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The global plasma environment of Titan as observed by Cassini Plasma Spectrometer during the first two close encounters with Titan

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[1] The Cassini spacecraft flew by Titan on October 26, 2004 and December 13, 2004. In both cases it entered the ionosphere of Titan, allowing exploration of its plasma environment. Using observations from the Cassini Plasma Spectrometer (CAPS) and the Cassini magnetometer along the inbound legs of both flybys, we examine Titan's global plasma environment. On both occasions CAPS detected plasma populations distinct from those of the Kronian magnetosphere at about 1–1.5 Saturn radii from the moon. Closer to Titan CAPS observed drifting ion ring distributions originating from Titan and, in addition, a corotating flow that was significantly decelerated around the moon due to mass loading. Near the moon, but above the ionosphere, very cold plasma was dominant. We also compare the CAPS data to those of Voyager 1. **Citation:** Szego, K., et al. (2005), The global plasma environment of Titan as observed by Cassini Plasma Spectrometer during the first two close encounters with Titan, *Geophys. Res. Lett.*, *32*, L20S05, doi:10.1029/2005GL022646.

1. Introduction

[2] Titan, the largest moon of Saturn, is a nonmagnetic body with a radius of 2575 km. It orbits Saturn at a distance of just over 20 Saturn radii (R_S). Moreover, it is the only satellite with an appreciable atmosphere, one which is composed mostly of nitrogen with some methane and H_2 [see, e.g., *Broadfoot et al.*, 1981]. Titan's interaction with Saturn's magnetosphere was first observed by Voyager 1, *Hartle et al.* [1982] and *Neubauer et al.* [1984] have given the most comprehensive analysis of the Titan interaction based on Voyager 1 data. This analysis was recently revisited by *Sittler et al.* [2005].

[3] There are three major ionisation sources affecting Titan's atmosphere: photoionisation, electron impact ionization and charge exchange processes; and pickup ions originating from the ionosphere mostly due to scavenging by the incoming flow [cf. *Sittler et al.*, 2005].

[4] Several models have been used to describe Titan's interaction with the ambient plasma. A three-dimensional MHD model was published by *Ledvina and Cravens* [1998], in which they assumed plasma conditions present at the time of the Voyager 1 encounter. This was improved upon by *Ma et al.* [2004], who took into account a more complex ion composition and used a higher spatial resolution grid. *Brecht et al.* [2000] published a hybrid model in which they found that the scale of the interaction region is dominated by the gyroradii of the heavy ambient and pickup ions rather than the size of Titan. Moreover, the upstream flow was perturbed as far as ~10 Titan radii (R_T) from the moon along the Cassini orbit, and pickup ions could be seen at ~5 R_T,. A conceptually different approach was taken by *Kallio et al.* [2004], who employed a 3D quasi-neutral hybrid model of the plasma environment, taking into account the effect of the corotating Saturnian plasma flow and the ionization of Titan's neutral environment by solar EUV. The model also considered local time variations along Titan's orbit. They found that the incoming flow direction differs from the corotation direction. *Sittler et al.* [2005] found finite gyroradius effects in the Voyager 1 data, in which the ambient ions are preferentially absorbed by Titan's atmosphere on the side where pickup ions are dominant.

2. Data Analysis

[5] In this paper we concentrate on a global description of Titan's plasma environment during the Cassini flybys of October 26 (DOY 300), 2004 and December 13 (DOY 348), 2004, (Ta and Tb, respectively), using data from the Cassini Plasma Spectrometer (CAPS) [*Young et al.*, 2004]. The spacecraft orbit for Ta is shown in Figure 1 together with the corresponding magnetic field data. We focus here on data taken on the sunlit side of Titan before closest approach (CA), because after CA during both flybys the magnetic field was observed to be very complex, very likely indicating a complex plasma flow pattern. The CA for the Ta flyby was at 15:30:05 UT (all times are spacecraft event times), and for Tb at 11:38:24 UT, respectively. The trajectory of the spacecraft relative to Titan was similar

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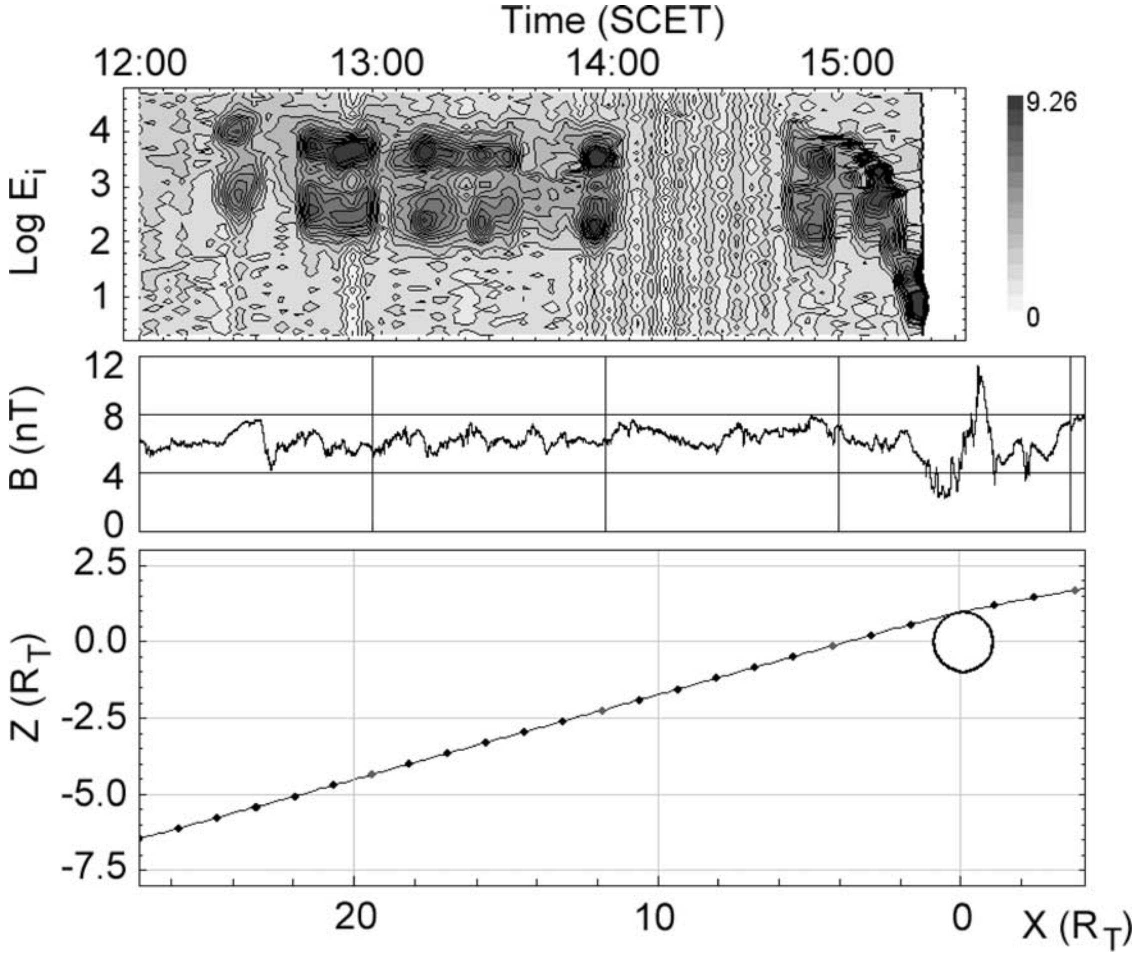

Figure 1. (top) The CAPS ion spectra summed over all elevation and azimuthal directions. The vertical axis is log (energy) in eV, the horizontal axis is spacecraft events time. The plot shows the logarithm of the counts above an average background collected in 63 energy channels during one full actuator turn. (The plot ends ~10 min before CA, when the actuator mode of operation changed.) (middle) The value of the total magnetic field along the spacecraft orbit. (bottom) The spacecraft orbit in a Titan centered frame of reference, the z-axis is along the rotation axis of Titan, the x-z plane contains the Sun direction. The units are in Titan radii. The approximate entry points of the four regions from "A" to "D" are marked by arrows.

for both flybys. The spacecraft performed complex attitude manoeuvres during both flybys to support the imaging experiments and radar; so that the field of view of CAPS relative to Titan varied considerably.

[6] CAPS has three independently operated sensors [*Young et al.*, 2004]: the ion mass spectrometer (IMS) designed to analyse ion composition and plasma dynamics, the electron spectrometer (ELS), and the ion beam spectrometer (IBS) to measure narrow, beam-like distributions without mass separation. The whole CAPS package can be actuated around a rotation axis parallel to the symmetry planes of the IMS and ELS fields of view. IMS in the mode we use here measured ion energy up to ~50 keV, in 63 channels with logarithmically increasing energy steps. Beyond ~1 R_T before CA during the intervals of interest here CAPS had a field of view coverage of almost 2π steradians. However, during some intervals (~14:06–14:50 UT in Ta and for a few drop-outs in Tb) the corotation flow direction was not in this field of view. The perpendicular direction from Saturn to Titan was almost always in the field of view during both flybys. During Ta, within ~1 R_T the actuator scanned across the spacecraft ram direction. In this study we mostly use uncalibrated IMS data that do not allow discrimination of different ion species; a more refined analysis will be the subject of future studies.

[7] During both flybys the spacecraft entered the plasma environment of Titan from the magnetosphere of Saturn. The last crossing of Saturn's magnetopause, based on magnetometer observations, was ~11:00 UT on DOY 300 for Ta, and earlier than 03:00 UT on DOY 348 for Tb. The magnetic field in the magnetosphere region was dipole-like and pointed southward, close to the direction perpendicular to the equatorial plane of Saturn, with B_{total} ~ 5 nT.

[8] During the first two encounters we identified four regions with distinct plasma populations. We identify these regions in this overview as regions A to D, "A" being the more distant from Titan (Figure 1). After having crossed these four regions, Cassini entered Titan's ionosphere 360 s before CA for a total period of 540 s on DOY 300 (and for a brief 32-s long period on DOY 348).

[9] In the upper part of Figure 1 we have plotted the energy spectra of the ion counts measured by IMS as a function of time. In this plot counts are summed over all elevation directions and over complete actuator sweeps in azimuth. On DOY 300 the low energy ion spectra, which were dominated by two large peaks, intensified relatively abruptly at 12:33 UT, ~3 h before CA at 58,700 km (~1 R_{Saturn}) from Titan. A preliminary analysis of the simultaneous time-of-flight data suggests that the light component consists of protons, while the heavy species is around 16 amu. A typical count versus energy/charge spectrum is shown in Figure 2 in grey. There is a peak centered at ~400 eV, and a broader one at ~ 6 keV. During Tb we identified the first ion spectrum that definitely differed from the magnetospheric ion populations, at 7:38 UT, at 82,400 km from Titan. The lower peak was centered around ~600 eV, the higher and broader one around ~9 keV, (Figure 2, black line). The two spectra from Ta and Tb are very similar to each other. We therefore identify region "A" as the location where spectra are dominated by light and heavy components. During the whole Tb encounter we measured a smaller heavy ion content in the plasma flow relative to Ta.

[10] The magnetic field changed character when the spacecraft entered region "A"; the presence of a very low frequency perturbation became evident (Figure 1, arrow at "A"). The ion spectra in "A" can be fit by assuming either broad, highly thermalised beams, or by shell distributions. If the distributions are fit with beams, the drift velocities of the light and heavy components differ for the most probable ion masses; an unlikely situation leading to instabilities which are not observed. The non-normalised distribution function of a shell in velocity space, drifting along the x-direction with a speed u, with a radius w, and thermal velocity v_T is

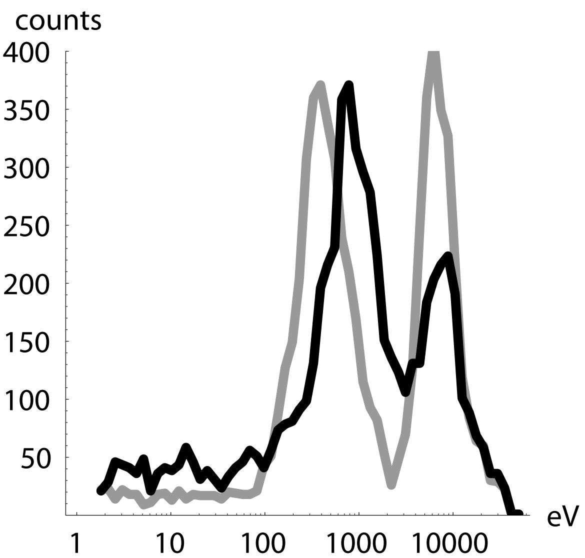

Figure 2. Ion spectra plotted as counts versus energy/charge for Ta (gray line, at 12:47 UT) and Tb (black line, 7:39 UT). The horizontal axis is energy in eV, the vertical axis denotes counts per energy bins, collected during 32-s, in a 20° degree wide elevation and 32° degree wide azimuth interval. In both cases the corotation direction was within the measured solid angle.

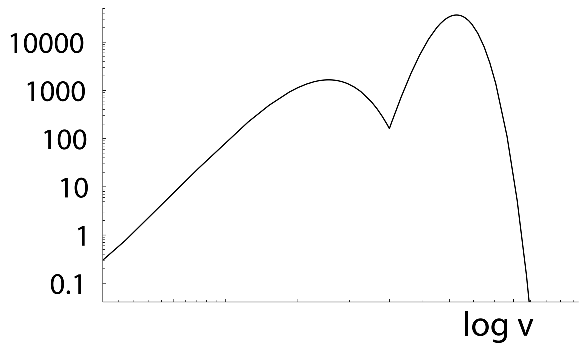

Figure 3. The appearance of a theoretical shell distribution in a count/velocity (energy) plot. The horizontal axis shows log speed, the vertical axis is counts in arbitrary units. The minimum in the middle part of the spectra is related to the drift velocity u, the two peaks around it to the shell radius w. The width is proportional to v_T. This plot is qualitatively similar to the structure of the energy spectra shown in Figure 2; see text for further discussion. For this plot u = 500 km/s, w = 200 km/s, and v_T = 100 km/s were chosen.

$\exp[-(((v_x - u)^2 + v_y^2 + v_z^2)^{1/2} - w)^2/v_T^2]/w^2 \; v_T \; \pi^{1/2}$. The appearance of such a shell distribution in a count/velocity plot is shown in Figure 3. By fitting shells, it is possible to obtain identical drift velocities in the 120–160 km/s range. This is compatible with the expected velocity of the co-rotating flow at Titan, and is similar to the flow velocity observed during the Voyager 1 encounter [*Hartle et al.*, 1982].

[11] Region A is so far from Titan that ions recently originating from the moon cannot populate it. Therefore we believe that this region consists of ejected neutrals that were ionized far from Titan. The basic idea of ions originating during earlier revolutions around Saturn was suggested by *Eviatar et al.* [1982]. The ion distributions in this region are similar to those observed by CAPS during SOI, shown by *Young et al.* [2005, Figure 1B]. We can state with high confidence that region A could be easily distinguished from the more distant regions of the Saturnian magnetosphere.

[12] We equate region "B" with the appearance of multiple peaks in the energy spectra (Figure 4). During Ta the first such spectrum was measured at 14:05 UT, at 27,200 km from Titan. During Tb similar spectra were measured from 10:40 UT (20,600 km) onward. Whereas the highest and lowest peaks are compatible with the assumption that we see a portion of the shells of the upstream flow, the middle two peaks are so narrow in thermal width that very likely they can only be beam-type distributions. The look direction of CAPS is compatible with the assumption that these ions originated from Titan. The energy of the third peak is exactly twice that of the second one. The two middle peaks therefore can be identified as a drifting ring distribution of picked-up heavy ions with different masses - as if we measured the ions emitted with about the same velocity in a magnetic mass separator. In region B the magnetic field is still dominantly dipole-like. From these data we can conclude that the plasma has multiple sources: the upstream rotating flow, the neutral corona of Titan, and its ionosphere.

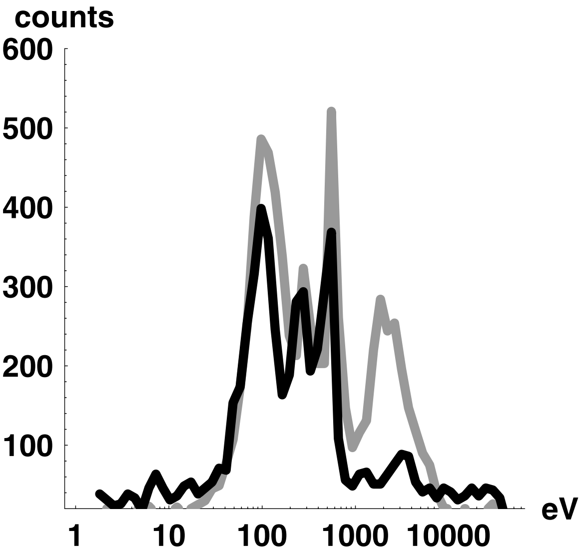

Figure 4. Ion spectra plotted as counts versus energy/charge for Ta (gray line, at 14:54 UT) and Tb (black line, 10:40 UT). The horizontal axis is energy in eV, the vertical axis denotes counts (multiplied by 4) per energy bins, collected during 4-s (16-s for Tb), in a 20° wide elevation and ~4° (~14° for Tb) wide azimuth interval. In both cases the view direction was close towards the Titan-Saturn direction.

[13] The weak ambient magnetic field in region B yields gyroradii for H^+ and N^+ equal to 413 km (0.16 R_T), and 5790 km (2.25 R_T), respectively. The distance from Titan where we detected the possible ring-like distributions is much farther than these estimates, therefore, we believe that the source of the two middle peaks shown in Figure 4 is the neutral corona which extends to several R_T [*Smith et al.*, 2004]. There is no sharp boundary between regions A and B (Figure 1).

[14] We have identified region "C" with the deceleration of the plasma flow as Cassini approached the moon. The loss in bulk energy was over 99.5%. The velocity drop was faster for Ta than for Tb, which might be connected with lower heavy ion content of the plasma during Tb. During Ta the deceleration started at 15:08 UT, (an altitude ~7000 km), and finished at 15:22 UT, (~2000 km). During Tb the deceleration started at 10:48 UT, (~11,800 km), and finished at 11:24 UT, (~3500 km). The loading of the incoming flow with planetary ions contributes significantly to the slowing. In the model of *Ma et al.* [2004] Cassini would have crossed the deceleration region (from a velocity of 150 km/s down to 10 km/s) in about 10 minutes. We observed longer time intervals (~15 min for Ta and ~36 min for Tb), which might be related to finite gyroradius effects not taken into account in MHD models. It is known that slowing of the flow takes place in the vicinity of the magnetic pile up boundary [*Cravens et al.*, 1998]. Along the inbound leg we cannot see the pileup boundary in B_{total}. However the magnetic field is known to drape there; which is clearly seen in the Cassini magnetometer data. After leaving the deceleration region, but still above the ionosphere Cassini entered a dense, cold plasma region with typical beam energy of a few eV, which we call region D (cf. Figure 1).

3. Conclusions

[15] There is a characteristic plasma region ~1 R_S in radius centered on Titan's orbit along the inbound leg of Cassini during Ta and Tb. This volume can be divided broadly into four main regions. Region "A", the farthest from Titan is characterised by two-peaked shell-like ion distributions, probably arriving from the corotation direction. The most important feature of the second region, "B", is the drifting ion rings originating from Titan's neutral corona and/or from its ionosphere. Region C is the deceleration region. The fourth ("D") is dominated by cold Titan plasma. The identification of regions A and B is, so far we know, new. The global properties of region C were known, but the cold plasma population above the ionosphere has not been measured before. Our data confirm the basic findings of the Voyager 1 encounter [*Sittler et al.*, 2005]. However, the region explored by Voyager was much closer to Titan (and consequently smaller in volume). The mass spectrum of pickup ions seen by Cassini is the topics of a forthcoming publication.

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