. (bottom) Count rate profile for 28–49 keV electrons for days 56 to 65 of 2006 and (top) two cycles of the count rates in SKR longitude. The rates have undergone half-hour averaging. The two sample cycles have been normalized to their maxima. The solid line in the upper panels indicates a third-order harmonic fit; the dot-dashed line shows the first-order angle of the fit, which generally corresponds to the center of the peak in longitude. The vertical dotted lines in Figure 1 (bottom) indicate radial distances in R_S.

2006, although the authors believe its validity should extend somewhat beyond day 240. To accommodate both the equatorial trajectories of Cassini and the region of validity, the present analysis is limited to the first 300 days of 2006.

3. Data Processing and Analysis

[8] Electron count rates at 3.125-second time resolution were averaged into 30-minute time bins for the first 300 days of 2006. For each 30-minute time period, the mean position of the spacecraft was determined from the Cassini navigation records, and an SKR "variable-period" longitude computed using the algorithms given by *Kurth et al.* [2007]. The System III longitudes of the International Astronomical Union (IAU) were also determined [e.g., *Davies et al.*, 1996].

[9] Figure 1 shows a sample C1 profile from one Saturn orbital pass during early 2006. The bottom panel shows the electron count rates at 30-minute time resolution, while the upper two panels show count rates in SKR longitude for two cycles. Dashed lines between the upper panels and lower panel indicate where the cycles occurred on the profile. The two sample cycles have been normalized by dividing by the maximum of each cycle; this normalization-by-cycle will be used in the following analysis.

[10] Each longitude profile has a maximum value that can serve as a "tracer" for the location of the center of the plasma sheet. The maximum can be determined simply by the highest value in the longitude profile. Alternately, the

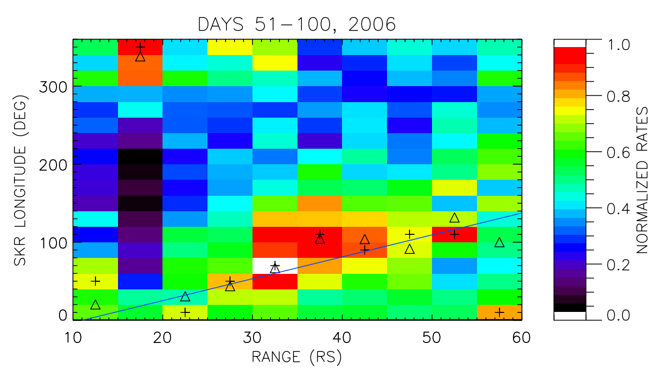

Figure 2. Bin-averaged count rates for 28–49 keV electrons for days 51–100 of 2006. Data were averaged into 30° longitude bins and 5 R_S range bins after normalization by cycle (as in Figure 1). The color indicates normalized intensity. Crosses indicate locations in longitude of the intensity peaks within each range bin; triangles indicate first-order angles from a harmonic fit of the same kind as in Figure 1. A blue line indicates a linear fit of the triangles.

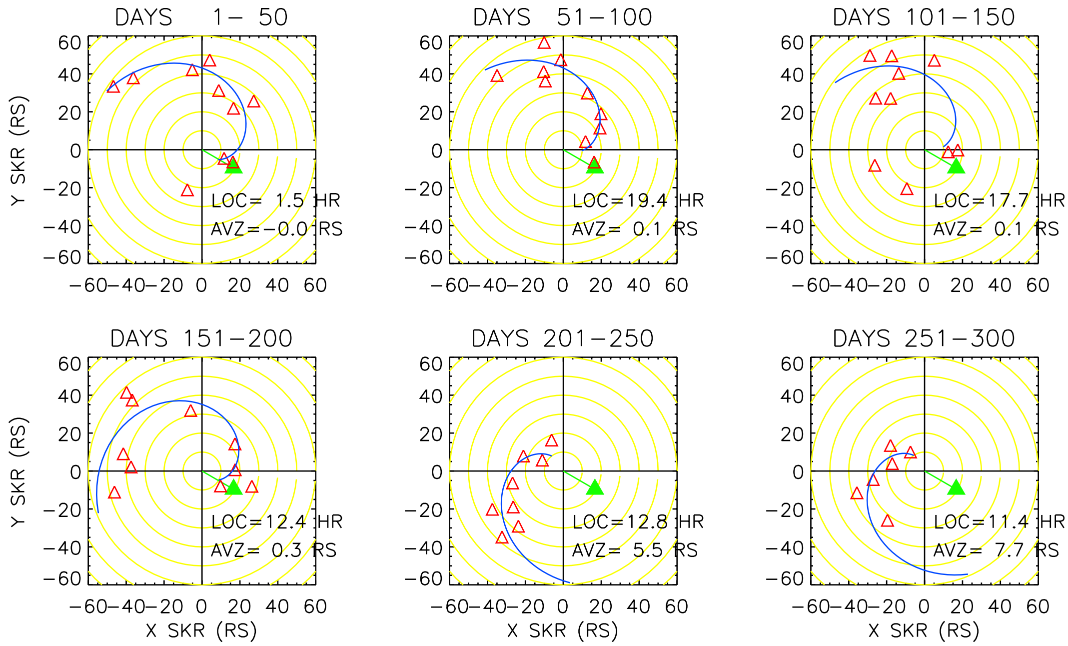

Figure 3. Locations of electron peaks in a polar SKR coordinate system for six 50-day periods in 2006. The red triangles represent first order harmonic angles from normalized rates within each 5 R_S range bin, while the blue spirals represent linear fits of these angles in radial distance. The outflow longitude implied from the corotating convection model of *Gurnett et al.* [2007] is shown as green arrows at 330°. LOC is the mean local time of the 50-day period, and AVZ is the mean Z value ($Z \approx 0$ is equator, $Z > 0$ is north of equator). Two aberrant points in the 101-150 frame were not used in the fit. Note that in this coordinate system an inertial frame would appear to rotate counterclockwise.

maximum can be derived from the first-order angle ϕ_1 of a third-order harmonic expansion in longitude ϕ:

$$C(\phi) = A_0 + \sum_{m=1}^{3} A_m \cos[m(\phi - \phi_m)] \tag{1}$$

where A_m are the harmonic amplitudes and ϕ_m are the harmonic angles. This harmonic analysis concentrates on the first order terms, which correspond to the main peak in the longitude distribution. Use of a harmonically fitted peak reduces noise introduced by merely using the maximum.

4. Results and Discussion

[11] Figure 2 shows the results of averaging all C1 electron data from days 51–100, 2006, into SKR longitude bins of 30° and radial distance bins of 5 R_S. As before, the count rates were normalized to their maximum value within each 5 R_S radial bin. The normalized count rates for each bin are coded as a color, with purples and blues signifying low values and yellows and reds signaling high. Maxima for each radial bin appear as crosses, while the triangles indicate first order angles from a harmonic fit to data in each radial bin. All valid count rates within the 50 day interval were used, both inbound and outbound, without regard to latitude or local time.

[12] A clear trend emerges in the peak locations for days 51–100. The peak locations migrate from low SKR longitudes near 0° to higher longitudes near 140° as the radial distance increases from ~15 R_S to ~60 R_S. The trend is approximately linear for the both types of peaks. The blue line in Figure 2 shows a linear fit to the harmonic peaks (triangles). The slope of this fit is 2.8°/R_S, which indicates the longitudinal change in the peak as a function of radial distance.

[13] The linear trend of these peaks translates to a spiral pattern in polar coordinates, which is shown in Figure 3 for six 50-day time periods during 2006. The locations of the first-order harmonic peaks are shown as red triangles. Linear fits to these triangles appear as blue spirals. The slopes of the spirals varied from 2.7°/R_S to 4.7°/R_S, with a mean of 3.4°/R_S ± 0.7°/R_S. The spirals are "swept back" in the sense expected of a viscous interaction with the outer magnetosphere, as if the outer regions ($r > 10\ R_S$) acted as a brake on the corotation of the inner regions ($r < 10\ R_S$). A viscous interaction would require a high β (= P_{plasma}/P_{mag} = pressure ratio), which has recently been detected by *Sergis et al.* [2006]. There is no evidence for more than one spiral arm in any single 50-day interval.

[14] The sequence of spirals in Figure 3 may reveal an interesting dynamical characteristic of the magnetosphere. From days 1–200, a single consistent spiral seems to exist. The base or inner terminus of this spiral lies near the ~330° "outflow" longitude suggested by the corotating convection model of *Gurnett et al.* [2007]. This outflow longitude appears as green arrows in Figure 3. However, from days 201–300, the spiral suddenly shifts to a new base approximately 180° away from the original "outflow" base. The spiral structure, then, may not be permanent at Saturn, but may change as its source (whatever it is) changes. Thus, the spiral for days 1–200 may represent a different source than the spiral for days 201–300. One might think of this as a

sort of "clock re-setting" for periodicities in the outer magnetosphere.

[15] Alternately, the shift in spirals may reflect a change of the spacecraft sampling from southern to equatorial to northern latitudes, in which case the spiral changes would result from a change in observing geometry. A spiral "twisted" at higher latitudes relative to lower latitudes would lead to the reconfiguration between the equatorial spirals (days 1–200) to the high latitude spirals (days 201–300).

[16] The drift in the spiral arms (or even the spiralization itself!) could also be caused by a drift in the SKR variable longitude itself. The present study is one of the first to use this new longitude system, which may prove useful in organizing magnetospheric phenomena. However, longitude system is based upon a polynomial fit that, strictly speaking, is not valid after day 240, 2006, so the longitude system itself may not be valid beyond that date, and the shift in spirals might reflect this. The variable longitude system does organize the electron peaks much better, even after day 240, than the System III longitude (not shown here). In that "fixed" longitude system, the electron peaks have an essentially random appearance and do not evidence a coherent structure.

[17] The spiral structure in the 28–48 keV electrons resembles to those known from other astrophysical contexts. Certain galaxies exhibit double or multiple-arm structures [e.g., *Sandage and Bedke*, 1994], and the interplanetary magnetic field displays a well-known spiral pattern [e.g., *Parker*, 1961]. Saturn's magnetic field also seems to have a spiral structure, which has been associated an MHD fast-mode wave propagating outwards from the planet [*Espinosa et al.*, 2003]. A recent analysis of SKR and Cassini magnetometer data indicates a periodicity in the electron density in Saturn's inner magnetosphere, which was interpreted in terms of a corotating convection pattern with an outflow near ~330° [*Gurnett et al.*, 2007]. This outflow longitude is shown as the green arrows in Figure 3 and appears to have some connection with the base of one of the spirals. The spiral pattern observed in the 28–48 keV electrons may therefore be one manifestation of the postulated outflow.

[18] A spiral pattern need not be inconsistent with a magnetodisk structure that is characteristic of a rapidly-rotating magnetosphere. The spiral may represent an outwardly-propagating "ripple" in the magnetodisk, or the spiral might represent the overall pattern of waves in a "wavy" magnetodisk.

5. Conclusions

[19] Averaging 28–48 keV electron count rates into radial and SKR longitude bins reveals a single-arm spiral pattern that increases ~3.4° in longitude for every R_S of radial distance, for radial distances beyond 10 R_S from Saturn. The spiral is not always present and can apparently change on time scales of ~50 days. The "source" region of the spiral can also change by over 100° in longitude, although at least one spiral arm has a "base" near the 330° longitude associated with the outflow of a postulated corotating convection pattern.

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