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## Warm flux tubes in the E-ring plasma torus: Initial Cassini magnetometer observations

J. S. Leisner,<sup>1</sup> C. T. Russell,<sup>1</sup> K. K. Khurana,<sup>1</sup> M. K. Dougherty,<sup>2</sup> and N. André<sup>3</sup>

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[1] Initial Cassini magnetometer observations in the E-ring plasma torus reveal the presence of previously unreported diamagnetic decreases in the magnetic field. The decrease in magnetic pressure on these flux tubes implies the presence of additional plasma energy densities up to  $1 \text{ keV/cm}^3$ . They are less stretched than surrounding flux tubes suggesting the centrifugal force acting on them is less, possibly because they have a lower mass content or lower azimuthal velocity than their neighbors. Outward from these isolated tubes, at about 6 Saturn radii, an irregular transition from predominantly cool to predominantly warm flux tubes is observed. A similar boundary is observed in the jovian magnetosphere at the outer edge of the Io torus. Both the saturnian and jovian boundaries are candidates for the interchange instability but other processes may also be acting. ULF waves are associated with some, but not all, of these flux tubes. **Citation:** Leisner, J. S., C. T. Russell, K. K. Khurana, M. K. Dougherty, and N. André (2005), Warm flux tubes in the E-ring plasma torus: Initial Cassini magnetometer observations, *Geophys. Res. Lett.*, 32, L14S08, doi:10.1029/2005GL022652.

### 1. Introduction

[2] Saturn's magnetosphere is expected to be intermediate between the terrestrial and jovian magnetospheres. The mass loading rate is expected to be much less than that at Io. The radiation belts and the radio and plasma wave emissions from the magnetosphere more resemble terrestrial emissions than jovian. We do, however, expect the circulation of the plasma in the inner corotation-dominated magnetosphere to be driven more by jovian-like processes (mass loading in the deep interior of the magnetosphere) [e.g., Hill *et al.*, 1981; Vasyliunas, 1983] than terrestrial (solar-wind driven) [e.g., Russell, 1972] because the evolution of the solar wind with heliocentric distance is expected to reduce the rate of reconnection [Huddleston *et al.*, 1997], and because of the rapid rotation and size of the saturnian magnetosphere. While the plasma added to the magnetosphere from the rings may be much less than that at Jupiter, it still must be removed from the system in steady state. Outward radial transport by spiraling convective flows, interspersed with buoyant convecting empty tubes or the more classical interchange instability, must play a role in

this plasma transport because it is difficult to remove the cool torus plasma along the field line or via the production of fast neutrals.

[3] The magnetometer on Cassini [Dougherty *et al.*, 2004] can assist with the investigation of plasma dynamics and transport, as well as the sources, through the identification of dynamical phenomena and structures in the plasma. At the very first entry into the otherwise quiescent E-ring torus, a series of diamagnetic depressions, not reported by the Pioneer 11 [Smith *et al.*, 1980] or Voyager 1 [Ness *et al.*, 1981] investigators were observed that shed some light on the physical processes occurring with the magnetosphere. Structures similar to these isolated depressions appear to be common in the Cassini data outside of 6 Saturn radii ( $R_s$ ,  $1 R_s = 60,268 \text{ km}$ ) obtained to date. It is the purpose of this paper to show examples of the features inside the quiet E-ring torus as well as to discuss several of their properties, including the presence of waves. The magnetic depressions, both inside and outside of the  $\sim 6 R_s$  boundary of the quiescent torus, are accompanied by particle signatures as discussed by papers from the Cassini particle teams [Mauk *et al.*, 2005; Burch *et al.*, 2005; Hill *et al.*, 2005] and by André *et al.* [2005].

### 2. Observations

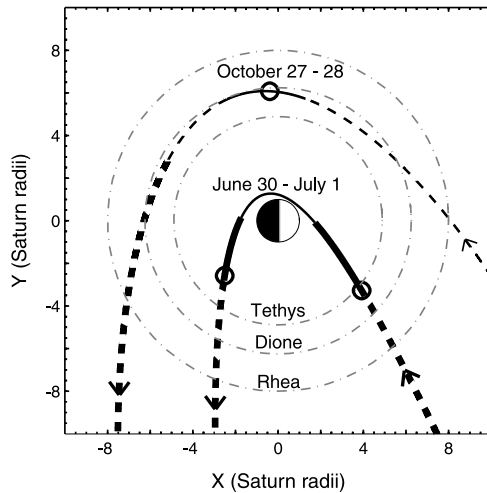
[4] The first two orbits of Cassini differed greatly in geometry but both provided clear examples of isolated diamagnetic depressions. The Saturn orbit insertion on June 30 and July 1, 2004 reached a very low planetocentric distance,  $1.3 R_s$ . The next pass on October 28 had a much higher closest approach distance,  $6.2 R_s$ . Figure 1 shows the trajectory of these two passes in the equatorial plane and the locations of the isolated events found on these two passes. Both passes are inclined to the ring plane so that they are in the northern hemisphere near periapsis, or perikron, and in the southern hemisphere at apoapsis, or apokron.

[5] Figure 2 shows an isolated diamagnetic depression inbound on the first orbit at 2105 UT on June 30, 2004, when the spacecraft was at  $9.4^\circ S$ , a radial distance of  $5.9 R_s$  and 0943 LT. Cassini had crossed an apparent turbulent boundary in plasma beta about 20 minutes earlier at which time the field increased about  $1 \text{ nT}$  and became much more steady. The changes in plasma beta across this interface and in the diamagnetic depressions observed in this region of the magnetosphere (e.g., in Figure 2) are small, of the order of 1 to 2%. Since it appears clear from the magnetic fluctuation level that the plasma beta is larger in the tube than outside of it, it is clear that as expected the magnetic pressure dominates over the plasma pressure variations here. The magnetic field is significantly stretched here, however. In an unperturbed dipole the cylindrical radial component of the

<sup>1</sup>Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California Los Angeles, California, USA.

<sup>2</sup>The Blackett Laboratory, Imperial College London, UK.

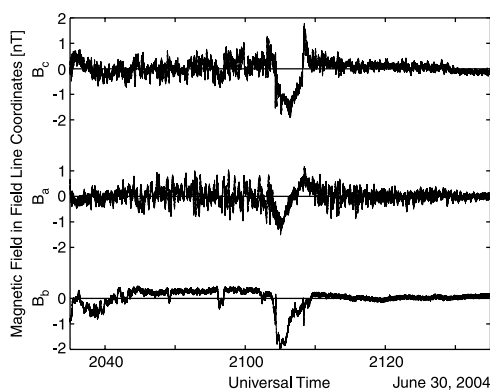
<sup>3</sup>CESR, Toulouse, France.



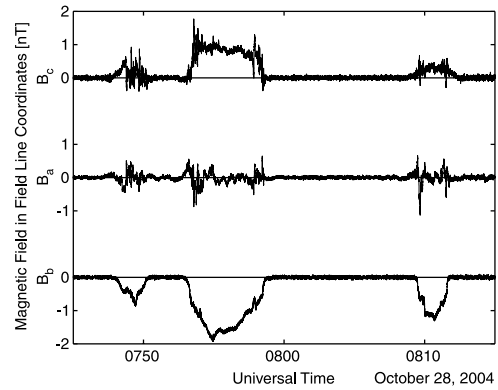
**Figure 1.** Trajectory of Cassini through the inner magnetosphere on the first two passes, projected into the equatorial plane, with  $z$  along the spin axis and  $x$  in the direction of the Sun. The dashed line indicates the places where the magnetometer observed the unsteady field and the thin line shows the parts of each pass where the spacecraft was above the equatorial plane. The three circles mark the positions of the three cavities discussed, two on the first pass and one set on the second. The three dot-dash lines mark the orbits of the largest three nearby satellites: Tethys, Dione, and Rhea.

field should be only 35% of the  $z$  component, but here it is 44%.

[6] The  $abc$  coordinate system used in Figure 2 is oriented as follows. The ‘ $a$ ’ direction in the azimuthal (corotational) direction, the ‘ $b$ ’ direction is downward along the background magnetic field and the ‘ $c$ ’ direction is inward, perpendicular to the magnetic field and roughly along the radius of curvature of the field line. A magnetic field varying from 80 nT at the beginning of the plot to



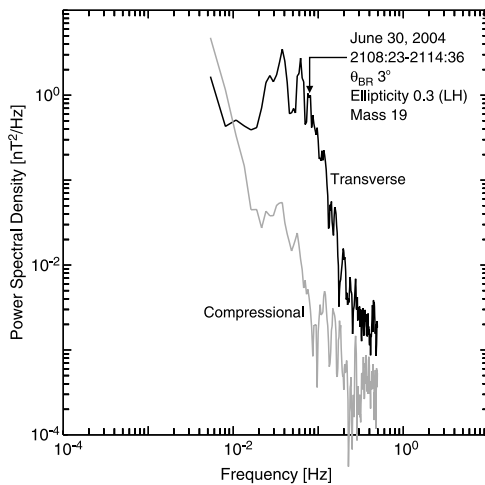
**Figure 2.** Diamagnetic cavity observed at 2105 UT on June 30, 2004 by Cassini’s fluxgate magnetometer, with the background field removed. The  $abc$  coordinates are defined such that  $B_a$  is the component perpendicular to the field line in the azimuthal direction;  $B_b$  is direction of the background field; and  $B_c$  is the component in the direction defined by  $a \times b$ , perpendicular to the field line and pointing towards Saturn. The background field magnitude rises from 80 nT at 2035 to 110 nT at 2135 UT.



**Figure 3.** Series of three diamagnetic cavities observed at 0800 UT on October 28, 2004 by Cassini’s fluxgate magnetometer, with the background field removed. The  $abc$  coordinates are defined such that  $B_a$  is the component perpendicular to the field line in the azimuthal direction;  $B_b$  is direction of the background field; and  $B_c$  is the component in the direction defined by  $a \times b$ , perpendicular to the field line and pointing towards Saturn. The background field magnitude rises from 82 nT at 0745 to 85 nT at 0815 UT.

110 nT at the end has been subtracted from the  $b$  component (the lower trace). If we assume pressure equilibrium between the tube and the surrounding magnetic field, as suggested by the quiet field strength in the ambient plasma, we can estimate the difference in plasma energy density in the tube. The depression in magnitude corresponds to an energy density (compensating for the missing magnetic pressure) of close to  $900 \text{ eV/cm}^3$ , which qualitatively agrees with the particle energy enhancement shown by *Burch et al.* [2005], and lasted for 6.4 minutes, giving an observed 0.31  $R_s$  cross-section at corotational speed. The top trace is in the inward direction and its predominantly negative perturbation indicates that the flux tube containing the warmer plasma is more dipolar than its neighbors. This warm flux tube with its diamagnetic depression is less stretched, and not more stretched, than its neighbors.

[7] This warm flux tube does not appear to be associated with any of the moons of Saturn. At the time of the observation Tethys and Dione, at 4.82  $R_s$  and 6.25  $R_s$  respectively, were 60 to 80 degrees downstream. Rhea, at 8.74  $R_s$ , was almost 130 degrees downstream. It is conceptually possible that the flux tube shown in Figure 2 is not an isolated tube but is a ripple on the boundary between the cool E-ring torus and a hotter plasma outside that was crossed at 6.2  $R_s$  20 minutes earlier. However, if that is the case the ‘‘ripple’’ would have to extend inward 0.3  $R_s$ , on the equatorial projection, to reach Cassini. We would expect such an inward moving ripple to have a wide longitudinal extent and that the depressions in field strength closer to the boundary would last longer than those further but this is not the case here. The events closer to the boundary are shorter and smaller not larger. In addition, there appears to be a twist in the field inside the depressed region. The ‘ $a$ ’ component reverses during the traversal. If this component were due to a shear in the field across a wavy boundary the ‘ $a$ ’ component would have remained approximately constant.



**Figure 4.** Power spectral density for a typical six minute period of magnetic wave activity surrounding the diamagnetic cavity at 2105 UT on June 30, 2004. Plot shows both transverse (black) and compressional (grey) power in the waves.

[8] A similar event was seen on the outbound leg at 0805 UT on July 1, when the spacecraft was at  $9.2^\circ\text{S}$ ,  $5.5 R_s$  and 0188 LT. Here the event had a peak additional plasma energy density of about  $550 \text{ eV/cm}^3$  and lasted 1.5 minutes, giving an observed cross-section of  $0.08 R_s$  at corotational speed. It was  $0.25 R_s$  inside the outer edge of the cool E-ring torus, measured radially on the equatorial projection. Again, it would be very difficult to reproduce this feature with a rippled surface or as a plasma-moon interaction. The features appear to be isolated from plasmas of similar properties and well separated from the moons.

[9] On October 28, 2004, Cassini entered the E-ring torus for a second time. Starting at 0600 on this day and extending to 1140, the magnetometer saw a series of magnetic depressions as it sped nearly azimuthally around the magnetosphere at about  $6.5 R_s$ . In Figure 3 we show examples of three such depressions, the largest of which lasted for about 6 minutes, which gives an observed cross-section of  $0.13 R_s$  at corotational speed, and had a peak additional plasma energy density of almost  $800 \text{ eV/cm}^3$ . In this case the spacecraft was  $13.5$  degrees above the equatorial plane. Now the  $c$  perturbation is positive, or inward, opposite to the example in Figure 2. Since

Cassini is above the equator, the inward disturbance is also that expected for a flux tube that is more dipolar than its neighbors. In addition to the three diamagnetic cavities shown in Figure 3, the spacecraft encountered a dozen similar structures on that pass, all of which were more dipolar within the disturbed region. Unlike the magnetic depressions observed on the spacecraft's first orbit of Saturn, however, these structures do not exhibit any significant twisting of their magnetic field.

### 3. ULF Waves

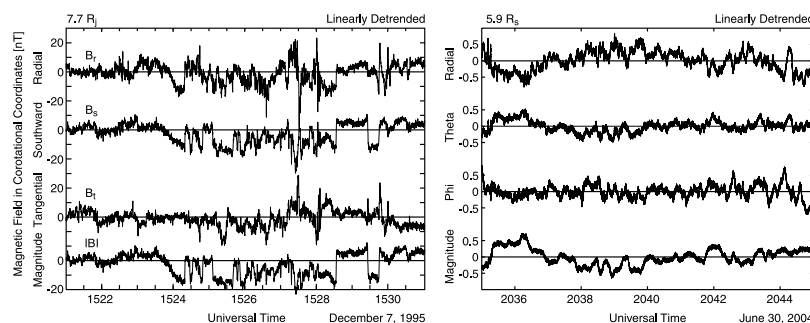
[10] One feature associated with the diamagnetic cavities on Cassini's first orbit, but not the second, is strong magnetic wave activity bordering the structures. The waves are seen to decrease with strength away from the depressions. These oscillations about the June 30 and July 1 cavities have, at their maximum,  $2 \text{ nT}$  and  $0.5 \text{ nT}$  peak-to-peak amplitudes and decrease to the background level within 35 and 15 minutes from either edge, all respectively.

[11] Figure 4 shows the power spectral density for a typical interval of wave activity. These associated waves are predominantly transverse in nature, having little component along the magnetic field. They are also broadband and linearly polarized, where the direction of maximum amplitude depends on the spacecraft's position relative to the diamagnetic cavity. Embedded within these linearly polarized waves is the signature of left-hand elliptically polarized waves traveling within a few degrees of the field line.

[12] Using the local magnetic field strength, the period of these left-hand oscillations is appropriate for ion cyclotron waves produced by particles of 19 proton masses. This is very close to the gyrofrequency for water group ions. Waves at these frequencies have been found within the E ring by Pioneer 11 [Smith and Tsurutani, 1983] and Voyager 1 [Barbosa, 1992]. Given the uncertainty in source locations, this value includes  $\text{O}^+$  ions, as inferred by Smith and Tsurutani [1983] and Barbosa [1992], as well as the recently reported  $\text{H}_3\text{O}^+$  ions [Young and the CAPS Team, 2005].

### 4. Summary and Conclusions

[13] The Cassini magnetometer data have provided us with previously unreported features within the E-ring cool plasma torus: warm flux tubes in which there is a diamag-



**Figure 5.** Linearly detrended time series of the periods in which (left) Galileo was  $7.7$  jovian radii away from Jupiter and at the edge of the Io torus [after Russell et al., 2001] and (right) Cassini was  $5.9$  saturnian radii away from Saturn and in the region of the outer edge of the E ring.

netic depression and ULF waves with linear polarization with a weak, water-group ion-cyclotron wave embedded in it. These features occur well inside the boundary that appears to be the outer edge of the cool plasma torus, where the magnetic field signals a transition in the plasma beta and the magnetic and plasma data have been interpreted in terms of the interchange instability. This boundary could be where the ionosphere can no longer sustain corotation, which is within the range provided by Richardson [1998] from the examination of Voyager 1 and 2 plasma velocity measurements. Figure 5 shows a similar turbulent behavior that has been reported at the outer edge of the Io torus and also interpreted as the interchange of flux tubes [e.g., Russell, 2001]. At Jupiter this is the region where corotation breaks down and where persistent hot electrons appear with fluxes comparable to those at Io [Frank and Paterson, 2000]. Here the change in magnetic field strength and the background field strength are about an order of magnitude greater than at the analogous boundary at Saturn, but the change in beta is very similar to that at Saturn, suggesting similarity in the processes at Jupiter and Saturn.

[14] We cannot immediately rule out that the warm flux tubes from Cassini's first orbit of Saturn represent boundary motions of the outer edge of the plasma torus, but the distance, scale size and temporal sequence of warm flux tube encounters suggest that these are distinct phenomena. Furthermore, these tubes contain twisted magnetic fields and not simply shear across their edges.

[15] The magnetic depressions observed outside of the cool plasma torus have been interpreted by Cassini plasma investigators [Burch et al., 2005; Hill et al., 2005; Mauk et al., 2005] as local injections of the warmer plasma moving inward. For those cavities shown in Figure 3, this interpretation appears consistent with the magnetometer data. These untwisted tubes, in the cool plasma torus, might be due to a series of local injections, as modeled by Burch et al. [2005].

[16] The more dipolar nature of this second set of warm tubes indicates that these tubes are less stressed and therefore contain less plasma than their neighbors. Thus they have less centrifugal force stretching them outward. Emptied flux tubes, gaining entry to the inner magnetosphere across the outer boundary of the E-ring plasma torus, will buoyantly move inward. Clearly the diamagnetic depression in field magnitude is due to an additional hotter component rather than a simple increase in density with the temperature of the ambient plasma. Ultimately they would fill up with new plasma from the E ring, and we would expect to see aging of the tubes. In fact, occasionally we do see evidence of some more rounded bottom flux tubes. In this scenario the warm plasma content of these tubes is not an on-going process but rather it was carried in with the tube.

[17] Inward moving flux tubes have been reported at Jupiter in the Io torus [Kivelson et al., 1997], but these tubes occur far inside the outer torus boundary and have strength increases and not decreases [Russell et al., 2000]. The saturnian flux tubes have a much different signature than those that may represent the same phenomenon at Jupiter.

[18] In short, we feel we have captured in these flux tubes a snapshot of the radial mass transport in the magnetosphere but it will take comparisons with the plasma measurements

and observations throughout the E ring to be certain of the source of these tubes and their fate.

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N. André, CESR, Toulouse F-31028, France.

M. K. Dougherty, The Blackett Laboratory, Imperial College London, SW7 2AZ, UK.

K. K. Khurana, J. S. Leisner, and C. T. Russell, Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California Los Angeles, CA 90095-1567, USA. (ctrussel@igpp.ucla.edu)