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Charged particle environment of Titan during the T9 flyby

K. Szego,[1] Z. Bebesi,[1] C. Bertucci,[2] A. J. Coates,[3] F. Crary,[4] G. Erdos,[1] R. Hartle,[5]
E. C. Sittler Jr.,[5] and D. T. Young[4]

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[1] The ion measurements of the Cassini Plasma Spectrometer are presented which were acquired on 26 December 2005, during the T9 flyby at Titan. The plasma flow and magnetic field directions in the distant plasma environment of the moon were distinctly different from the other flybys. The near-Titan environment, dominated by ions of Titan origin, had a split signature, each with different ion composition; the first region was dominated by dense, slow, and cold ions in the 16–19 and 28–40 amu mass range, the second region contained only ions with mass 1 and 2, much less dense and less slow. Magnetospheric ions penetrate marginally into region 1, whereas the region-2 ion population is mixed. A detailed analysis has led us to conclude that the first event was due to the crossing of the mantle of Titan, whereas the second one very likely was a wake crossing. The split indicates the non-convexity of the ion-dominated volume around Titan. Both ion distributions are analysed in detail. **Citation:** Szego, K., Z. Bebesi, C. Bertucci, A. J. Coates, F. Crary, G. Erdos, R. Hartle, E. C. Sittler Jr., and D. T. Young (2007), Charged particle environment of Titan during the T9 flyby, *Geophys. Res. Lett.*, *34*, L24S03, doi:10.1029/2007GL030677.

1. Introduction

[2] The ninth flyby (T9) of the Cassini spacecraft at Titan took place on 26 December 2005, the closest approach (CA) was at ~18:59:30 UT, ~5 R_{Titan}, at 3.1 h Saturn clock angle position; the spacecraft speed was 5.6 km/s relative to Titan. More than a day before CA along Cassini orbit the magnetic field orientation in the magnetosphere was dipole-like; after that the field direction changed significantly and became less inclined to the equatorial plane, and stayed in the new configuration. The magnitude of B varied between 4 to 10 nT on the day of the encounter; the CA took place near minimum. The real specialty of this encounter, however, was the split signature observed in the near-Titan plasma interaction volume: that is the spacecraft crossed twice plasma regions dominated by ions of Titan's origin. This paper summarises the ion measurements of the Cassini Plasma Spectrometer (CAPS), the companion papers describe the results of other plasma instruments flying onboard of Cassini.

[3] The CAPS instrument [*Young et al.*, 2004] has three independently operated sensors, here we use data of the ion mass spectrometer (IMS) designed to analyse ion composition and plasma dynamics, and the electron spectrometer (ELS) data. During the flyby the whole CAPS package was actuated around a rotation axis parallel to the symmetry planes of the IMS field of view. In the SINGLES mode we use here, IMS measured ion energy up to ~50 keV/charge, in 63 channels with logarithmically increasing energy steps in 4-s long time intervals, without mass separation. By construction the IMS field of view is about 10–12° wide in azimuth; the 8 elevation channels each has about 20° wide field of view in the perpendicular direction. CAPS also performed time-of-flight analysis of the ions by summing data for a 256 s long period of time ("TOF" mode) over all directions. We shall use both SINGLES and TOF data in this analysis.

[4] The flyby geometry is shown in Figure 1 in the Saturn equatorial reference frame (SSQ). In Figure 1 ancillary data are also exhibited to facilitate the analysis: data collected during the red and blue segments of the spacecraft orbit (events 1 and 2) are the split events of high interest in what follows, the green line (marked "M") is the average magnetic field direction during the red portion of the orbit; and the CAPS field of view (f.o.v.) during one actuator turn are shown in three inserts for different significant times. The plots of the electron and ion energy spectra summarised over all elevation channels are shown in Figure 2. The CAPS electron data are analysed in a companion paper [*Coates et al.*, 2007].

2. Data Analysis

[5] At the beginning of the flyby the magnetospheric plasma flow direction was not in CAPS f.o.v., requiring that the angle between the flow and corotation directions should be >40°. If the flow direction had been right at that edge of the f.o.v. where the counts were maximal, it would have been parallel to the −y direction in Figure 2 at 18:00 UT. Magnetospheric ions started to get decelerated somewhat after 18:00 UT. On other flybys the broad ion deceleration region occurs generally on the anti-Saturn side, opposite to the situation here. After the deceleration region, as observed on all flybys, the spacecraft (sc) entered into a dense, cold plasma region at 18:25 UT at about 6.3 R_T from Titan, marked red in Figure 1 and as "event-1" in Figure 2; the flow direction returned into the f.o.v. The electron density (and by implication the ion density), according to the Langmuir probe (LP) data increased ~20 times to ~10/cc [*Modolo et al.*, 2007], the ELS electron spectrum changed abruptly, as shown in Figure 2. The sc exited at ~18:44 UT

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[1] Research Institute for Particle and Nuclear Physics, Central Research Institute for Physics, Hungarian Academy of Sciences, Budapest, Hungary.

[2] Space and Atmospheric Physics Group, Imperial College London, London, UK.

[3] Mullard Space Science Laboratory, University College London, Dorking, UK.

[4] Southwest Research Institute, San Antonio, Texas, USA.

[5] NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

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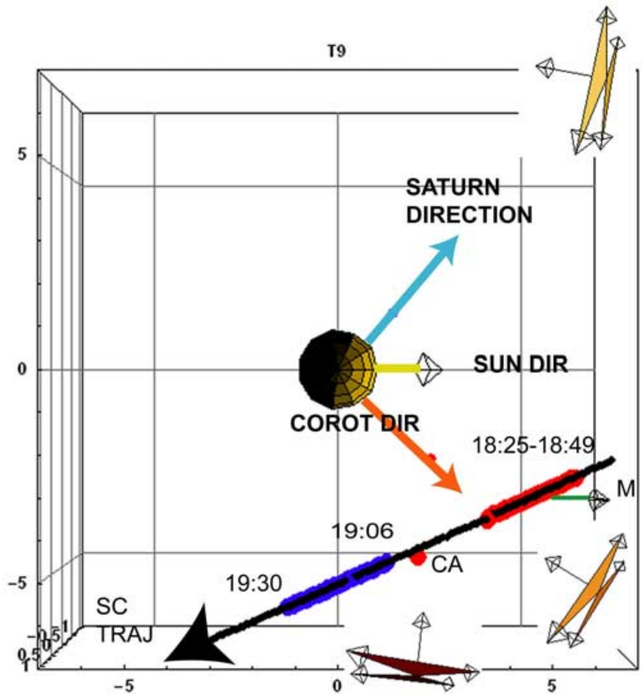

Figure 1. The flyby geometry is shown in the Saturn equatorial reference frame (SSQ), its z-axis is parallel to Saturn rotation axis, the x-y plane is the equatorial plane, and the z-x plane contains the solar direction which was 19° below the x-axis of the equatorial plane on the day of T9. Data collected during the red and blue segments of the spacecraft orbit (events 1 and 2) are the split events, the green line (marked "M") is the average magnetic field direction during the red portion of the orbit. The CAPS field of view (f.o.v.) during one actuator turn is shown in three inserts corresponding to 18:00 UT, and the time of the middle of the red and blue orbital segments (the arrow is the central line of the f.o.v., the triangles are the end-positions of the 8 elevation directions).

from this region, at about 5.4 R_T from the moon. During event-1 CAPS made five actuator turns, and along each turn it detected cold ions, in this 19 minutes long time interval the sc orientation changed by ~20°.

[6] The TOF spectra measured during "event-1" (not shown here) prove that the cold ions are composed mostly of particles in the 16–19 amu and 28–40 amu range, and the count rates indicate similar density for these two groups. Light ions are also present, but in a much less density. Magnetospheric electrons penetrate into this region as can be seen from Figure 2. Ion data collected in SINGLES mode during the actuator turn between 18:29:24–18.31:30 UT provides more information on these ions. The 1-d distribution functions (that is counts/energy^2 per bins) for the different elevations are shown in Figure 3. If a 18 amu particle hits the detector with the sc ram velocity, its energy would be ~3 eV, and the beam would have arrived in the 6th elevation channel (at elevation angle 143°), about 25° actuator angle; this direction is marked by the thick vertical line. From LP data we know that the sc potential at that time was about −2 V, this accelerated further the incoming beam. To facilitate the analysis of the data, we marked also the magnetic field direction (provided by the magnetometer team) by a thin line, this intersects the 5th elevation channel (at 115° elevation angle) about 15° actuator angle.

[7] It is clear from Figure 3 that the particles do not have a simple distribution. Ions, reaching the spacecraft from the direction parallel to the magnetic field, are the most energetic ones; they are more energetic than particles arriving from the nominal ram direction; and particles arriving near-perpendicular to the magnetic field, (~−60° actuator angle) are the least energetic. We proceed by analysing parts of the distribution.

[8] (1) In the near-perpendicular case (from −22° to −60° actuator range) the peak of the lower mass population is almost on top of the higher mass population (mass 28–40); and the peak energy is in the 7.2 eV bin. Transforming back this part of the distribution (for amu = 18) from the spacecraft frame of reference (SCFR) to the Titan frame of reference (TFR) after having subtracting the sc potential, we obtain ions having ~3–4 km/s velocity perpendicular to **B**, and a small speed parallel to **B**. Hence this part of the spectrum consists of particles rotating around **B**; the sense of the rotation is what we expect for positively charged ions. As the gyrofrequency is ~0.03 s^{-1}, their gyroradius is ~100–130 km. The 3–4 km/s speed, however, is much higher than the escape speed of the ions.

[9] (2) It is also evident that the population arriving dominantly along **B** (in SCFR) has a parallel velocity (in TFR) much higher than those described above, but they still keep a small perpendicular velocity (in TFR) since **B** is not parallel to the ram velocity. We interpret that the parallel-propagating population has undergone significant acceleration due to such type of wave-particle interaction where the wave energy flow was parallel to **B**. If we identify the highest peak with amu = 18, the parallel velocity of this part of the distribution in TFR is about 5–7 km/s.

[10] (3) From a detailed analysis it follows that in addition to the ram velocity and sc potential accelerations measured in SCRF, the whole ion population has an average bulk speed in TFR with a positive component >3.5 km/s along the magnetic field lines. Hence, the whole population is spiralling towards the spacecraft along the magnetic field lines.

[11] (4) The derived ion temperature of the different ion populations are of a few eV.

[12] After "event 1", as it can be seen in Figure 2, the spacecraft returned into the ambient plasma, and the flow direction got outside of our field of view. The plasma structure changed again between 19:06–19:30 UT, corresponding to 5–6.4 R_T in distance (event-2). The TOF analysis confirmed that these are mostly light, amu = 1 and 2 ions. These particles were heralded by the change of the magnetic field direction (c.f. C. Bertucci et al., unpublished manuscript, 2007), the magnetic field became highly inclined to the ecliptic plane, and the electron density increased to ~2/cc. In Figure 4 the contours of the 1-d distributions comprises "event 2" are shown as observed during consecutive actuator turns. These ions are rather "bunch of particles" than beams, and are quite scattered, we observed m = 1&2 ions in the 20–100 eV energy range arriving by and large from the −y direction of Figure 2, with large variation (~30 degrees) in arrival directions. The ion count rates were low, only about three times above

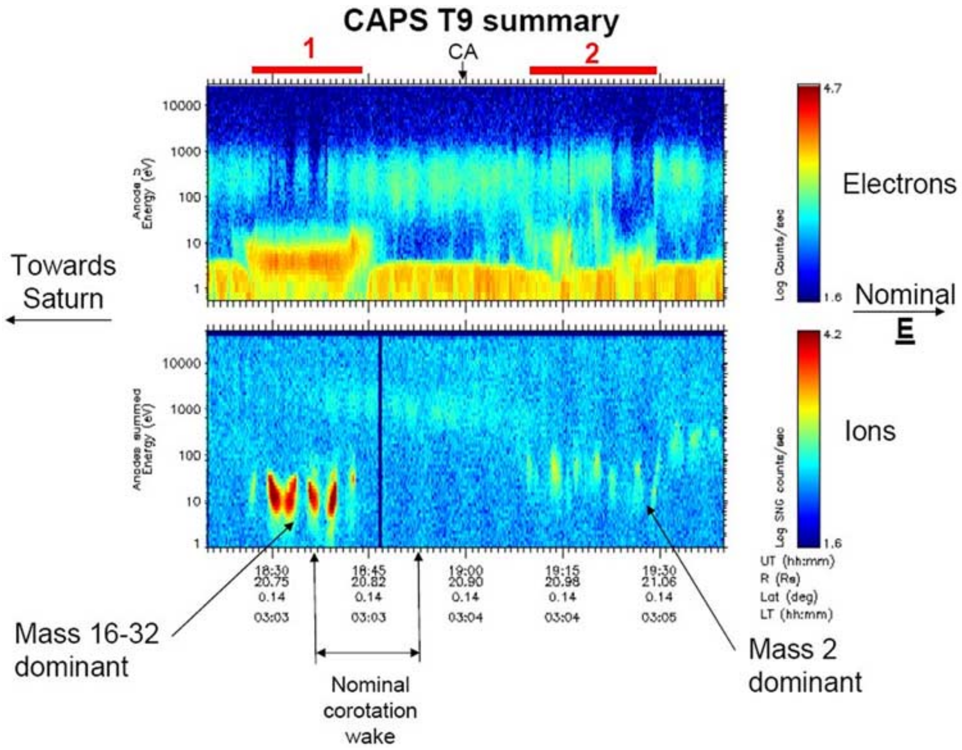

Figure 2. The ion and electron spectra are shown integrated over the elevation directions. The event-1 and event-2 intervals are marked in red at the top. The plot exhibits the position of the nominal corotation wake, that is the undistorted wake direction corresponding to the corotation flow direction.

background, and had a variable angular extent. Higher energy magnetospheric ions are mixed with colder ions, this can be seen from Figure 2. The colder ions must be of Titan origin.

3. Discussion

[13] As we have mentioned already, during all flybys CAPS observed cold, dense plasma layer above the ionosphere. For TA ions it was published by *Szego et al.* [2005] for T5 electrons it was described by K. Agren et al. (unpublished manuscript, 2007) as an "exoionosphere" based on Langmuir probe data. These cold ions are certainly of ionospheric origin including direct ion escape and neutral escape followed by subsequent ionisation. K. Agren et al. (unpublished manuscript, 2007) and *Modolo et al.* [2007] argued that the density of the cold layer is higher than that of we can expect from thermal ion escape from the ionosphere.

[14] During event-1 we observed the penetration of the magnetospheric electrons into the cold plasma region. This might indicate that the cold population cannot withhold the magnetospheric pressure, and there is a moderate pressure gradient. The penetration of magnetospheric electrons into the cold mantle was frequently observed by the Pioneer-Venus instruments around Venus; actually the observation of the penetrating electron population has lead to the name "mantle" by *Spenner et al.* [1980] for this adjacent layer above the ionosphere. We suggest to keep the word "mantle" as well for the cold plasma population seen above the ionosphere of Titan. To explore the similarities and differences between the mantle of Titan and Venus, a separate study is required. The mantle crossing, that is "event 1" is an expected event, though it occurred farther away from Titan than usual. We believe that this is due to the special magnetic field configuration; that is during "event 1" the ions and the spacecraft were magnetically connected.

[15] The scenarios how cold ions get energized depend on the characteristic time of the pickup process and the energisation process. At comets first a ring distribution is formed, and during the wave-particle interaction process the ring distribution undergoes a change, at the beginning – while keeping particle energy- particles scatter to a shell, then due to the energisation the shell gets further distorted. This picture does not fit well to our data, because in T9 the cold ion density is high relative to the possible external flow density. A different wave particle interaction mechanism that might operate in the mantle has been offered by *Dóbé et al.* [2007]. In the mantle waves are generated by the interaction of the magnetospheric plasma and the plasma of Titan origin. In this model the ions as they leave the ionosphere, due to the wave-particle interaction, are thermalised up to 10 eV, and they also acquire a few km/s bulk speed; the wave energy flux is parallel to **B**. The characteristic time scale of this thermalisation and acceleration is related to the growth rate of the excited waves, and in this case it is order of magnitude shorter than the local gyroperiod. After that the ions are picked up fully by the local magnetic field at their random thermal velocity. The model was verified with a hybrid code in which the physical quantities vary in 1-d. Due to the required grid resolution, higher dimension models are not yet available. Compared to current 3-d models that describe Titan's interaction with its plasma environment, this model is "local"; it models only

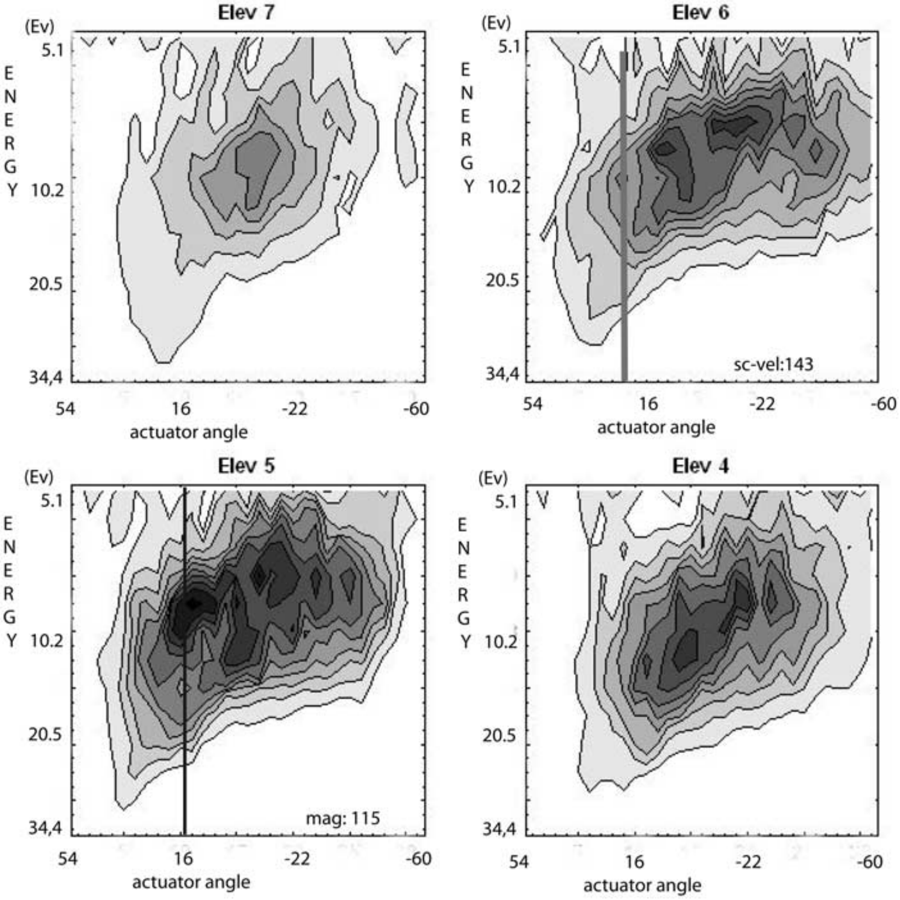

Figure 3. Contour plots of 1-d distribution functions of "event-1" in four elevation channels as a function of actuator angle and energy. The elevation channel number is shown at the top of each panel. The dark line in elevation 6 is the ram direction, the dark line in elevation 5 is the magnetic field direction. Each contour line increases by 10% of the maximal value.

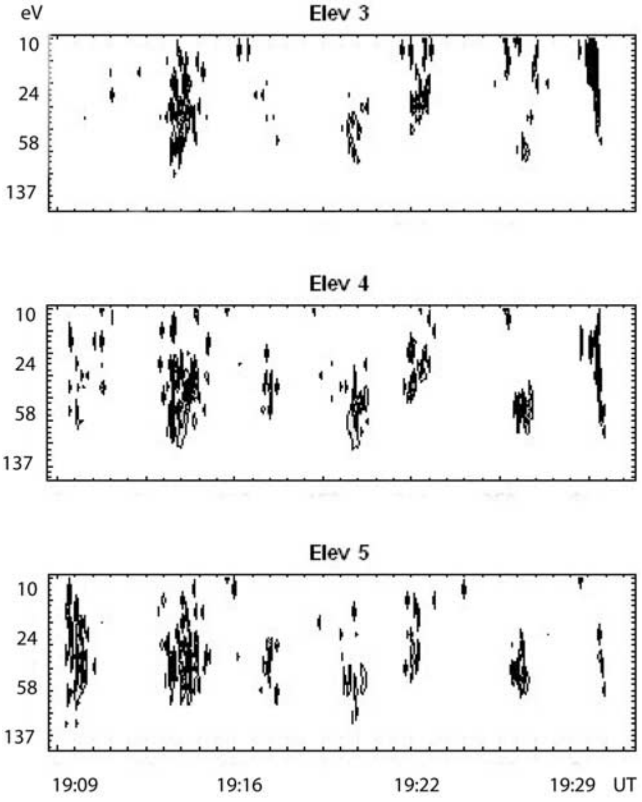

Figure 4. Outer contours of 1-d distribution functions of “event-2” in three elevation channels as a function of time and energy. The elevation channel number is shown at the top of each panel. A background at 8 counts level was subtracted.

the local wave-particle interaction, whereas the global models cannot resolve yet this type of wave excitation.

[16] Due to the mixed mass composition of the distribution functions seen during T9 in SCRF, we cannot conclude on the real 3-d shape of the distribution function in TRF. During other flybys Cassini made several measurements in the cold mantle at a broader altitude range above Titan, including near-exosphere altitudes; the full analysis of those data might allow to reason for the shape of the ion distribution functions in the mantle in a more conclusive manner.

[17] The magnetospheric plasma population was preserved later on between event-1 and 2 as can be seen in Figure 2. The plasma was slightly decelerating; we do not understand its cause.

[18] The real surprise of the flyby is that during the second crossing of cold plasma region we observed only light ions. Nobody expects that the Titan-ion dominated volume is convex, therefore a second crossing is certainly likely, but that the ion composition so widely differs from the other region is unexpected. The significant variation of the magnetic field direction during “event 2” makes it likely that this was the crossing of the distant tail, or at least the edge of the distant wake. However, we have not yet encountered other wake events where only light ions were present.

4. Conclusions

[19] The T9 flyby was really outstanding because neither the flow direction, nor the magnetic field configuration was even close to their average values. Two special regions were observed along the sc orbit where the ion energy was lower than the ambient magnetospheric flow, and the electron density was higher. We believe that the second region (event-2) belongs to the distant tail region of Titan, whereas “event-1” was the result of a specific magnetic field configuration that allowed ions to escape by spiralling along the magnetic field lines towards the spacecraft from the mantle of Titan.

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Z. Bebesi, G. Erdos, and K. Szego, Research Institute for Particle and Nuclear Physics, Central Research Institute for Physics, Hungarian Academy of Sciences, P.O. Box 49, H-1525 Budapest, Hungary. (szego@rmki.kfki.hu)

C. Bertucci, Space and Atmospheric Physics Group, Imperial College London, Exhibition Road, London SW7 2BZ, UK.

A. J. Coates, Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK.

F. Crary and D. T. Young, Southwest Research Institute, 6220 Culbra Road, P.O. Drawer 28510, San Antonio, TX 78228-0510, USA.

R. Hartle and E. C. Sittler Jr., NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.