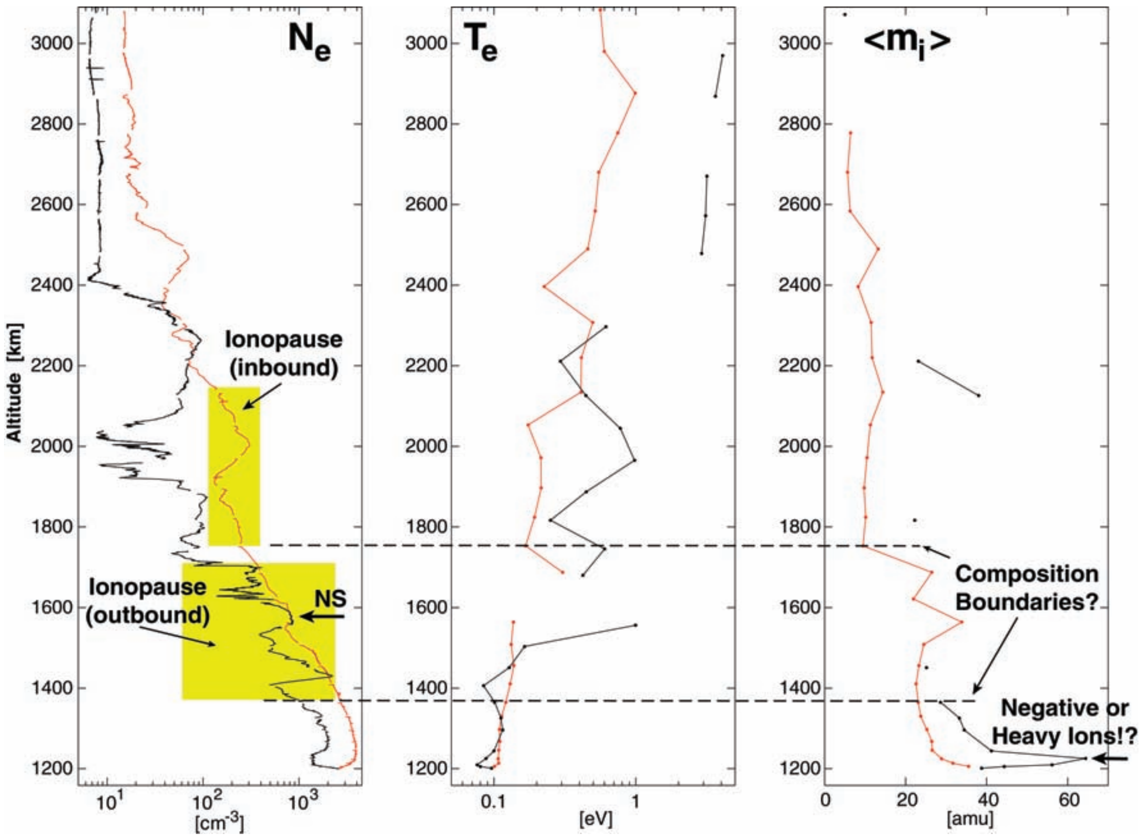

Fig. 4. Altitude profiles of electron number density (N_e), electron temperature (T_e), and mean ion mass ($\langle m_i \rangle$) during the T_A flyby. The ionopause regions and the magnetic wake neutral sheet (NS) are indicated. There seem to be composition boundaries associated with the lower part of the ionopause regions. The RPWS LP also detected signatures below the maximum density signatures, which could be due to substantial amounts of heavy ions (60 to 70 amu) or possibly negative ions.

the LP in a mode that provides better accuracy for low-temperature values.

References

1. D. A. Gurnett *et al.*, *Science* **307**, 1255 (2005); published online 16 December 2004 (10.1126/science.1105356).
2. M. Blanc *et al.*, *Space Sci. Rev.* **104**, 253 (2002).
3. H. Backes *et al.*, paper presented at the American Geophysical Union fall meeting, San Francisco, 2004.
4. T. E. Cravens *et al.*, in preparation.
5. D. A. Gurnett *et al.*, *Space Sci. Rev.* **114**, 395 (2004).
6. A. Coates *et al.*, paper presented at the American Geophysical Union fall meeting, San Francisco, 2004.
7. H. Backes *et al.*, *Science* **308**, 992 (2005).
8. R. Lundin, S. Barabash, *Adv. Space Res.* **33**, 1945 (2004).
9. D. Vignes *et al.*, *Geophys. Res. Lett.* **27**, 49 (2000).
10. D. A. Gurnett, F. L. Scarf, W. S. Kurth, *J. Geophys. Res.* **87**, 1395 (1982).
11. S. A. Ledvina *et al.*, *Adv. Space Res.* **33**, 2092 (2004).
12. E. Kallio *et al.*, *Geophys. Res. Lett.* **31**, L15703 (2004).
13. A. F. Nagy *et al.*, *J. Geophys. Res.* **106**, 6151 (2001).
14. A. F. Nagy *et al.*, *Space Sci. Rev.* **111**, 33 (2004).
15. C. N. Keller, T. E. Cravens, *J. Geophys. Res.* **99**, 6527 (1994).
16. A. Roboz, A. F. Nagy, *J. Geophys. Res.* **99**, 2087 (1994).

14 January 2005; accepted 24 March 2005
10.1126/science.1109807

REPORT

Energetic Neutral Atom Emissions from Titan Interaction with Saturn's Magnetosphere

D. G. Mitchell,[1]* P. C. Brandt,[1] E. C. Roelof,[1] J. Dandouras,[2] S. M. Krimigis,[1] B. H. Mauk[1]

The Cassini Magnetospheric Imaging Instrument (MIMI) observed the interaction of Saturn's largest moon, Titan, with Saturn's magnetosphere during two close flybys of Titan on 26 October and 13 December 2004. The MIMI Ion and Neutral Camera (INCA) continuously imaged the energetic neutral atoms (ENAs) generated by charge exchange reactions between the energetic, singly ionized trapped magnetospheric ions and the outer atmosphere, or exosphere, of Titan. The images reveal a halo of variable ENA emission about Titan's nearly collisionless outer atmosphere that fades at larger distances as the exospheric density decays exponentially. The altitude of the emissions varies, and they are not symmetrical about the moon, reflecting the complexity of the interactions between Titan's upper atmosphere and Saturn's space environment.

Interactions between charged particles and neutral gases are ubiquitous throughout much of the solar system, the Galaxy, and the universe. In the magnetosphere of a magnetized planet, charge exchange between energetic ions and the exosphere of the planet or any of its moons can modify the rate of erosion of the gravitationally bound atmosphere. This process also results in the loss of energy and material from the magnetosphere. A fast ion exchanges charge with a cold neutral atom, becomes an ENA, and freely escapes its previous magnetic confinement as a newly born neutral. Left behind is the former cold neutral gas atom, now a cold ion, which is then typically picked up in the planetary magnetic and electric fields and swept out of the exosphere where it originated.

[1]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 21042, USA. [2]Centre D'Etude Spatiale Des Rayonnements, 31028 Toulouse, France.

*To whom correspondence should be addressed. E-mail: don.mitchell@jhuapl.edu

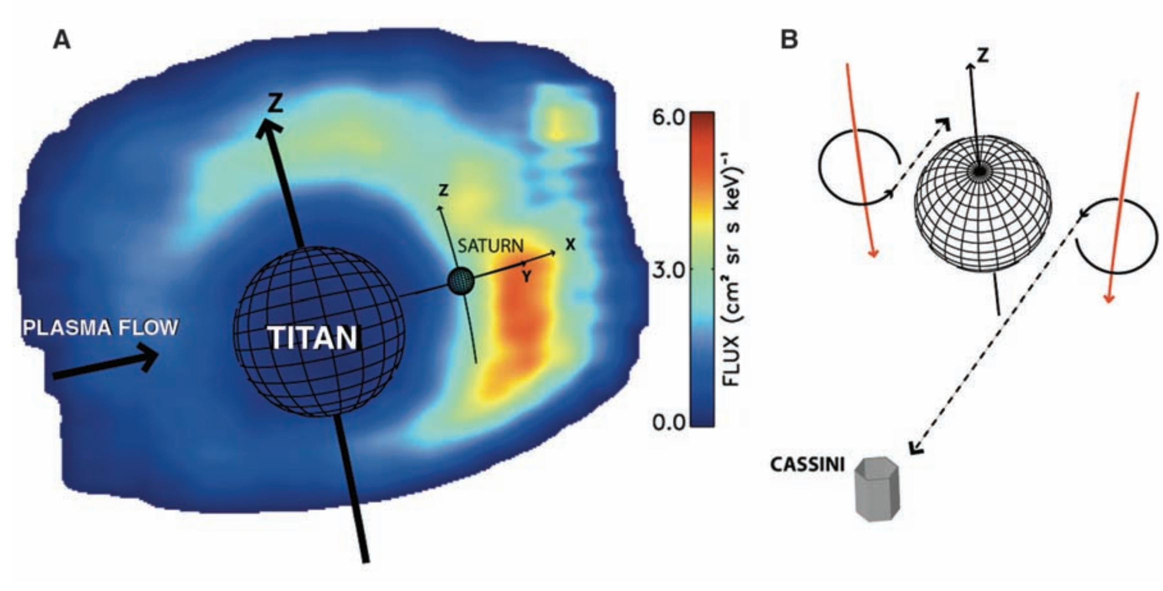

Fig. 1. (**A**) ENA image in 20 to 50 keV H of magnetically trapped protons charge-exchanging in Titan's exosphere. Intensity is color-coded on a linear scale from 0 to 10 ENAs cm^{-2} s^{-1} sr^{-1} keV^{-1}. The limits of the emission are circumscribed by the INCA sensor 90°-by-120° FOV. The latitude-longitude grid locates Titan (north up) at 15:14:25 UT on 26 October 2004, the midpoint of the 8-min image integration. Saturn is shown to the right of Titan. The ENA emission is dominated by the Titan interaction; general Saturnian magnetospheric emission is obscured by Titan's atmosphere. (**B**) Schematic proton gyration in a southward field at Titan. As the magnetic field guiding the proton to the left approached Titan, the right side of its circle of gyration encountered the dense atmosphere (absorbing the proton) before the left side, with the appropriate velocity vector to appear as an ENA at Cassini, reaches the altitude (exospheric density) of maximum likelihood for charge exchange.

The initial close encounter between the Cassini spacecraft and Titan took place on 26 October 2004 as Cassini approached within a few Titan radii of the moon (Titan's radius is 2575 km). This encounter took place as Cassini was inbound on the day side, at 10:30 local time and about 4 hours after the last inbound magnetopause crossing. The first resolved MIMI/INCA (*1*) ENA image of Titan's exosphere (Fig. 1A) confirms some theoretical expectations. The hole in the emission, centered on Titan, was expected and is a result of the absorption of the ambient energetic ions by Titan's dense lower atmosphere (*2*). The crescent shape to the emission region was also anticipated: The left side (upstream side in the corotating plasma flow) is much dimmer than the downstream side. Dandouras *et al*. (*3*) predicted this feature and explained it in terms of shadowing of the ambient magnetically trapped energetic ions. Protons with energies covered by this observation gyrate about the magnetic field, and the sizes of the gyroradii are comparable to Titan's diameter (Fig. 1B). For a nominal magnetospheric magnetic field directed from north to south (downward in the figure), the protons that are converted to ENAs to the left side of Titan may intersect Titan's atmosphere before they reach the point in their gyrating trajectories where they can be efficiently converted to observable ENAs. Protons converted to ENAs on the right side of Titan have trajectories that originate far from Titan's atmosphere, so they are free to complete their gyration about the magnetic field without encountering a high-density neutral gas region. Those particles that are observed after their conversion to ENAs intersect the densest part of the Titan exosphere, close to the region where they are traveling, tangent to constant atmospheric density contours. At the altitude where the exospheric density is such that they begin to have a high probability for conversion to ENA, a bright emission is observed. Above that peak, the emission drops again as the exospheric density falls roughly exponentially (*2*). Oxygen ENAs are also generated in this interaction, but the statistics are insufficient to analyze the images in detail.

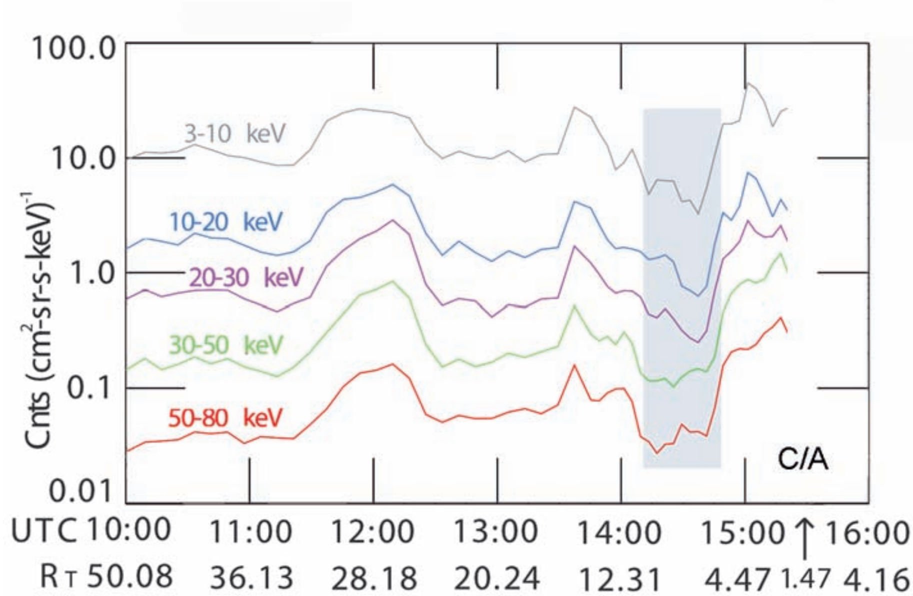

Fig. 2. ENA flux integrated over hydrogen images for specific energy pass bands versus time during the approach to Titan on 26 October 2004. Between 14:10 and 14:40 UT, the Cassini spacecraft reoriented for radar imaging of Titan, removing Titan from the INCA FOV and creating the dip in ENA intensity (shaded area).

The ENA emissions (like those in Fig. 1) varied substantially with time. This is because Titan is 20 planetary radii from Saturn and orbits in the equatorial plane, a region where ion intensity can vary by orders of magnitude over hours or even minutes (*4*). The ENA emission strength varies because the intensity of energetic ions interacting with Titan varies; Titan's atmosphere and exosphere do not vary much on these time scales. Consistent with this supposition, in situ measurements for this flyby as well as for the 13 December flyby showed essentially random ion intensity variations along the Cassini trajectory.

The image-integrated ENA emission from Titan's exosphere is displayed in Fig. 2. For the distances represented in Fig. 2 (between 50 and 2 Titan radii), the entire exospheric emitting region is contained within the INCA field of view (FOV) of 90° by 120°, and a constant emission source would vary in integrated strength by the inverse square law. However, a simple inverse

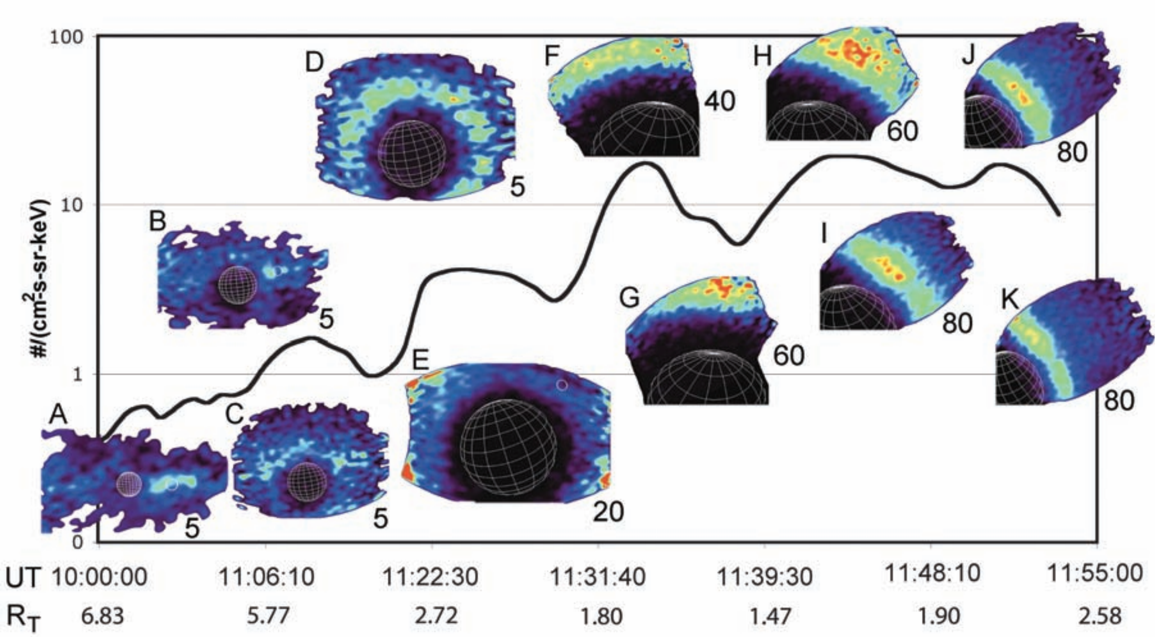

Fig. 3. Energetic hydrogen images in the 20 to 50 keV pass band during the 13 December 2004 encounter. The images are located according to their acquisition time. The timeline is highly nonlinear. Each image is scaled linearly in color (intensity) between 0 and the number immediately to the lower right, in ENAs cm^{-2} s^{-1} sr^{-1} keV^{-1}. R_T indicates Titan radii (2500 km).

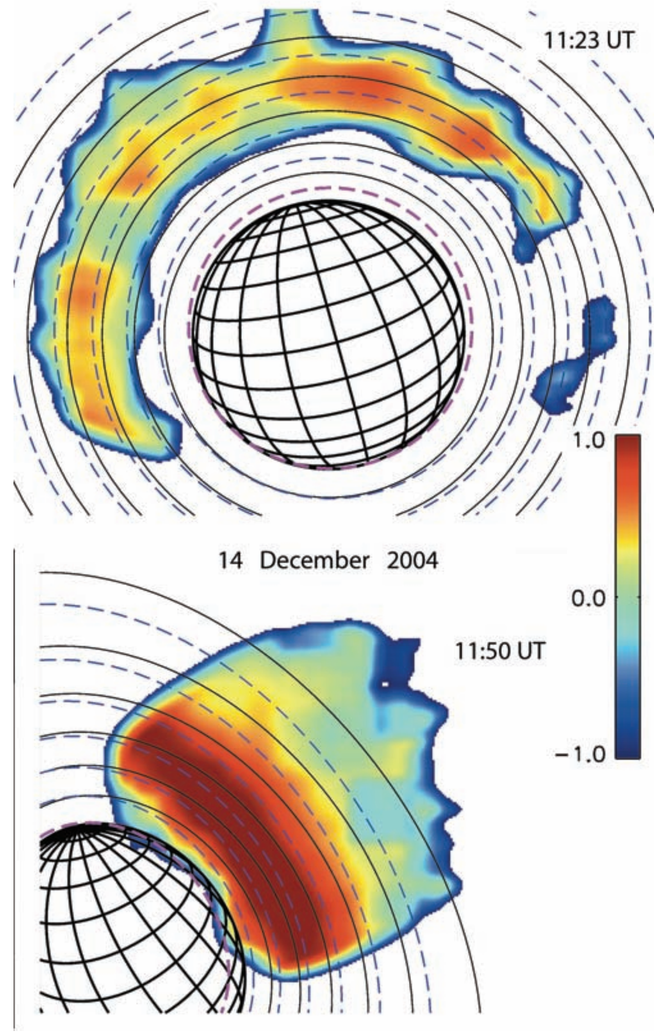

Fig. 4. One-minute exposure images in 50 to 80 keV H during the 13 December 2004 Titan encounter. Intensity is scaled logarithmically between 0.1 and 10 cm^{-2} s^{-1} sr^{-1} keV^{-1}. The latitude-longitude grid represents Titan's position (north up) at the beginning of the image acquisition, whereas the heavy dashed violet line represents Titan's limb at the end of the acquisition. Likewise, the light solid curves locate the intersections of the lines of sight from Cassini to the tangent point of spherical shells about Titan at 500, 1000, 1500, ..., 3000 km altitude in the atmosphere at the beginning of image acquisition, whereas the light blue dashed curves locate the same points at the end of acquisition. (**Top**) H ENA emission as it appeared during approach to Titan. (**Bottom**) H ENA emission as it appeared after closest approach, when the low altitude boundary appears to be close to Titan's limb.

square law is not evident. Instead, the emission varied considerably with time, because clouds of magnetically confined ions were swept over Titan and its atmosphere by the rotation of Saturn's magnetic field, which rotates more or less rigidly with the planet about once every 10 hours 45 min. Indeed, a major peak in the ENA flux from Titan was measured almost 4 hours before closest approach. As a precautionary measure against high voltage breakdown in Titan's atmosphere, for this encounter the INCA sensor was turned off before closest approach, so no data are available during or after closest approach.

On 13 December 2004, Cassini made its second close flyby of Titan. The geometry for the second encounter was nearly identical to that for the first (including the fact that Cassini was close to but inside the magnetopause), so we expected to see essentially the same features. Instead, the observed interactions were more complex (Fig. 3). On the approach, the ENA emission associated with the Titan exospheric interaction once again varied strongly with time. However, Titan-associated ENA emission remained low until just before closest approach, when a cloud of trapped ions swept over Titan, lighting up the exosphere in ENA. This time, the ENA emission was relatively symmetric about the moon, with little hint of a crescent shape [(Fig. 3, D and E) Titan is not centered in the FOV, so the circle of emission is cut off to Titan's south]. Unlike the 26 October flyby, INCA remained on until 17 min after closest approach, so the emission was imaged from a variety of positions.

The horizontal axis in Fig. 3 is not linear in time; rather, the time intervals along the axis have been scaled by the reciprocal of the spacecraft distance to Titan. This representation emphasizes the time around closest approach and provides a format through which the associated ENA images can be easily cross-referenced to both time and the variation in flux. The first hour of this 2-hour segment was characterized by no discernable ENA emission from the Titan exosphere (Fig. 3, A and B). Titan and its atmosphere measurably absorbed the ENA emission from Saturn's magnetosphere (Fig. 3B). In Fig. 3C, which corresponds in time with the first increase in the integrated ENA flux (black curve), a hint of the halo emission seen in the October Titan encounter is evident. Later (Fig. 3D) the characteristic halo emission is quite evident, including the dark region in the lower atmosphere where the neutral density is too high for survival of the magnetically trapped ions (*2*, *3*).

By 11:27 universal time (UT) (Fig. 3E) the peak of the ENA emission was no longer within the 90°-by-120° FOV. The ENA intensity increased all the way to the edge of the FOV. The emission was considerably more intense: The color in this image is scaled to a peak value of 20 cm^{-2} s^{-1} sr^{-1} keV^{-1}, four times the peak in the preceding images.

Beginning in Fig. 3F, the orientation of the INCA FOV relative to Titan changed, and Titan's limb remained in the FOV for the remainder of the observation. The peak intensity in the images also rose (note the rescaling of the color bar). As shown in the last several images, a qualitative change occurred: The peak emission, which in Fig. 3, D to F, remained well above the limb, moved closer and closer to the limb until the time of Fig. 3, I to K, and then it appeared at a much lower apparent altitude.

With the use of the currently accepted range for the Titan exospheric density profile (*5*, *6*), we calculated the altitude at which we expect to find the maximum emissions by using the same approach outlined in Amsif *et al*. (*2*) and Dandouras *et al*. (*3*). Because the density profile was slightly different than that assumed in (*2*) and (*3*), the predicted altitude of the peak was a bit lower (1400 km versus 1700 km). Emissions are expected to fall steeply below that altitude, because the mean free path for the ions and ENAs rapidly shortens in the dense lower atmosphere (scale height of roughly 150 km). The observed peak in emission for the October encounter, at an altitude of ~2000 km for the tangent point of the line of sight, was higher than the predicted ~1400 km. In the 13 December encounter, the peak emission moved from about the same tangent point altitude (~2000 km) to an apparent altitude much lower than can be easily explained (~1000 km) toward the end of the encounter (Fig. 4). The model we used to predict the location of the peak intensity did not include the complex and important physics of the interaction between the ionosphere of Titan and the corotating, magnetized medium in which Titan is immersed. Treated as noninteracting, the magnetic field close to Titan has the same magnitude and direction as the field that intercepts Titan, and the ion interaction with the exosphere can be described by simple geometry (*3*).

In actuality, the highly conducting ionosphere interacts strongly with the flowing, magnetized medium about it, and magnetic flux piles up on the upstream side and drapes about Titan into a long tail on the downstream side, quite analogous to a comet tail in the magnetized solar wind. This Alfvénic interaction creates much higher magnetic field strengths than in the unperturbed medium as well as far different vector directions of the field. The trapped, gyrating ions are controlled by that field close to the moon, executing much more complex motions than those predicted by the simple noninteracting model. Consideration of effects of the actual measured magnetic field on ion trajectories during each flyby suggests that the unexpectedly high altitude for the peak emission during each Titan approach may be explained by the departure of these near-Titan magnetic field characteristics from the model used by Amsif *et al*. (*2*). Images taken after closest approach on 13 December (with the peak ENA emission occurring at anomalously low apparent altitude) will likewise require a more sophisticated treatment.

The energetic neutral atom images of Titan thus have revealed unexpected aspects of the interaction between the trapped energetic plasma and the exosphere of an outer planet moon. As is often the case, simple models are not adequate to describe all of the features found in the images. The Cassini MIMI images reveal the structure of ENA emission from the Saturn magnetosphere–Titan exosphere interaction to be quite complex. The emission is sensitive to quantitative details of the electromagnetic interaction of Titan's atmosphere and ionosphere, with the fast flowing corotating magnetosphere surrounding them. Magnetohydrodynamic and kinetic effects lead to extreme departures of the magnetic field direction and strength from the nominal conditions in the unperturbed medium, and the ENA images affirm that improved models of the interaction are required to represent that complexity.

References and Notes

1. S. M. Krimigis *et al.*, *Space Sci. Rev.* **114**, 233 (2004).
2. A. Amsif, J. Dandouras, E. C. Roelof, *J. Geophys. Res.* **102**, 22169 (1997).
3. J. Dandouras, A. Amsif, *Planet. Space Sci.* **47**, 1355 (1999).
4. S. M. Krimigis *et al.*, *Science* **307**, 1270 (2005).
5. R. J. Vervack, B. R. Sandel, D. F. Strobel, *Icarus* **170**, 91 (2004).
6. R. V. Yelle, *Astrophys. J.* **383**, 380 (1991).
7. The MIMI program at the Johns Hopkins University Applied Physics Lab is supported by the NASA Office of Space Science under task order 003 of contract NAS5-97271 between the NASA/Goddard Space Flight Center and the Johns Hopkins University.

14 January 2005; accepted 16 March 2005
10.1126/science.1109805

REPORT

Titan's Magnetic Field Signature During the First Cassini Encounter

Heiko Backes,[1*] Fritz M. Neubauer,[1] Michele K. Dougherty,[2] Nicholas Achilleos,[2] Nicolas André,[3] Christopher S. Arridge,[2] Cesar Bertucci,[2] Geraint H. Jones,[4] Krishan K. Khurana,[5] Christopher T. Russell,[5] Alexandre Wennmacher[1]

The magnetic field signature obtained by Cassini during its first close encounter with Titan on 26 October 2004 is presented and explained in terms of an advanced model. Titan was inside the saturnian magnetosphere. A magnetic field minimum before closest approach marked Cassini's entry into the magnetic ionopause layer. Cassini then left the northern and entered the southern magnetic tail lobe. The magnetic field before and after the encounter was approximately constant for ~20 Titan radii, but the field orientation changed exactly at the location of Titan's orbit. No evidence of an internal magnetic field at Titan was detected.

We report results from the Cassini magnetometer experiment obtained during the first close encounter [closest approach (CA) altitude: 1174 km] of Cassini with Saturn's moon Titan on 26 October 2004. This was the first opportunity to investigate Titan's environment with in situ measurements since the Voyager 1 flyby in 1980. With its extended neutral atmosphere, Titan orbits Saturn at a distance of 20.3 Saturn radii (R_S) and an orbital period of 15.95 days. For most of its orbit Titan is inside Saturn's magnetosphere (*1*), which is populated by neutral atoms and plasma from several potential sources (Saturn atmosphere and rings, icy satellites, Titan, solar wind) and at least partially corotates with the planet. Because Titan's orbital period is much larger than Saturn's rotational period (10.7 hours),