Direct observation of warping in the plasma sheet of Saturn

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Received 10 September 2008; revised 7 November 2008; accepted 21 November 2008; published 23 December 2008.

[1] The ENA images from the Ion Neutral CAmera (INCA) on the Cassini spacecraft are projected onto the noon-midnight plane of Sun-Saturn orbital coordinates, and a composite “image” of Saturn’s plasma sheet is constructed from dawn-side observations of 20–50 keV hydrogens obtained from days 352 to 361 in 2004. The maxima in the intensity contours define the center of the plasma sheet in the noon-midnight plane. This plasma sheet surface displays a distinct bending or “warping” above Saturn’s equatorial plane at radial distances of beyond ~15 Rs on the nightside. On the dayside, the plasma sheet lies close to the equator all the way to the magnetopause. The observed warping agrees with the “bowl” model derived from measurements of Saturn’s magnetic field, but fits more closely a simple third-order polynomial. Citation: Carbary, J. F., D. G. Mitchell, C. Paranicas, E. C. Roelof, and S. M. Krimigis (2008), Direct observation of warping in the plasma sheet of Saturn, Geophys. Res. Lett., 35, L24201, doi:10.1029/2008GL035970.

1. Introduction

[2] The magnetic axis of Saturn is very closely aligned with the spin axis of the planet [e.g., Davis and Smith, 1990; Dougherty et al., 2005]. However, the spin and magnetic axes of Saturn are tilted rather severely to Saturn’s orbital plane and also to the nominal solar wind flow direction near solstices. In fact, Saturn has an orbital obliquity of 26.7°, one of the largest in the solar system (D. R. Williams, Saturn fact sheet, 2007, NASA Goddard Space Flight Center, http://nssdc.gsfc.nasa.gov/planetary/factsheet/saturnfact.html). The solar wind ram pressure compresses Saturn’s magnetosphere on the dayside, and the solar wind flow elongates the magnetosphere on the nightside. During the early Cassini epoch in 2004, Saturn was near southern solstice and solar wind pressure on Saturn’s plasma sheet may have displaced it away from the spin equator on both the sunward and anti-sunward sides, with the displacement becoming larger with increasing radial distance. In fact, analysis of Cassini magnetometer data indicates that the magnetic equator of Saturn is indeed warped into a “bowl” shape that has been statistically modeled [Arridge et al., 2007, 2008]. The addition of a longitudinal asymmetry in the plasma density to a rotating magnetosphere may produce a “weighting” that alternately moves the plasma inward and outward in the tail, which generates waves traveling down the magnetotail and causing the periodicities seen by various Cassini instruments [Carbary et al., 2007]. Additionally, the asymmetric weighting may cause the plasma sheet to move up and down against the solar wind ram pressure, which will also generate waves traveling down the magnetotail [e.g., Khurana et al., 2008].

[3] These models all advocate a bending of the magnetic equatorial plane at distances between 15 and 20 Rs (1 Rs = 60268 km) down the tail in response to solar wind flow. Under certain viewing conditions, the Ion Neutral CAmera (INCA) on the Cassini spacecraft can provide direct imaging of the plasma sheet by observing energetic neutral atoms produced directly from charge-exchange collisions between neutrals and energetic (>10 keV) ions traversing the plasma sheet. This paper reports the first “edge-on” imaging of Saturn’s plasma sheet using several days’ worth of viewing from the dawn side of the magnetosphere. These observations clearly show the pronounced tilt of the plasma sheet at the expected obliquity angle, and they also demonstrate the warping of the plasma sheet at radial distances of 15–20 Rs.

2. Instrument and Data Set

[4] INCA is one of three sensors that comprise the Magnetospheric IMaging Instrument (MIMI) on the Cassini spacecraft. INCA measures energetic neutral atoms (~7–200 keV/nuc). The complete instrument and its capabilities are described by Krimigis et al. [2004] and Mitchell et al. [2004]. INCA can operate in an ion detection mode or a neutral particle detection mode. In the latter mode, incoming neutrals encounter a thin foil and produce secondary electrons, which are electrostatically focused onto the first of a dual-microchannel plate (MCP) arrangement. The time of flight between MCPs indicates the speed of the incident ENA, while the position of the event on the second, two-dimensional MCP indicates the angular location of the particle. Thus, INCA effectively functions as a spectrographic imager for energetic neutral particles. INCA has a field of view of 120° × 90°. For this paper, a spatial resolution of 32 × 32 pixels is used.

[5] The instrument responds to neutral particles with energies of ~7 keV to ~200 keV per nucleon and separates particles by species. A wide range of energy-mass combinations can in principle be sampled, but because of favorable geometry factors, this investigation will discuss only neutral hydrogen in the 20–50 keV range. INCA obtains one 2D image in a time between 3 and 8 minutes, depending on instrument mode. The statistical ensemble treated here involves combining many images from several days into a single composite image. A more complete description of INCA operation can be found by Carbary et al. [2008].

INCA does not continuously make ENA observations. Moreover, spacecraft pointing may allow INCA to obtain only partial views of Saturn’s magnetosphere. However, during one outbound pass of Cassini in late 2004, INCA did observe the magnetosphere continuously for

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was within the INCA field of view. This tilt = \|C2\| \|C2\| \[2006\]; the inner magnetopause shows the case for a low ram pressure. Within radial distances of \(\sim 15 \text{ Rs} \), the triangles lie in a straight line tilted at an angle of \(\sim 22^\circ\) with respect to the \(x_{\text{KSM}}\) axis. This tilt would be expected for the equatorial plane of Saturn. Outside \(\sim 15 \text{ Rs} \), however, the triangles begin to deviate from the equatorial plane where the plasma sheet is clearly warped upward (i.e., +z) relative to the equator. On the

emphasized that the KSM z axis is not the spin axis of Saturn. At the epoch of the observations the Saturn spin axis is inclined at about 22.4° relative to the KSM z axis.

\[6\] The projected, hour-averaged images were manually surveyed for aberrations caused by, for example, spacecraft pointing, sun contamination, and ion-mode observations. These unsatisfactory images were flagged and not used in subsequent processing; the invalid images amounted to no more than a few percent of the 240 hour-averaged images available. The valid images were then combined into a single composite image. The composite image consisted of the pixel intensities averaged into 2 \(\times\) 2 Rs bins in the xz plane. The top plot of Figure 2 shows a color-contour version of the resulting composite image in which reds and yellows indicate high ENA intensity and blues and purples represent low intensity.

\[9\] The most intense parts of ENA emission in Figure 2 represent the plasma sheet of Saturn where ENAs are generated by the collision between energetic ions and cool neutrals. The top plot of Figure 2 confirms the nominal 22.4° tilt of the plasma sheet. Caution must be exercised in interpreting the composite image. The extent of the sheet is caused in part by several factors including the instrument point spread function, smearing caused by the relative motion of the spacecraft and the sheet, and effects due to integrating along the line of sight through the sheet (which itself may be twisted along the line of sight). Detailed modeling of the ENA emissions may reveal their relation to the plasma sheet [Brandt et al., 2008]. Moreover, the overall symmetry of the sheet with respect to the nominal equatorial plane suggests the composite represents a good average edge-on depiction of the plasma sheet.

\[10\] The shape of the plasma sheet may also be extracted from the composite image. A simple way to do this is to use the CONTOUR procedure of the Interactive Data Language (IDL) that was used to plot Figure 2. The contour procedure generates a set of \(\{x_i, z_i\}\) coordinates in the KSM frame for each of the 32 intensity contours in Figure 2. The 32 pixel images of neutral hydrogen in the energy range 20–50 keV were first averaged into one-hour time bins for days 352 to 361 in 2004. The averaged images were then smoothed using a 5 \(\times\) 5 spatial boxcar averaging and then projected onto the noon-midnight (xz) plane of the Kronocentric Solar Magnetospheric (KSM) coordinate system. In KSM coordinates, the x axis points toward the Sun, the y axis is the cross product of the magnetic (or spin) axis and the x axis, and the z axis completes the right-hand system [Arridge et al., 2008]. KSM coordinates are the Saturn equivalent of GSM coordinates at Earth and are employed rather than spin-aligned coordinates so that solar wind effects may be more clearly apprehended. It must be

3. Method of Analysis

\[7\] The 32 \(\times\) 32 pixel images of neutral hydrogen in the energy range 20–50 keV were first averaged into one-hour time bins for days 352 to 361 in 2004. The averaged images were then smoothed using a 5 \(\times\) 5 spatial boxcar averaging and then projected onto the noon-midnight (xz) plane of the Kronocentric Solar Magnetospheric (KSM) coordinate system. In KSM coordinates, the x axis points toward the Sun, the y axis is the cross product of the magnetic (or spin) axis and the x axis, and the z axis completes the right-hand system [Arridge et al., 2008]. KSM coordinates are the Saturn equivalent of GSM coordinates at Earth and are employed rather than spin-aligned coordinates so that solar wind effects may be more clearly apprehended. It must be

4. Results and Discussion

\[11\] Figure 3 plots the contour maxima (red triangles) on the composite image of the 20–50 keV neutral hydrogens. The closed white contours are those from which maxima were found. The crosses on the right side of the frame indicate two magnetopauses from the model of Arridge et al. [2006]; the inner magnetopause shows the case for a high solar wind ram pressure, while the outer magnetopause shows the case for a low ram pressure. Within radial distances of \(\sim 15 \text{ Rs} \), the triangles lie in a straight line tilted at an angle of \(\sim 22^\circ\) with respect to the \(x_{\text{KSM}}\) axis. This tilt would be expected for the equatorial plane of Saturn. Outside \(\sim 15 \text{ Rs} \), however, the triangles begin to deviate from the equatorial plane where the plasma sheet is clearly warped upward (i.e., +z) relative to the equator. On the
Figure 2. Method of determining maxima. (top) One intensity contour of a composite ENA image and (bottom) the radial distances of each contour. The two radial maxima in the contour mark (red triangles) mark the center of the plasma sheet at two points, one on the night side and one on the dayside. The locus of the maxima from the contours defines the plane of the plasma sheet as seen in this “edge-on” geometry.

Figure 3. Contour maxima peaks (red triangles) shown on contour map of projected image from 20–50 keV hydrogens. The dashed lines show the KSM X and Z coordinate axes, while the crosses indicate a model magnetopauses for very high and very low solar wind ram pressures [Arridge et al., 2006]. The blue solid red line represents a third-order polynomial fit to the red triangles. The yellow line represents the “bowl” model [Arridge et al., 2007, 2008].
dayside, the plasma sheet lies essentially in the equatorial plane all the way to the magnetopause.

[12] The deviation from the equator can be quantified by fitting the maxima to a third-order polynomial, which appears as the solid red line in Figure 3. This polynomial is:

$$z(x) = A_0 + A_1x + A_2x^2 + A_3x^3$$

where x and z are specified in units of Saturn radii (1 $R_S = 60268$ km), and Table 1 enumerates the A coefficients. The standard deviation of the polynomial fit using 51 maxima points was 0.6 $R_S$. The fit should be valid from $\sim 30 R_S$ on the nightside to $\sim 25 R_S$ (or to the magnetopause) on the dayside.

[13] A “bowl” model of the plasma sheet has also been suggested [Arridge et al., 2007, 2008]. Derived from magnetometer measurements, this model has the form:

$$z(r) = (r - r_0 \tan h(r/r_b)) \tan h(\lambda_{sun})$$

where r is the (cylindrical) radial distance and is the same as x, measured in the equatorial plane, for the noon-midnight projection, $\lambda_{sun}$ is the latitude of the sun, and $r_b$ is a “hinge” distance. The sun latitude is 22.4°, and the hinge distance lies somewhere between 16 and 29 $R_S$ [Arridge et al., 2008]. Using $r_b = 25 R_S$, the bowl model is overplotted for comparison with the polynomial fit in Figure 3.

[14] Because the observed deflection of the plasma sheet is similar to the bowl shape derived from the magnetometer, the ENA emissions are not being importantly constrained by the distribution of cold neutral gas relative to Saturn’s spin equator. In other words, if the cold neutral gas were confined very closely to the spin equator, as the water products seem to be in the region much closer the Enceladus, then the ENA intensity distribution would be dominated by the gas distribution, and no warping would be observed. However, because the deflection is seen, apparently undistorted, the scale height in z of the cold neutral gas about the spin equatorial plane is large compared to the observed deflection in the z dimension.

[15] The nightside warping of the plasma sheet suggests the influence of solar wind flow as predicted by the bowl model and as expected theoretically. However, the dayside warping is less well described by the bowl model. The discrepancy may arise from dynamical effects hitherto not included in the models. For example, a complete dynamical description of the plasma sheet should include energetic particle pressure in addition to the usual magnetic pressure and cold plasma pressure. The energetic particle pressure at Saturn exhibits a day-night asymmetry in which the plasma sheet “inflation” on the dayside greatly exceeds that on the nightside [Krimigis et al., 2007]. This particle pressure asymmetry may be related to the plasma sheet asymmetry noted here.

[16] Depending on the statistics of the data, the projection-maxima method employed here may possibly be applied to individual hour averages of ENA images so that time variations in the plasma sheet can be tracked. If this can be accomplished, the individual hour averages may reveal a rocking motion predicted by the “asymmetric lift” model [Khurana et al., 2008]. Also, the solar wind effects of speed and pressure on the plasma sheet may be determined if these parameters can be estimated, perhaps by extrapolation from Earth observations. Examination of the latter effects would allow an evaluation of the hypothesis of solar wind control of the outer plasma sheet on the dayside.

5. Conclusions

[17] Energetic ions trapped in Saturn’s magnetosphere near the magnetic equator collide with cold neutral particles, charge exchange, and become energetic neutrals that emerge from the plasma sheet approximately parallel to the equatorial plane. By viewing the magnetosphere from the dawn side, the INCA imager observed energetic neutrals coming directly from the plasma sheet close to the magnetic equator. When projected onto the noon-midnight plane of Saturn, a composite image of energetic H emissions (20–50 keV) reveals that close to the planet (within $\sim 15 R_S$) the plasma sheet lies in the equatorial plane of Saturn. Further from the planet, the plasma sheet warps away from the equatorial plane on the nightside, with the warp increasing with radial distance beyond $\sim 15 R_S$. On the dayside, the plasma sheet lies in the equatorial plane all the way to the magnetopause. This observation is the first direct measurement of warping of Saturn’s plasma sheet, which has been suggested to have a bowl shape on the basis of magnetometer data, but which can also be characterized by a third order polynomial, at least in the noon-midnight plane.

References


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