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Ionospheric electrons in Titan's tail: Plasma structure during the Cassini T9 encounter

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[1] We present results from the CAPS electron spectrometer obtained during the downstream flyby of Titan on 26 December 2005, which occurred during a period of enhanced plasma pressure inside the magnetosphere. The electron data show an unusual split signature with two principal intervals of interest outside the nominal corotation wake. Interval 1 shows direct evidence for ionospheric plasma escape at several R_T in Titan's tail. Interval 2 shows a complex plasma structure, a mix between plasma of ionospheric and magnetospheric origin. We suggest a mechanism for plasma escape based on ambipolar electric fields set up by suprathermal ionospheric photoelectrons.
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1. Introduction

[2] Titan is a moon lacking significant intrinsic magnetization, [e.g., *Neubauer et al.*, 1984, and references therein; *Backes et al.*, 2005] and is normally immersed in Saturn's rapidly rotating magnetosphere. Of the 31 encounters by Cassini so far, all have occurred with Titan inside the magnetosphere. These encounters were designed partly to provide information on plasma interactions at different local times (with respect to both Saturn and Titan), altitudes and Titan latitude and longitude of closest approach.

[3] The T9 encounter was unusual in that it was a relatively distant wake (with respect to corotation) pass, with closest approach at an altitude of 10,408 km (about 5 R_T from the centre of Titan) along the tail. During Voyager 1's closer (~2.7 R_T) wake crossing, ionospheric ions were observed flowing away from Titan [*Hartle et al.*, 1982]. *Gan et al.* [1992] modeled magnetospheric and ionospheric plasma along the trajectory, and *Gan et al.* [1993] extended this to include draping and mirroring. Here, we present clear evidence for ionospheric plasma within the Titan wake downstream of the moon.

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2. Instrumentation and Encounter Geometry

[4] We use data from the CAPS electron spectrometer (ELS) [*Young et al.*, 2004; *Linder et al.*, 1998] and Ion Mass Spectrometer (IMS). During this encounter ELS produced a 63-point energy spectrum every 2s, with $\Delta E/E \sim 17\%$ (intrinsic and step). The 160x5° field of view is divided into 8 angular sectors. Here we examine data from anode 5, one of those least affected by spacecraft-plasma interactions. The CAPS actuator was operating during the encounter; this increases the angular coverage of the CAPS sensors. The scan angle in this case was ~ -100 to +104 degrees with respect to the spacecraft $-X$ axis, with a period of 279 seconds.

[5] The geometry of the encounter is illustrated in Figure 1. Cassini was on an outbound section of its orbit around Saturn, with closest approach at 18:59 UT on 26 December 2005. The encounter occurred at a local time of ~03:00 with respect to Saturn. The nominal corotation speed in Saturn's magnetosphere at Titan's location of ~20 Rs from the planet is faster than Titan's orbital speed. Consequently, the spacecraft flew through the nominal corotation wake, which would be at an angle of approximately 135° to the solar wake (see Figure 1), in Titan's orbital plane, with Titan's subsolar latitude $\sim -19°$. However, the upstream conditions are far from the dipole and corotation assumptions. The background field orientation was closer to the orbital plane and below Saturn's current sheet [*Bertucci et al.*, 2007; *Wei et al.*, 2007; C. Bertucci et al., unpublished manuscript, 2007]. Measured [*Szego et al.*, 2007] and inferred (C. Bertucci et al., unpublished manuscript, 2007) ion flow is significantly away from Saturn. We provide further evidence for an outward flow direction here: if intervals 1 and 2 (indicated in red, see later discussion) are assumed to be symmetric within the tail structure, the actual tail direction must have a component away from Saturn.

3. Upstream Plasma Conditions

[6] Figure 2 shows the electron plasma environment of the T9 encounter. ELS data are presented as an energy-time spectrogram of the count rate (proportional to differential energy flux). Saturn periapsis occurred late on 24 December. As usual in Saturn's inner magnetosphere, a cold electron population is seen with a characteristic 'V' shape in the time series. A high energy electron component is also visible in the inner magnetosphere [cf. *Young et al.*, 2005; *Rymer et al.*, 2007], injection events are clearly seen [cf. *Burch et al.*, 2005; *Hill et al.*, 2005] and in a region near periapsis the more energetic electrons disappear, perhaps due to interactions with neutrals [e.g., *Young et al.*, 2005].

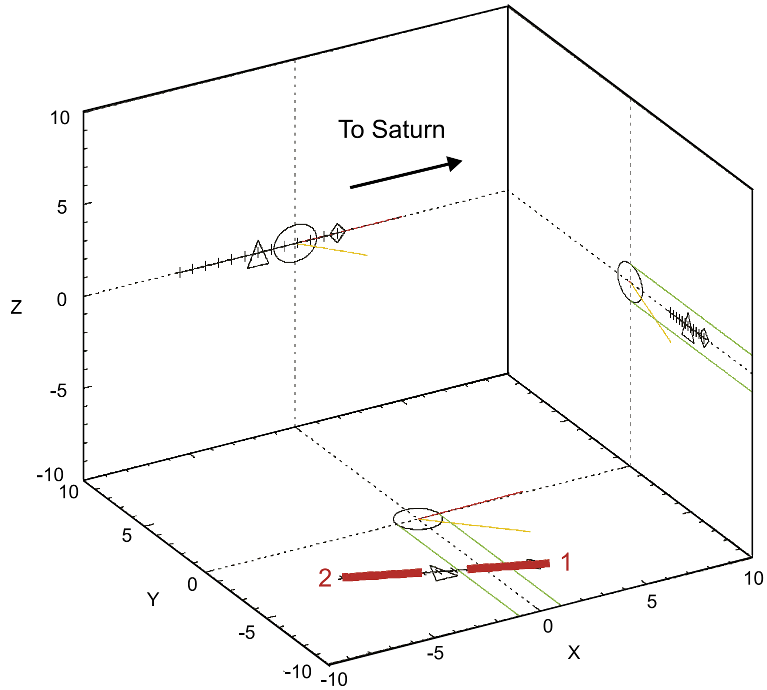

Figure 1. Encounter geometry shown in Titan-centred coordinates. The spacecraft trajectory is shown for ±30 minutes from closest approach. The strict corotation wake is in the −y direction in this plot. The solar direction (yellow) and Saturn direction (red) are indicated. The location of intervals 1 and 2 are shown (see text).

[7] After ~12:00 UT on 25 December the spacecraft photoelectrons (population below ~10 eV) reappear as the spacecraft potential becomes positive again. In this long baseline plot a periodicity in the plasma pressure (~100–1000 eV plasma sheet electrons) is clearly seen, related to the rotation period of Saturn (~10.75 hours). This phenomenon is also seen in the ELS and in other datasets on different encounters and has been discussed elsewhere as associated with motion of plasma away from Saturn in a spiral pattern [e.g., *Clarke et al.*, 2006; C. Bertucci et al., unpublished manuscript, 2007; M. W. Morooka et al., unpublished manuscript, 2007]. This would be consistent with the wake asymmetry implied by Figure 1.

[8] Figure 2 shows that the upstream conditions for the T9 encounter were associated with an intensification of plasma pressure as seen in the plasma sheet electrons. The

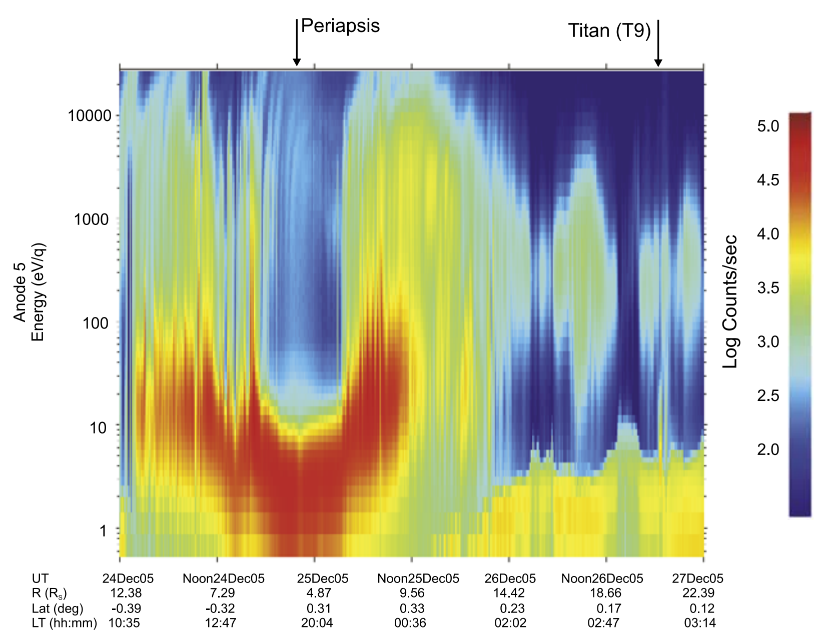

Figure 2. Electron spectrogram showing the location of the T9 encounter in Saturn's magnetosphere.

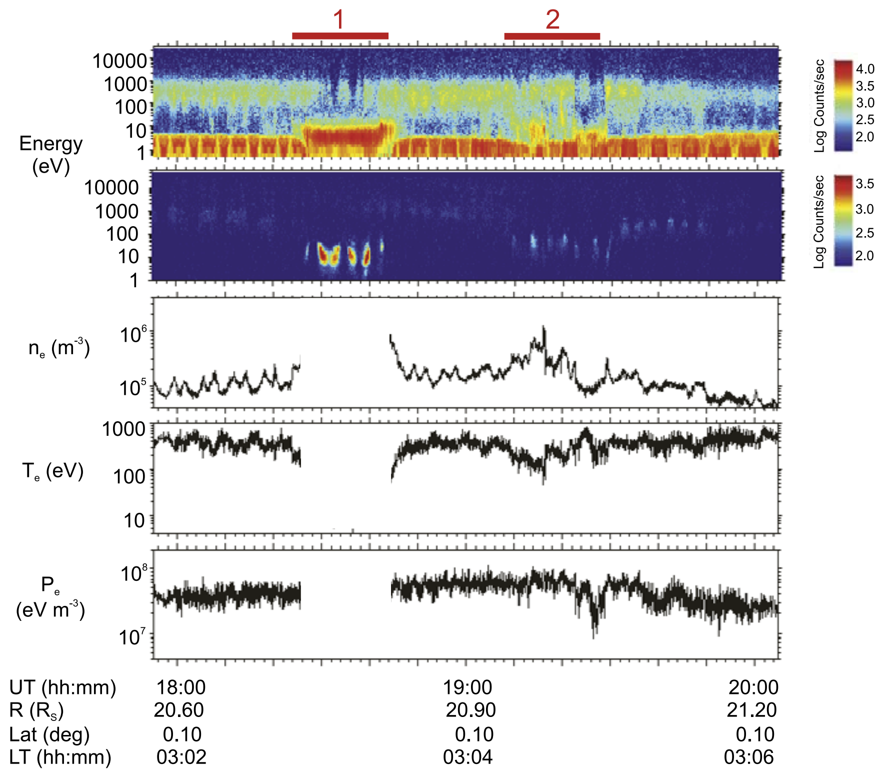

Figure 3. Closer view of the T9 encounter as seen in ELS electron (upper and lower 3 panels) and IMS ion data (second panel).

context for the T9 encounter is therefore that it occurs during a spin-periodic increase in the plasma pressure.

4. Plasma Data During T9

[9] In Figure 3 we show ELS and IMS data from an interval of just over 2 hours near the T9 encounter. The upper panel shows an electron energy-time spectrogram. In this plot, the population at <10 eV is due to spacecraft photoelectrons, except near the interval marked 1. This indicates that the spacecraft potential is positive for most of the plot interval, except near the interval marked '1' where it goes negative by 1–2 volts [*Modolo et al.*, 2007]. In general, the data are modulated to some extent by the actuator motion.

[10] The second panel shows ion data from IMS for comparison. As the actuator scans the IMS through the narrow ion beams in intervals 1 and 2, ions of m/q = 16–32 (in interval 1) and m/q = 2 (interval 2) are detected (see *Szego et al.* [2007] for detailed analysis).

[11] We also show moment values calculated from the ELS data for intervals where the spacecraft potential is positive. The third panel in Figure 3 shows electron density, the fourth panel shows electron temperature and the lower panel shows electron thermal pressure. In order to calculate the moments, the counts data from anode 5 (a central anode least affected by spacecraft-plasma interactions) are first converted to phase space density, then corrected for spacecraft potential (when this is positive and within the energy range of ELS) using Liouville's theorem. Then a moment integration is performed, assuming isotropy (see G. R. Lewis et al., Derivation of density and temperature from the Cassini-Huygens CAPS Electron Spectrometer, submitted to *Planetary and Space Science*, 2007). The moment values obtained during negative spacecraft potential intervals need to be corrected for negative spacecraft potential and are not shown here.

[12] Looking at the spectrogram, the plot starts with a population of magnetospheric electrons with density about 10^{-1} cm^{-3} and temperature about 400 eV, giving an energy density ~40 $eVcm^{-3}$. These upstream values are slightly different (lower density, higher temperature, lower energy density) by the end of the plot, but not too different for most of the period. However there are two intervals (marked 1 and 2) with strikingly different populations present as we describe below.

[13] Interval 1 (~18:24–18:44 UT) is a period of somewhat depleted magnetospheric electrons (this population is also anisotropic during these depletions), but the bulk of the population consists of electrons below 10 eV. As the spacecraft potential is negative here, this population is real and its energy outside the spacecraft potential sheath would be slightly higher than measured. This population appears very similar to the ionospheric plasma seen by ELS on other Titan close approaches [e.g., *Hartle et al.*, 2006; A. J. Coates et al., Discovery of heavy negative ions in Titan's ionosphere, submitted to *Geophysical Research Letters*, 2007, hereinafter referred to as Coates et al., submitted manuscript, 2007], however, at this time Cassini is much further from Titan along the wake (see Figure 1).

[14] At the same time as our observation of apparently ionospheric electrons, intense, narrow fluxes of ions at about 5–30 eV, with mass 16–32 amu/q, are seen by the CAPS IMS sensor as the actuator scans the IMS field of

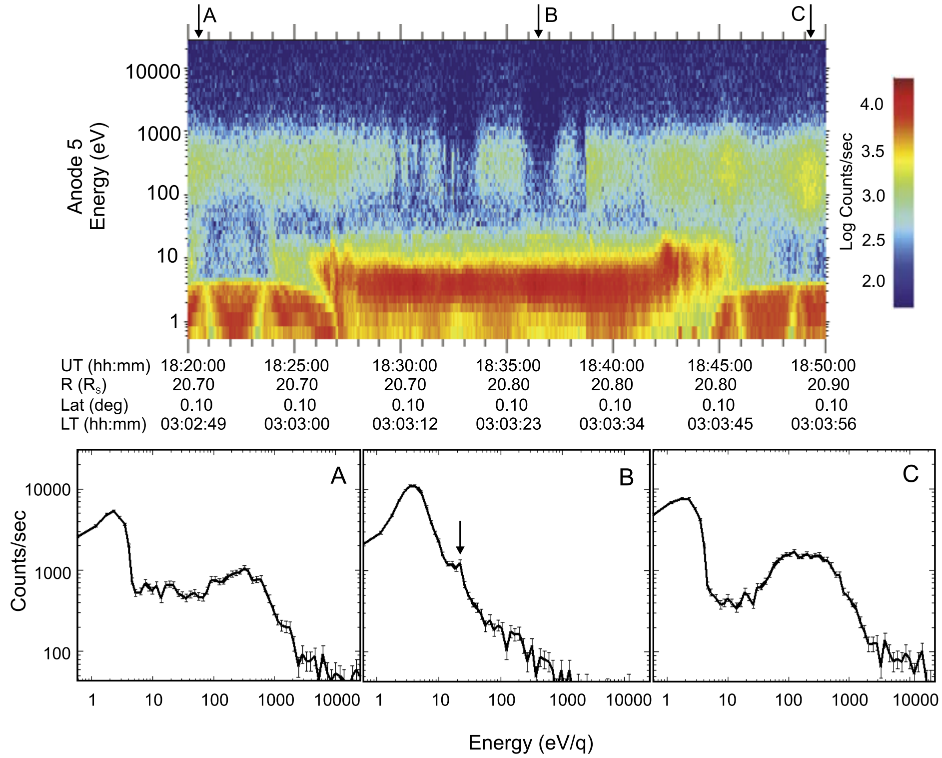

Figure 4. Expanded view of interval 1, with some individual electron spectra shown for comparison.

view through the ion beam [see *Szego et al.*, 2007, Figure 2]. Hence, we interpret the low energy plasma seen during interval 1 as ionospheric plasma from Titan which is escaping along the tail. This is in agreement with the interpretation of the magnetometer data by *Wei et al.* [2007] and it suggests that Cassini is indeed magnetically connected to Titan's ionosphere at this time. The ionospheric plasma escapes along the draped magnetic field [*Wei et al.*, 2007; *Bertucci et al.*, 2007] produced by the interaction, and it is consequently visible in the tail.

[15] Electron angular data during interval 1 (not shown) indicate flow away from Titan, i.e., field-aligned (cf. C. Bertucci et al., unpublished manuscript, 2007). Directions towards Titan, which may be populated [*Gan et al.*, 1993], were not sampled.

[16] Between intervals 1 and 2 there is a region of almost undisturbed magnetospheric plasma, during which Cassini is probably not magnetically connected to Titan. Interval 2 (~19:04–19:29 UT) has a more complex structure, with magnetospheric plasma (100–1000 eV) mixed with a simultaneous and highly variable low energy electron population (~ 10–20 eV). At the same time, IMS sees beams of ions between ~10–100 eV with mass 2 amu/q dominant [*Szego et al.*, 2007]. Again, it is possible that intermittent magnetic connection to Titan is occurring allowing the detection of the low energy ionospheric electrons and the m/q = 2 ions, but the connection is probably to different regions of Titan's ionosphere. Some of the dynamically varying low energy electrons and ions are at higher energy than that seen in Interval 1 and we suggest that these could be regions of accelerated ionospheric plasma from Titan. The predominantly light ion composition (mass per charge 2 amu/e) in this interval indicates that the escaping plasma from the source region is different from that observed in region 1. This may either be due to differences in the source location towards the antisolar side of Titan's ionosphere, or due to the actual magnetic connection from Interval 2 being to a different height above Titan's surface, where lighter ions dominate. Finite gyroradius effects may also separate masses [e.g., *Luhmann*, 1996]; these appear not to be dominant at T9, our data are more consistent with spatial effects of the source.

[17] In Figure 4 we present an expanded view of interval 1. There is clearly fine structure in both the higher and lower energy electron populations as they vary with time, and also, for the low energy portion, there is fine structure in the energy spectrum. Three individual electron spectra are shown at times A (18:20:21), B (18:36:25) and C (18:49:05). Each spectrum is averaged over eight individual 2-second raw spectra (i.e., over 16 second intervals) to reduce noise from counting statistics. In spectra A and C the low energy (~2 eV) peaks are due to spacecraft photoelectrons but the higher energy peaks (~200–300 eV) are clearly magnetospheric electrons.

[18] Spectrum B shows a much colder electron spectrum. Again, spacecraft potential is ~−1 to −2V at this time [*Modolo et al.*, 2007] so the electrons in spectrum B are real but again are of slightly higher energy than indicated. The broad low energy spectrum has a peak at 3–4 eV and is characteristically ionospheric, with a spectrum consistent with models [e.g., *Cravens et al.*, 2005; *Galand et al.*, 2006] and with other observations [e.g., *Hartle et al.*, 2006]. There is also clearly a statistically significant peak at ~21–22 eV. Correcting for negative spacecraft potential gives a full

energy for this peak of ∼22–24 eV. This population is also seen in the spectrogram plot for significant portions of interval A but it is variable. Angular distributions (not shown) of both electrons and ions [*Szego et al.*, 2007] indicate that usually this population is flowing away from Titan along the magnetic field.

[19] We interpret this 22–24 eV peak as due to ionospheric photoelectrons produced from solar He 30.4 nm radiation ionizing N_2 in Titan's ionosphere [e.g., *Galand et al.*, 2006; *Cravens et al.*, 2005]. When present this feature clearly indicates that the magnetic connection is to the sunlit part of Titan's ionosphere and supports the interpretation of escaping plasma moving along the tail.

[20] Interval 2 shows a much more dynamic structure with highly variable peak energy in the low energy population. It is possible that the ∼24 eV photoelectron peak is seen for a few spectra about 19:15 but is otherwise absent, indicating connection to the shadowed (or highly attenuated, sunlit) portion of Titan's ionosphere for most of interval 2. There are clear signs of dynamic acceleration of the low energy component, perhaps associated with electric fields or with wave-particle interactions between the ionosphere and the spacecraft. The magnetospheric electrons are also attenuated for parts of this period, and they are anisotropic at these times. Interval 2 is further from Titan and further away from the axis of the nominal corotation wake (see Figure 1).

5. Discussion

[21] The ionospheric plasma seen in interval 1, far from Titan in the tailward extension of the wake, is most likely related to the atmospheric escape process at Titan. Electrons produced with an energy of up to ∼24 eV are more energetic than the ambient ionospheric population of a few eV (see spectrum B). We observe these electrons escaping from Titan along the wake. This would set up an ambipolar electric field at the top of the ionosphere and enhance pressure-driven plasma escape, in a mechanism similar to the polar wind at Earth (e.g., *Ganguli* [1996, and references therein]; a similar mechanism was suggested at Venus [*Hartle and Grebowsky*, 1995], and an electric field escape mechanism at Titan was modelled by *Keller and Cravens* [1994]). Indeed, the heavy ions seen during interval 1 are highly directional and of approximately the right energy (5–30 eV) to be escaping due to this process. The lighter ions in Interval 2 have a similar energy (10–100 eV) to heavy ions at the end of Interval 1, and are thus escaping at an even higher speed.

[22] We should note that ionospheric photoelectrons are indeed seen during other Titan encounters. They are always seen in sunlit conditions, and as sunlight reaching the spacecraft is occulted by Titan's atmosphere, the population is attenuated as expected (e.g., Coates et al., submitted manuscript, 2007).

[23] Escaping ionospheric photoelectrons are also seen in the tail of Mars [*Frahm et al.*, 2006, 2007]. Modelling showed that this could also be due to a magnetic connection to the Martian ionosphere [*Liemohn et al.*, 2006]. This is another similarity between the plasma interactions at both of these objects lacking significant intrinsic magnetization, despite the different parameter regimes and the fact that Mars is immersed in the cold solar wind rather than Saturn's hot magnetosphere. Ionospheric photoelectrons have also recently been observed at Venus [*Coates et al.*, 2007].

6. Summary and Conclusions

[24] The T9 encounter has an unusual split signature in the electron and ion data. The upstream electron pressure was $P_e \sim 40$ eVcm^{-3} at this encounter, and the encounter occurred during a high plasma pressure phase of the spin-period fluctuations in Saturn's magnetosphere.

[25] During interval 1, we observe that ionospheric electrons dominate, moving away from Titan, at the spacecraft location in the tail and outside the nominal corotation wake of Titan. A clear feature at ∼24 eV in the electron spectrum is strong evidence that this population is from Titan's ionosphere. These ionospheric photoelectrons are observed far from Titan in the tail, and thus play a role in plasma escape from Titan. Heavy ions are also observed escaping from Titan at this time. During interval 1 there are some magnetospheric electrons, the flux of which is variable with time and anisotropic.

[26] Interval 2 shows a complex structure, consisting of mixed magnetospheric plasma with a variable and dynamic low energy electron population. The ion beams here are of lower mass. We interpret these observations as being due to accelerated ionospheric particles whose source location, unlike that in interval 1, is mainly in shadow or regions of attenuated sunlight. The source may also be at higher altitude to explain the composition difference.

[27] The split nature of the electron signature at T9 is related to the wake structure, but is significantly different from the nominal corotation direction. We note that this split signature is the only one observed during the Titan flybys to date – in particular, a later somewhat closer wake flyby (T11, not shown) showed no evidence for a split signature. We suggest that this is due to a significant difference in the ambient plasma and field conditions during the two encounters, consistent with magnetometer observations (C. Bertucci et al., unpublished manuscript, 2007).

[28] **Acknowledgments.** We thank L.K.Gilbert and G.R.Lewis for spectrogram plotting and data analysis software. We acknowledge PPARC (UK) for financial support of ELS and NASA/JPL contract 1243218 for financial support of the CAPS investigation.

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