On the cause of Saturn's plasma periodicity

J. L. Burch,[1] J. Goldstein,[1] P. Mokashi,[1] W. S. Lewis,[1] C. Paty,[1] D. T. Young,[1]
A. J. Coates,[2] M. K. Dougherty,[3] and N. André[4]

Received 6 June 2008; accepted 26 June 2008; published 31 July 2008.

[1] Periodic plasma enhancements are examined for all Cassini orbits from December 29, 2005 through September 7, 2006. The events, which have UT durations of 3–4 hours, are centered near SLS3 longitude 10° at radial distances near 15 R_S and at larger W longitudes at larger distances, reaching 180°W by 49 R_S. Magnetic-field data within the events and outside 30 to 35 R_S show signatures of neutral-sheet crossings and magnetic reconnection (i.e., plasmoids). We conclude that plasmoids move outward from 30–35 R_S along a spiral path that rotates with the planet. The duration of these events is similar to that of SKR events, and they are ordered in the SKR-based SLS3 longitude system. A conceptual model, in which the plasmoids are triggered in the pre-midnight quadrant following (with a predictable delay) the appearance of SKR at the magnetopause and then propagate outward in a rotating spiral pattern, can explain the connection among periodicities observed in Saturn's charged particles, magnetic fields, and kilometric radiation. **Citation:** Burch, J. L., J. Goldstein, P. Mokashi, W. S. Lewis, C. Paty, D. T. Young, A. J. Coates, M. K. Dougherty, and N. André (2008), On the cause of Saturn's plasma periodicity, *Geophys. Res. Lett.*, *35*, L14105, doi:10.1029/2008GL034951.

1. Introduction

[2] Periodicities in Saturn Kilometric Radiation (SKR) near the planet's rotation rate have been known since the time of the Voyager flybys [*Desch and Kaiser*, 1981]. Similar periodicities in the Voyager magnetic-field data were analyzed by *Espinosa and Dougherty* [2000] and *Espinosa et al.* [2003a, 2003b]. Cassini makes possible more detailed and longer-term investigation of this important phenomenon along with similar periodicities observed in the plasma and energetic-particle data. Because of Saturn's lack of surface features, SKR measurements provide the only continuous indicator of its rotation rate; but observations that the spin rate is gradually slowing down [*Galopeau and Lecacheux*, 2000] have cast doubt on the assumption that the SKR rate reflects rigid rotation of the planet.

[3] A suggestion about why the SKR emissions are closely related to the planetary rotation rate has been made by *Gurnett et al.* [2007], who show how a two-cell interchange-driven convection pattern can transport plasma outward from a source at Enceladus through a restricted range of longitudes. In their model SKR is generated where this plasma stream, which slips in phase with respect to the internal Saturn rotation, intersects the dayside magnetopause in the late morning hours.

[4] Rotation-like periodicities have also been observed in the Cassini energetic particle data [*Krupp et al.*, 2005; *Carbary et al.*, 2007]. Carbary et al. found that 28–48 keV electron fluxes peaked along a spiral pattern anchored at ~330°W SLS2 longitude with a lag of ~3.4° per R_S of radial distance. Although not specifically related to periodic fluctuations, *Jackman et al.* [2007] and *Hill et al.* [2008] showed magnetic signatures of reconnection and plasmoids in Saturn's tail region. The evidence for reconnection was primarily the appearance of strongly northward magnetic-field components within an intrinsic field that is everywhere southward across its equatorial plane. This evidence is similar to the southward components that gave the first indication of reconnection in the Earth's magnetotail [*Hones*, 1976].

[5] This paper reports on a study of plasmas and magnetic fields obtained by the Cassini CAPS and MAG instruments [*Young et al.*, 2004; *Dougherty et al.*, 2004] over all orbits between December 29, 2005 and September 7, 2006. The results are consistent with those of *Jackman et al.* [2007], *Carbary et al.* [2007], and *Hill et al.* [2008], but taken together they lead to a new idea about how the periodic variations are generated and how they relate to the globally-observed periodicities in SKR emissions.

[6] In this report we show that the spatial and temporal relationships between the observed periodic plasma and magnetic-field events and SKR events support a hypothesis in which localized interchange-driven plasma outflow produces magnetic reconnection when it reaches local times in the pre-midnight quadrant where plasma can flow freely down Saturn's magnetic tail resulting in the detachment of plasma bubbles or plasmoids [e.g., *Kivelson and Southwood*, 2005]. The fixed longitudinal separation between the spiral paths followed by the outward-moving plasmoids and the average SKR generation site allows predictions of when (relative to the most recent SKR burst event) the periodic plasma and magnetic-field events will appear at any given radius and local time.

2. Observations

[7] Figure 1 shows an ion spectrogram and plots of the three vector KSO components of the magnetic field and the total magnetic field for the time period July 14–22, 2006. The ion energy spectra show two components—one at several keV produced by water-group ions, and at times one below ~1 keV from light ions including hydrogen and helium. These mass identifications are supported by the CAPS ion mass spectrometer data (not shown).

[1]Southwest Research Institute, San Antonio, Texas, USA.
[2]Mullard Space Science Laboratory, Dorking, UK.
[3]Blackett Laboratory, Imperial College, London, UK.
[4]European Space Technology Centre, Noordwijk, Netherlands.

0094-8276/08/2008GL03495

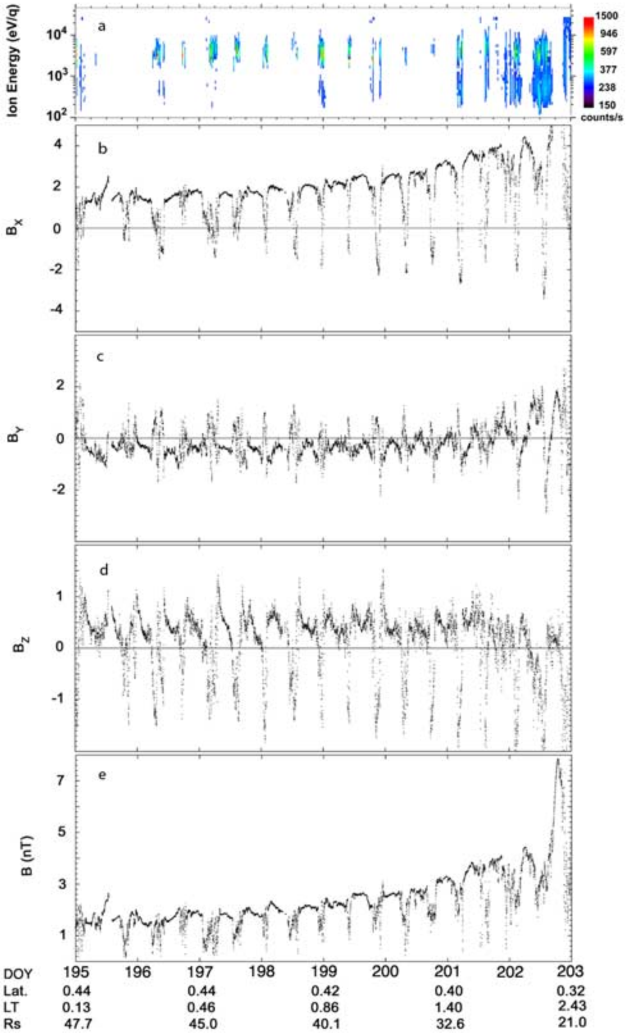

Figure 1. (a) Spectrogram of ion count rates averaged over 1152 s and summed over all view directions. (b–d) Plot of the three KSO components of the magnetic field, and (e) the total magnetic field for the time period July 14–22, 2006. The beginning of day 200 (distance ~35 R_S) separates the outer region where strong positive-Bz plasmoid signatures are often seen from the inner region where they are not seen.

[8] The magnetic field data in Figure 1 are consistent with a current-sheet crossing as follows: (1) Bx is positive outside each event, which is consistent with a spacecraft location below the current sheet in Saturn's tail region; (2) Bx reverses to negative values within the events, which is consistent with the current sheet moving across the spacecraft, being below it in the core of the event; (3) By is negative outside the events and reverses to positive in concert with the Bx reversals; (4) Bz is slightly positive outside the events, which is consistent with a tail-like field produced by a current sheet tilted slightly southward of Saturn's orbit plane; (5) during the core of the event Bz shows a decrease to negative values, which is expected near the current-sheet midplane where the magnetic field lines cross that plane; and (6) the magnetic-field magnitude is depressed throughout each event.

[9] In addition to the signatures of a current-sheet crossing in Figure 1, there is another striking feature that consistently occurs in these events—a transition to significant positive Bz components at their trailing edges. The appearance of strong positive Bz in Saturn's tail can best be explained by a region of reconnection located just planetward of the spacecraft. *Jackman et al.* [2007] and *Hill et al.* [2008] have in fact noted such events and interpreted them in just this way. Hill et al. provided the additional evidence that the plasma flow velocities at the plasmoid were outward from the planet.

[10] Figure 2 plots the approximate SLS3-longitude [*Kurth et al.*, 2008] midpoint of each ion flux event observed between December 29, 2005 and September 7, 2006. The results in Figure 2 are similar to those obtained for energetic electron events using SLS2 longitudes [*Kurth et al.*, 2007] during an earlier time period when SLS2 was valid [*Carbary et al.*, 2007]. That is, the events are anchored near 10° SLS3 longitude at distances near 15 R_S and show a corotation lag at larger distances, reaching 180° (540° in the plot) by 49 R_S.

[11] Figure 3 shows the distribution in radius and local time of the set of events plotted in Figure 1. Two subsequent Cassini orbits (Revs 29 and 30) provided coverage at earlier local times in the pre-midnight sector but showed very few if any ion events. This negative result could possibly be attributed to the increasing inclination of the orbit during this period, or might reflect a finite time for the onset of reconnection (and plasmoid formation) on flux tubes rotating past the dusk terminator. This latter possibility is discussed in more detail in the next section.

3. Discussion and Conclusions

[12] The data in Figures 1 and 2 show that (1) periodic plasma and magnetic-field events in Saturn's nightside magnetosphere are consistent with current sheet crossings; (2) strong positive Bz signatures are observed for all events at radii >35 R_S, especially near their trailing edges; and (3) the events are well-ordered in SLS3 longitude with an anchor point inside ~15 R_S near 10° and extend along a spiral lag path to near 180° by a distance of 48 R_S. While there have been previous reports of each of these signatures, they are noted here for the first time together and in association with periodicities near the Saturn SKR rotation rate.

[13] These features are now shown to support a conceptual model that explains why the periodic events observed in SKR, magnetic fields, and charged particles are closely related. The conceptual model we propose is illustrated in Figure 4. From *Kurth et al.* [2008], SKR bursts occur in late-morning local time (~8–11 Hrs) when 100° SLS3 longitude rotates past noon local time. The SKR bursts are suggested to result from the interaction of a rotating outflow region with the subsolar magnetopause [*Gurnett et al.*, 2007]. Gurnett et al. proposed this rotating outflow region to explain a broad density peak they observed near 330° SLS2 longitude in the inner magnetosphere (3–5 R_S), and suggested that the longitudinal phase lag between the density feature and the SKR burst resulted from a spiral path of the outflow from the inner magnetosphere to the dayside magnetopause.

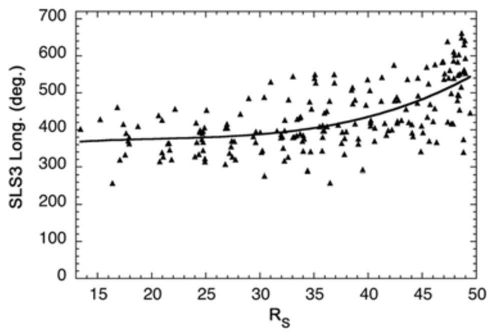

Figure 2. Plot of the SLS3 longitude of the approximate center of each ion flux event of the type shown in Figures 1 and 2 were observed from December 29, 2005 through September 7, 2006. A third-order polynomial fit to the data is shown.

[14] The spiral pattern shown in Figure 2 suggests a similar plasma outflow producing mass-loaded corotating flux tubes but with much less lag than indicated by the plasma plumes hypothesized in association with SKR by *Gurnett et al.* [2007]. This less-tightly-coiled spiral suggests lower plasma densities, but its base near 10° SLS3 at 15 R_S suggests that its source may be the same two-cell convection outflow attributed by Gurnett et al. to the density enhancement they observed near 330° SLS2 at 3–5 R_S. As the spiral shown in Figure 2 rotates into the evening sector, the plasma-loaded flux tubes along it can propagate to larger and larger distances, ultimately leading to magnetic reconnection on closed field lines as proposed for Jupiter by *Vasyliunas* [1983] and *Kivelson and Southwood* [2005]. Plasmoids produced by such reconnection, which amounts to the breaking off of plasma bubbles from extended, plasma-filled flux tubes undergoing interchange, should flow outward along the observed spiral path.

[15] As an alternative, magnetic reconnection could result from the opening of magnetic flux at the magnetopause and its subsequent closure in the tail as suggested by *Mitchell et al.* [2005]. Definitive results are not yet available on the response of SKR to solar-wind and interplanetary magnetic field parameters, so this second possibility cannot be assessed with the data now available.

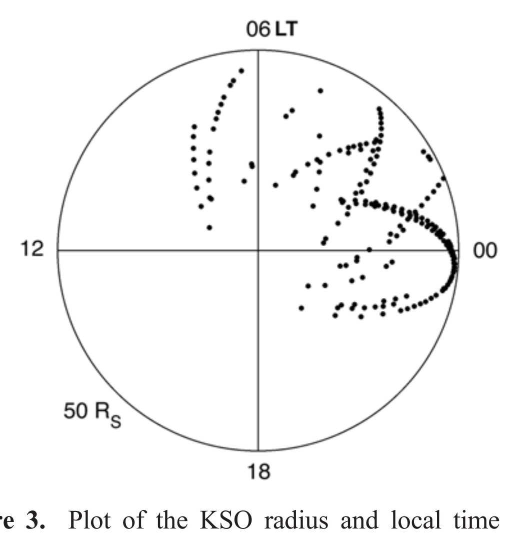

Figure 3. Plot of the KSO radius and local time of the midpoint of all 198 periodic ion events plotted in Figure 2.

[16] The fact that the data from Figure 2 are well-ordered in the corotating frame indicates that the proposed multiple plasmoids emerge from the reconnection site in a train that follows the corotating (r, longitude) trajectory (shown in Figure 4). It is notable that, as shown in the Figure 1a, the ion events inside 30–35 R_S are stronger and cover a wider energy range than those outside 30–35 R_S as would be expected if the ≤30–35 R_S ion events result from the dipolarization (planetward moving) component of reconnection exhaust. The fact that water-group ions are dominant on both sides of the reconnection regions is consistent with the fact that reconnection on previously closed field lines is required for plasmoid formation.

[17] The conceptual model presented here can be summarized as follows: (1) A longitudinally-localized region of outflowing plasma passing through ∼10° SLS3 longitude at 15 R_S produces a spiral-shaped pattern of plasma and magnetic-field disturbances that extends outward to at least 50 R_S as it rotates with the planet; (2) The magnetic

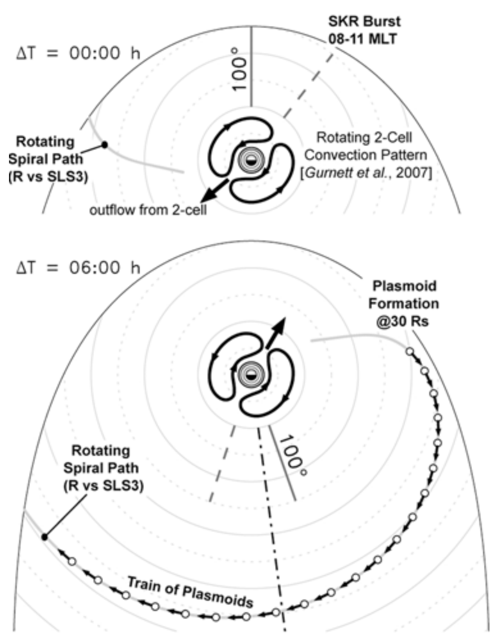

Figure 4. Schematic diagram of our conceptual model of periodic events in Saturn's magnetosphere. (top) A burst of SKR is emitted when the 100° SLS2 (or SLS3) longitude rotates past noon local time [*Kurth et al.*, 2007, 2008]. *Gurnett et al.* [2007] hypothesized that the SKR burst is triggered when plasma from the Enceladus torus, which flows outward in a spiral path as a result of an interchange-driven two-cell convection pattern, interacts with the magnetopause in the late morning hours. We propose that the two-cell convection pattern also produces an outflow of lower-density plasma, perhaps originating at higher altitudes than the Enceladus torus, that has less corotation lag than the Enceladus plasma and so can expand into the tail region where interchange-driven reconnection produces the plasmoids that we observe along the corotating spiral path (bottom). This interchange-driven plasmoid formation is suppressed on the dayside because of the confining/stabilizing effect of the magnetopause.

signatures of these events suggest that beyond R∼30–35 R_S reconnection-produced plasmoids flow outward along the spiral at velocities higher than corotation; (3) as the spiral rotates into the dayside hemisphere, the plasmoids are lost to the magnetosheath so that continued presence of the periodic events relies on newly-activated reconnection as the plasma-loaded flux tubes again extend into the tail in the dusk-to-midnight sector; and (4) the finite time required for onset of reconnection may account for the observation (Figure 3) that the periodic events favor the midnight-to-dawn sector.

[18] Inward propagating plasma and magnetic-field disturbances produced inside the magnetopause distance of ∼20 R_S will continue to rotate with the planet, while material outside that distance will be lost through the magnetopause before reaching the subsolar region. Continuation of the periodic SKR, plasma and magnetic-field disturbances will therefore rely on repeated encounters of the longitudinally-restricted plasma outflow with the magnetopause followed by its expansion into the magnetotail where interchange-driven reconnection can occur.

[19] Questions that need to be addressed with additional data include: (1) what is the source of plasma in the observed spirals? and (2) why doesn't the interaction of the observed plasma spirals with the magnetopause lead to SKR events? A preliminary suggestion is that the proposed outflow from Enceladus [*Gurnett et al.*, 2007] would have to undergo strong corotation lag in order to intersect the late-morning magnetopause within the observed longitude range (∼115°–160°). In contrast, our observed plasma spirals show much less corotation lag, indicating much lower densities, which may also explain the lack of their direct spatial association with SKR events. A possible source region of less dense plasma could be at altitudes well above the Enceladus torus—perhaps encompassing Tethys and Dione, as suggested as outflowing plasma sources by *Burch et al.* [2007].

[20] **Acknowledgments.** This research was supported by JPL contract 959930 with Southwest Research Institute. Helpful discussions with William Kurth and Krishan Khurana are gratefully acknowledged.

References

Burch, J. L., et al. (2007), Tethys and Dione: Sources of outward flowing plasma in Saturn's magnetosphere, *Nature*, *447*, doi:10.1038/nature05906.

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.

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

Dougherty, M. K., et al. (2004), The Cassini magnetic field investigation, *Space Sci. Rev.*, *114*, 331–383.

Espinosa, S. A., and M. K. Dougherty (2000), Periodic perturbations in Saturn's magnetic field, *Geophys. Res. Lett.*, *27*, 2785–2788.

Espinosa, S. A., D. J. Southwood, and M. K. Dougherty (2003a), Reanalysis of Saturn's magnetospheric field data view of spin-periodic perturbations, *J. Geophys. Res.*, *108*(A2), 1085, doi:10.1029/2001JA005083.

Espinosa, S. A., D. J. Southwood, and M. K. Dougherty (2003b), How can Saturn impose its rotation period in a noncorotating magnetosphere?, *J. Geophys. Res.*, *108*(A2), 1086, doi:10.1029/2001JA005084.

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

Gurnett, D. A., et al. (2007), The variable rotation period of the inner region of Saturn's plasma disk, *Science*, *316*, 442–445.

Hill, T. W., et al. (2008), Plasmoids in Saturn's magnetotail, *J. Geophys. Res.*, *113*, A01214, doi:10.1029/2007JA012626.

Hones, E. W., Jr. (1976), Observations in the Earth's magnetotail relating to magnetic merging, *Sol. Phys.*, *47*, 101–113.

Jackman, C. M., C. T. Russell, D. J. Southwood, C. S. Arridge, N. Achilleos, and M. K. Dougherty (2007), Strong rapid dipolarizations in Saturn's magnetotail: In situ evidence of reconnection, *Geophys. Res. Lett.*, *34*, L11203, doi:10.1029/2007GL029764.

Kivelson, M. G., and D. J. Southwood (2005), Dynamical consequences of two modes of centrifugal instability in Jupiter's outer magnetosphere, *J. Geophys. Res.*, *110*, A12209, doi:10.1029/2005JA011176.

Krupp, N., et al. (2005), The Saturnian plasma sheet as revealed by energetic particle measurements, *Geophys. Res. Lett.*, *32*, L20S03, doi:10.1029/2005GL022829.

Kurth, W. S., et al. (2005), An Earth-like correspondence between Saturn's auroral features and radio emission, *Nature*, *433*, 722–725, doi:10.1038/nature03334.

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.

Kurth, W. S., T. F. Averkamp, D. A. Gurnett, J. B. Groene, and A. Lecacheux (2008), An update to a Saturnian longitude system based on kilometric radio emissions, *J. Geophys. Res.*, *113*, A05222, doi:10.1029/2007JA012861.

Mitchell, D. G., et al. (2005), Energetic ion acceleration in Saturn's magnetotail: Substorms at Saturn?, *Geophys. Res. Lett.*, *32*, L20S01, doi:10.1029/2005GL022647.

Vasyliunas, V. M. (1983), Plasma distribution and flow, in *Physics of the Jovian Magnetosphere*, edited by A. J. Dessler, pp. 395–453, Cambridge Univ. Press, New York.

Young, D. T., et al. (2004), Cassini plasma spectrometer investigation, *Space Sci. Rev.*, *114*, 1–112.

N. André, Research and Scientific Support Department, ESTEC, Keplerlaan 1, Noordwijk, 2200 AG, Netherlands. (nandre@rssd.esa.int)

J. L. Burch, J. Goldstein, W. S. Lewis, P. Mokashi, C. Paty, and D. T. Young, Southwest Research Institute, P. O. Box 28510, San Antonio, TX 78228-0510, USA. (jburch@swri.edu; jgoldstein@swri.edu; pmokashi@swri.edu; wlewis@swri.edu; cpaty@swri.edu; dyoung@swri.edu)

A. J. Coates, Mullard Space Science Laboratory, University College London, Dorking, RH5 6NT, UK. (ajc@mssl.ucl.ac.uk)

M. K. Dougherty, Blackett Laboratory, Imperial College, London, SW7 2BZ, UK. (m.dougherty@ic.ac.uk)