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REPORT

Cassini Measurements of Cold Plasma in the Ionosphere of Titan

J.-E. Wahlund,^{1*} R. Boström,¹ G. Gustafsson,¹ D. A. Gurnett,² W. S. Kurth,² A. Pedersen,³ T. F. Averkamp,² G. B. Hospodarsky,² A. M. Persoon,² P. Canu,⁴ F. M. Neubauer,⁵ M. K. Dougherty,⁶ A. I. Eriksson,¹ M. W. Morooka,¹ R. Gill,¹ M. André,¹ L. Eliasson,⁷ I. Müller-Wodarg⁶

The Cassini Radio and Plasma Wave Science (RPWS) Langmuir probe (LP) sensor observed the cold plasma environment around Titan during the first two flybys. The data show that conditions in Saturn's magnetosphere affect the structure and dynamics deep in the ionosphere of Titan. The maximum measured ionospheric electron number density reached 3800 per cubic centimeter near closest approach, and a complex chemistry was indicated. The electron temperature profiles are consistent with electron heat conduction from the hotter Titan wake. The ionospheric escape flux was estimated to be 10^{25} ions per second.

The giant planet Saturn and its magnetosphere rotate with a period of ~ 11 hours, which can be inferred from radio measurements (I). At the distance of the large moon Titan [20 Saturn radii (R_S)], this corotation causes a magnetospheric plasma flow of several hundred kilometers per second that affects the upper ionized part of the thick atmosphere of Titan. Atoms and molecules in the upper atmosphere are ionized by solar ultraviolet (UV) radiation and by impacts of energetic particles that originate mainly from the magnetosphere. The aeronomic and electrodynamic processes involved in the interaction further produce a complex organic chemistry within the nitrogen- and methane-rich atmosphere of Titan as well as a loss of atmospheric constituents, providing in turn a source of plasma for the magnetosphere of Saturn (2).

The two first flybys of Titan (T_A and T_B) on 26 October and 13 December 2004 were

very similar. Both occurred at 10.5 Saturn local time (LT) near the front side of Saturn's magnetosphere, and both approached inbound from the sunlit side and through the wake of Titan (Fig. 1). The outbound passes partly traversed a shaded region caused by Titan's thick atmosphere at a latitude of 30° to 40° N.

The structure and thermal state of the ionosphere of Titan were affected by the saturnian magnetosphere all the way down to closest approach (1176 km) during both flybys (Figs. 2 and 3). The general shape of the two main number density maxima near closest approach in Fig. 2 is broadly consistent with photoionization by UV light from the Sun and impact ionization by magnetospheric electrons (3, 4). However, the plasma density was otherwise very structured and could be related to similar structures in the magnetic field data. The density data in Figs. 2 and 3 were collected at a high time resolution (20 samples/s) and are derived from the probe current at a constant bias voltage ($\sim +10$ V), corrected for electron temperature and adjusted to fit the potential sweep data points for density. The LP sensor (5) samples the total electron number density surrounding the spacecraft, which includes the naturally occurring plasma electrons as well as a nearly constant level of photoelectrons around the spacecraft. The spacecraft-generated photoelectrons dominated the magnetospheric part of the flyby. According to measurements by the Cassini Plasma Spectrometer (CAPS), the magnetospheric electron density near Titan was just below 0.1 cm^{-3} during T_A (6).

The calculated magnetic pressure ($B^2/2\mu_0$) of the magnetosphere and the electron thermal pressure ($n_e k_B T_e$) of the ionosphere (where B is magnetic field strength, μ_0 is magnetic permeability, n_e is electron number density, k_B is the Boltzmann constant, and T_e is electron temperature) were largely of the same order of magnitude during the T_A flyby (Fig. 2B). Both flybys traversed the wake of Titan, and the effect of the magnetospheric dynamic pressure ($n_i m_i v_i^2/2$, where n_i is ion number density, m_i is average ion mass, and v_i is ion ram velocity) should therefore be small near closest approach. The ionopause, the region where the ionospheric thermal pressure balances the magnetospheric pressure, covered an extended region on both the inbound and outbound trajectories (yellow area in Fig. 2). The close relationship between cold plasma density signatures and magnetic field fluctuations and comparable values of ionospheric electron thermal and magnetospheric magnetic field pressures confirms the view that the saturnian magnetosphere is important for the structure and dynamics in Titan's ionosphere.

The Titan wake "neutral" sheet, where the magnetic field sharply rotates and relates to an electrical current, was identified by the Dual-Technique Magnetometer (MAG) near 15:35 UT (7). At this time, the RPWS LP detected a sharp peak in both electron number density (850 cm^{-3}) and electron thermal pressure (900 eV/cm^3). The altitude thickness of the compressed plasma sheet was 60 km, which is on the order of the ion gyroradius.

The LP provides estimates of n_e and T_e , but under some circumstances, values can also be obtained for m_i , v_i , n_i , ion temperature (T_i), solar UV intensity, and spacecraft potential. An estimate of the effective ion temperature ($T_{i,\text{eff}}$), which is the sum of the thermal random ion temperature and the ram ion directed flow energy [$T_{i,\text{eff}} = T_i + (m_i v_i^2/2e)$, expressed

¹Swedish Institute of Space Physics, Box 537, SE-751 21 Uppsala, Sweden. ²Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA. ³Department of Physics, University of Oslo, NO-0316 Oslo, Norway. ⁴Centre d'Etude des Environnements Terrestre et Planétaires/CNRS/Institut Pierre Simon Laplace, 78140 Vélizy-Villacoublay, France. ⁵Institute for Geophysics and Meteorology, Köln University, D-50923 Köln, Germany. ⁶Blackett Laboratory, Imperial College London, London SW7 2BW, UK. ⁷Swedish Institute of Space Physics, Box 812, SE-981 28 Kiruna, Sweden.

*To whom correspondence should be addressed. E-mail: jwe@irfu.se

as electron-volts], can be obtained from the slope of the ion current-bias voltage characteristic. If the total ion current to the LP is dominated by the ram contribution, the ion current for a given bias voltage is proportional to $n_i v_i / m_i$, and $T_{i,eff}$ gives a value of $m_i v_i^2$. Thus, by using the condition that the plasma must be electrically neutral ($n_e = n_i$), it is possible to estimate the ion mass and ram velocity. This method only works if there is an ion current signature to the LP and $T_i \ll m_i v_i^2 / 2e$. The maximum ion velocity that can be measured with reasonable certainty is 100 km/s, and larger ion ram velocities may become underestimated (gray areas in Figs. 2 and 3).

The ion velocity during T_A (Fig. 2C) decreased from ~ 100 km/s near 15:14 UT to the spacecraft ram velocity (black line) of ~ 6 km/s near 15:24 UT. This is the mass-loading region, and the boundary near 15:14 UT [1.7 Titan radii (R_T) from Titan] is called the mass-loading boundary (MLB) (8). In the mass-loading region, heavy ions from the ionosphere are accelerated (picked up) downstream by the magnetospheric $\mathbf{v} \times \mathbf{B}$ induced electric field (around 1 to 2 mV/m). At the same time, the magnetospheric ion flow slows down because of the heavy loading of matter by the ionosphere. A corresponding mass-loading region and MLB were detected on the outbound pass between 15:34 and 15:40 UT. Magnetic enhancements (pileup) were detected inside both the MLBs as seen from Titan, which suggests that the magnetic pileup boundary (MPB) (9) was collocated with the MLB.

No large asymmetry of the mass-loading region could be detected between the inbound and outbound passes during T_A , in stark contrast to the findings of the Voyager 1 flyby (10) and the T_B flyby. An extended pickup region was expected on the side of Titan facing away from Saturn because the gyroradii of the heavy ionospheric ions should be in excess of 1000 km. Gyroating ions would to a large degree be absorbed by collisions in the dense atmosphere of Titan on the side that faces Saturn, thereby causing an

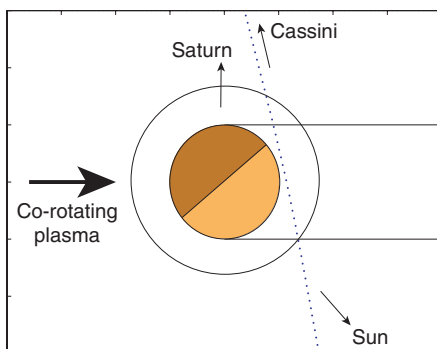


Fig. 1. The T_A flyby trajectory. Titan's surface and approximate ionopause boundary are indicated. The flyby occurred within the magnetosphere at 10.6 Saturn LT. The T_B flyby was similar.

asymmetry in the induced magnetosphere around Titan.

During the inbound pass of the T_B flyby (Fig. 3), plasma of ionospheric origin, as indicated by the enhanced number density of 10 to 100 cm^{-3} and slowed ion ram speed, was found as far as 9 R_T (20,000 km) from Titan. Thus, the MLB was located at nearly 9 R_T inbound, whereas a sharp increase in the ion ram velocity occurred closer to Titan on the outbound pass. The RPWS LP data during the T_B flyby therefore confirm the existence of an extensive mass-loading region on the anti-Saturn side of Titan under certain magneto-

spheric conditions, as suggested from theoretical predictions (11, 12). During other conditions, the ionospheric plasma is concentrated closer to Titan (e.g., 15:18 to 15:40 UT during T_A). Data from further flybys and comparison with data from other instruments are needed to infer the degree of control that the saturnian magnetospheric conditions exert on the structure of the induced space environment around Titan.

The tail or wake region is an outflow region where plasma escapes a planet or moon. A non-magnetized (or almost nonmagnetized) object such as Titan is directly exposed to the external (corotating magnetospheric or solar wind) flow.

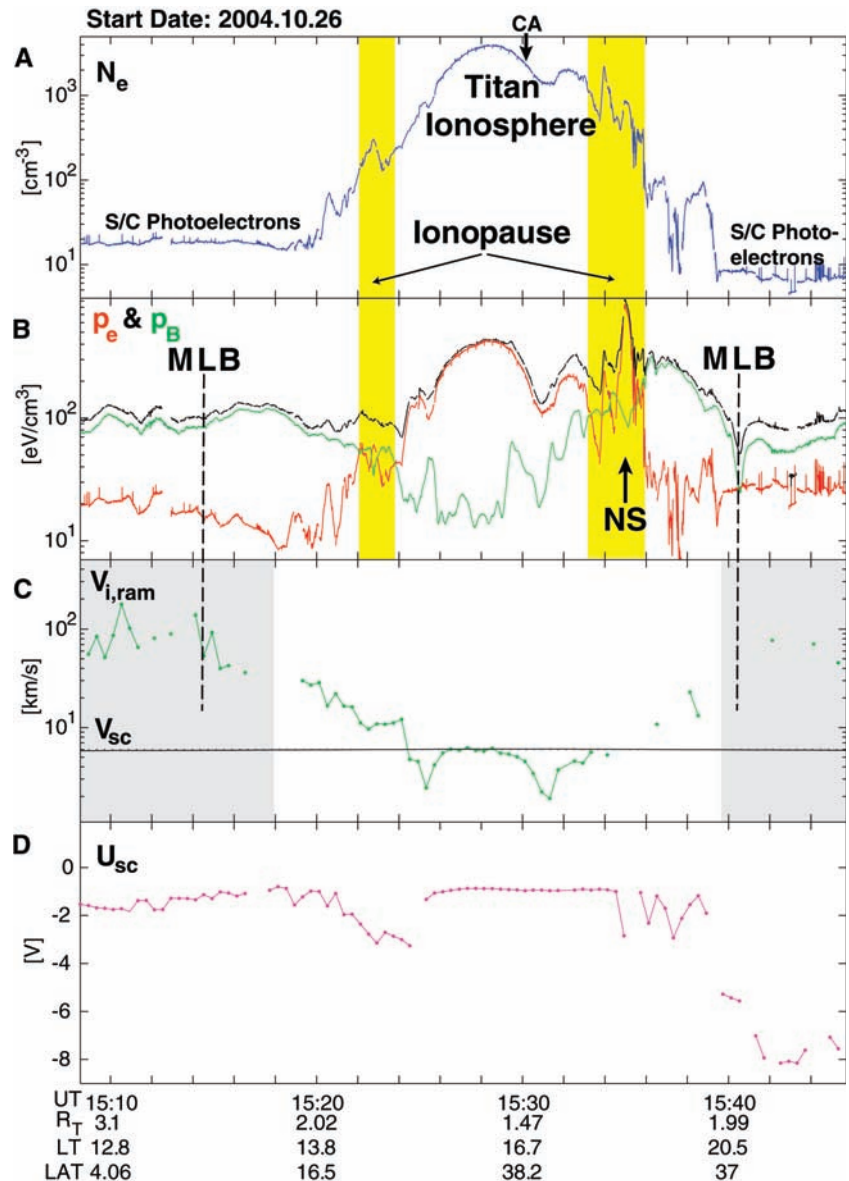


Fig. 2. Cold plasma characteristics during T_A . The data reveal a rather symmetric but dynamic interaction with the magnetosphere of Saturn. The peak in the measured electron number density N_e is shifted inbound from closest approach because Cassini traversed the dayside hemisphere on its inbound pass. The MLBs, magnetic wake neutral sheet (NS), and extended ionopause regions (yellow shading) are indicated. The displayed parameters are (A) N_e ; (B) electron thermal pressure (p_e , red), magnetic pressure (p_B , green), and the sum (black); (C) ion ram speed ($v_{i,ram}$) and spacecraft speed (v_{sc}); and (D) spacecraft potential (u_{sc}). The gray shaded areas in (C) indicate possibly underestimated ion ram speeds.

Consequently, the erosion of the atmosphere of Titan may be quite substantial. A total plasma outflow of 1.2×10^{24} ions/s was estimated from Voyager 1 observations in the far Titan wake with the use of simple pressure balance considerations (10). The RPWS instruments on Cassini are able to monitor the ion outflow (and related processes) more directly. An order of magnitude estimate can be calculated for the ion outflow during T_A (Fig. 2) from the product $n_e v_i$ if we assume that the geometry of the wake region is cylindrical. The density around 15:22 UT was 100 cm^{-3} and the ram velocity was 10 km/s, giving a flux of $\sim 10^{12}$ ions $\text{m}^{-2} \text{ s}^{-1}$. A similar flux is inferred between 15:18 and 15:24 UT (or over a distance of 1000 km across the tail). For the assumption of a cylindrical geometry, the resulting total escape flux amounts to 10^{25} ions/s. This number will most likely vary with magnetospheric and illumination conditions as well as orbit position of Titan, but it is in rough agreement with theoretical predictions (13).

Figure 4 shows the inbound (red) and outbound (black) altitude profiles of the electron density and temperature as well as the averaged ion mass during the T_A flyby. The maximum densities near 1250 km were 3800 cm^{-3} (inbound) and 2000 cm^{-3} (outbound). During T_B the maximum number density was 3200 cm^{-3} . The inbound pass traversed the more sunlit dayside, whereas the outbound pass traversed the shaded region behind the atmospheric terminator. Photoionization and ionization by magnetospheric electrons could explain the overall ionospheric shape (3, 4), whereas the detailed plasma density features most probably were related to the electrodynamic interaction with the magnetospheric flow. The altitudes 1750 km (inbound) and 1400 km (outbound) were associated with changes in ion composition (Fig. 4), whereas at lower altitudes the averaged ion mass stayed above 20 to 30 amu. The ionopause was not sharply defined but rather smeared over an extended region from 1750 to 2150 km (inbound) and from 1400 to 1700 km (outbound). This smearing can be expected in Titan's wake, and it is similar to the ionopause characteristics at Mars (14) and in contrast to the sharp ionopause boundary near Venus. On Titan the ionopause will vary, as it did during T_A , with magnetospheric and illumination conditions.

An intriguing result is the sharp increase in averaged ion mass (up to 60 to 70 amu) near closest approach on the outbound pass, which traversed a region that was less illuminated by the Sun. The ion mass is derived under the assumptions that the ion thermal energy is negligible and that quasi-neutrality applies so that $n_i \approx n_e$. If the ion temperature becomes larger than 1 eV, or if negative ions become a fair part of the total plasma number density, then the derived ion mass must be modified accordingly. The CAPS instrument has de-

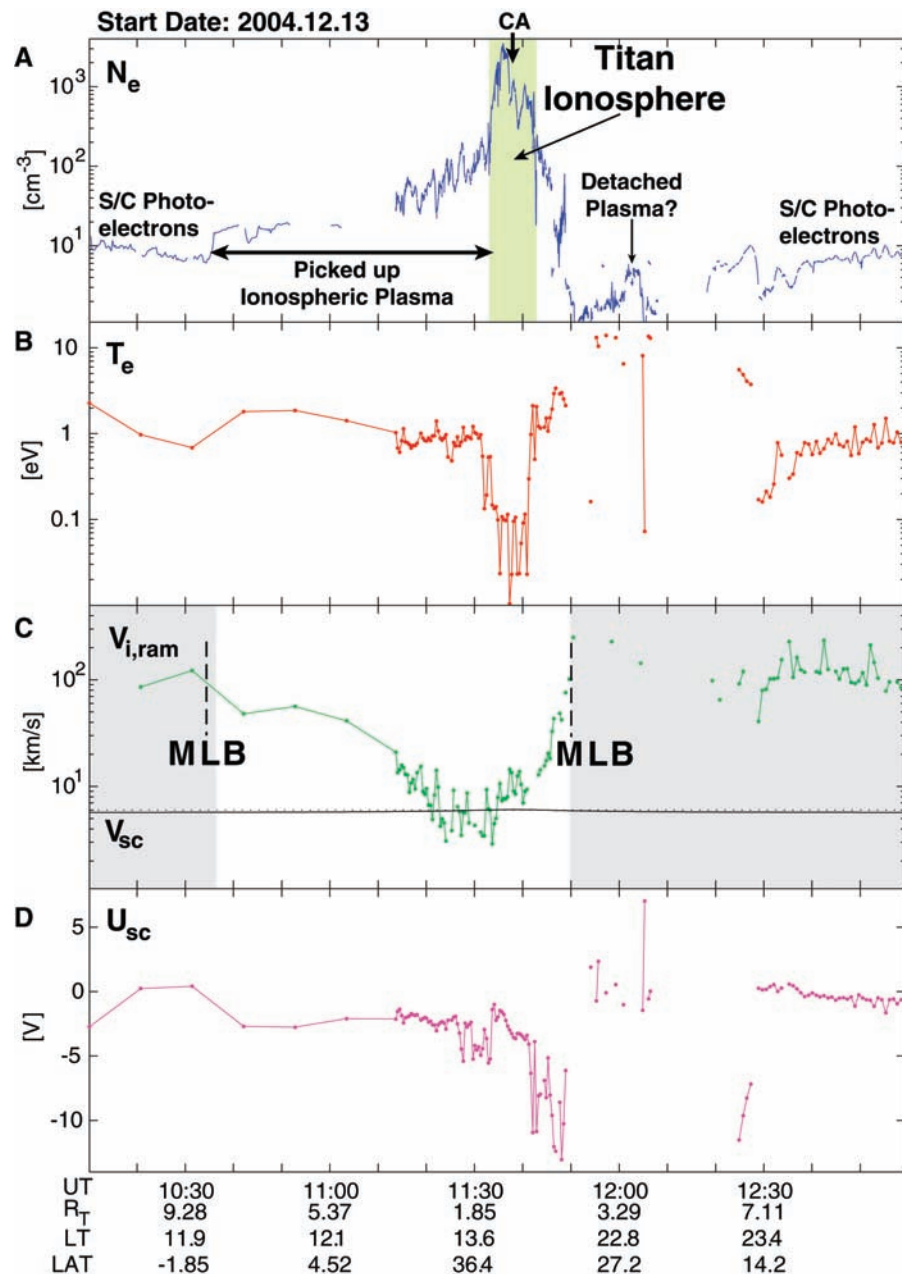


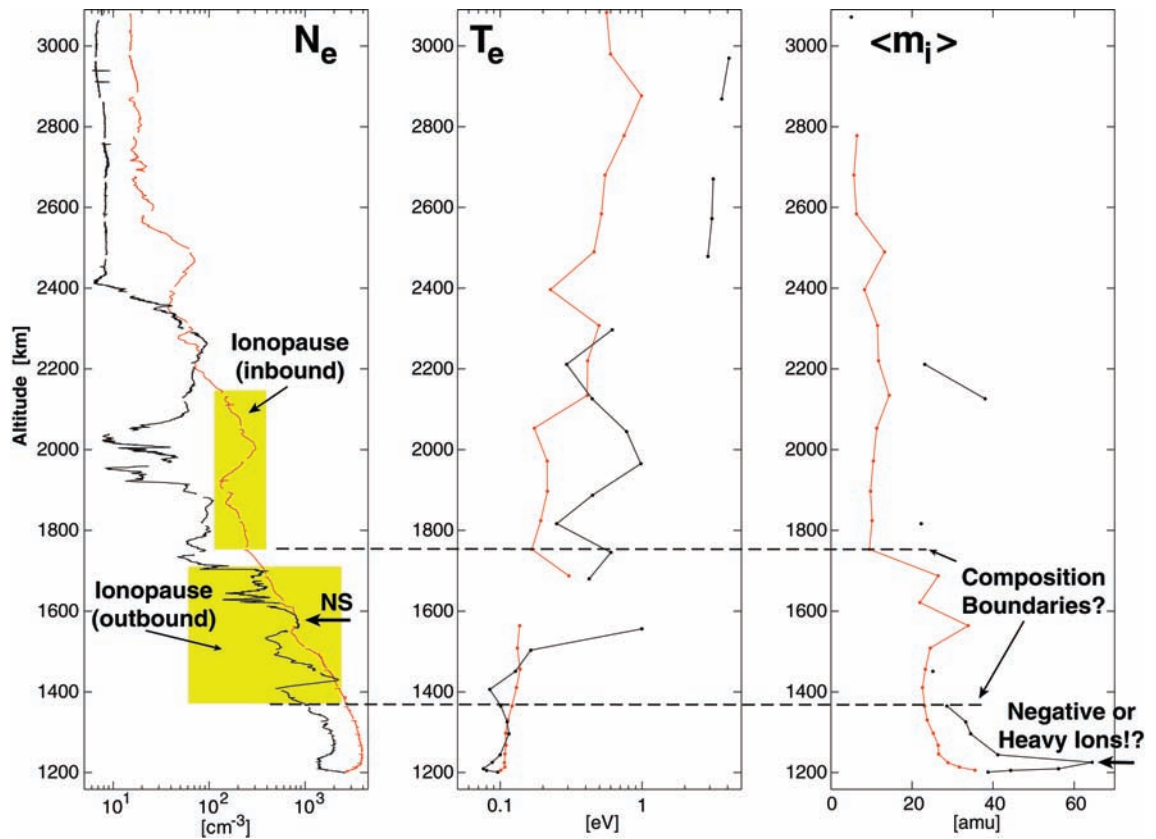
Fig. 3. Cold plasma characteristics during T_B . The data reveal a large and asymmetric interaction where the magnetosphere of Saturn picked up ionospheric plasma as far out as $9 R_S$ inbound from Titan. The outbound (Saturn-facing) MLB was much closer to Titan and similar to the T_A flyby. The displayed parameters are (A) electron number density, (B) electron temperature (T_e), (C) ion ram speed and spacecraft speed, and (D) spacecraft potential. The gray shaded areas in (C) indicate possibly underestimated ion ram speeds.

tected negative ions near Titan (6). Therefore, this increase in averaged ion mass might be due to the presence of some negative ions (and/or very hot ions, which seems unlikely in the dense atmosphere that exists here). In any case, it points to a situation where very complex organic ion-molecule chemistry occurs in the lower ionosphere.

The closest approach T_A electron temperatures (Fig. 4) were 1200 to 1400 K and increased from these values with altitude. The magnetic geometry was rather complicated during the outbound pass, and it was hard to

justify an estimate of the electron heat conduction. However, the magnetic geometry did not change considerably during the inbound pass, and the estimated electron temperature gradient (0.1 to 0.8 meV/km) is more reliable. We conclude that the ionospheric electron energy balance is controlled mostly by electron heat conduction from Titan's wake into the atmosphere, which is in qualitative agreement with theoretical predictions (15, 16). The derived electron temperatures near closest approach during the T_B flyby were lower (110 to 1200 K, Fig. 2). Future studies will use

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.

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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. Mauk¹

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 pro-

cess 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.

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

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