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by N. J. T. Edberg et al.

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Extreme densities in Titan's ionosphere during the T85 magnetosheath encounter

N. J. T. Edberg,[1] D. J. Andrews,[1] O. Shebanits,[1] K. Ågren,[1] J.-E. Wahlund,[1]
H. J. Opgenoorth,[1] E. Roussos,[2] P. Garnier,[3,4] T. E. Cravens,[5] S. V. Badman,[6,7]
R. Modolo,[8] C. Bertucci,[9] and M. K. Dougherty[10]

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[1] We present Cassini Langmuir probe measurements of the highest electron number densities ever reported from the ionosphere of Titan. The measured density reached 4310 cm^{-3} during the T85 Titan flyby. This is at least 500 cm^{-3} higher than ever observed before and at least 50% above the average density for similar solar zenith angles. The peak of the ionospheric density is not reached on this flyby, making the maximum measured density a lower limit. During this flyby, we also report that an impacting coronal mass ejection (CME) leaves Titan in the magnetosheath of Saturn, where it is exposed to shocked solar wind plasma for at least 2 h 45 min. We suggest that the solar wind plasma in the magnetosheath during the CME conditions significantly modifies Titan's ionosphere by an addition of particle impact ionization by precipitating protons.

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1. Introduction

[2] The moon Titan orbits Saturn at a distance of around 20 Saturn radii (1 R_S = 60,268 km) with an orbital period of 16 days. The magnetopause of Saturn has an average standoff distance along the Sun-Saturn line of about 21 R_S [*Kanani et al.*, 2010], and therefore, Titan is normally orbiting within Saturn's magnetosphere. However, the moon can occasionally be situated in the magnetosheath of Saturn when the solar wind dynamic pressure is higher than normal, which has only been observed unambiguously and studied during the T32 flyby [*Bertucci et al.*, 2008; *Garnier et al.*, 2009].

[3] Titan has a nitrogen-rich atmosphere, which is primarily ionized by the solar EUV flux, but energetic particle impacts from Saturn's corotating plasma also add to the total ionization rate [*Cravens et al.*, 2005; *Ågren et al.*, 2007, 2009]. The ionospheric electron density peaks at an average altitude of 1100 km but this altitude increases with solar zenith angle (SZA). The dayside ionospheric peak electron density is around 3000 cm^{-3} but decreases with increasing SZA [*Ågren et al.*, 2009]. The ionospheric structure is variable and radio occultation measurements of Titan's ionosphere revealed during a few occasions extreme peak electron densities of up to 3000 cm^{-3} near the terminator plane [*Kliore et al.*, 2011]. These observations suggested that additional ionization by particle precipitation was involved.

[4] The Langmuir probe (LP) [*Wahlund et al.*, 2005] on Cassini is capable of measuring bulk plasma parameters, including density, which we use in this paper. We also examine data from the Radio and Plasma Wave Science (RPWS) antennas, which are able to track the emission of Saturn Kilometric Radiation (SKR), and 1 s averaged magnetic field measurements from the magnetometer (MAG) [*Dougherty et al.*, 2004]. We also use solar wind velocity and pressure data from the In-situ Measurements of Particles and CME Transients/Plasma and Suprathermal Ion Composition (IMPACT/PLASTIC) instruments on the Stereo-B spacecraft [*Luhmann et al.*, 2008; *Galvin et al.*, 2008].

[5] In this paper, we use measurements from those instruments to report that during the T85 Cassini flyby of Titan, the moon was observed in the magnetosheath of Saturn, close to the bow shock, while the highest ever electron densities were measured in the deep ionosphere of Titan.

2. Observations

2.1. Titan in the Magnetosheath

[6] The T85 flyby occurred on 24 July 2012 with a closest approach (C/A) of 1012 km at 20:03 UT at a SZA of 56° and at 13 h Saturn local time. Figure 1 shows the flyby geometry in Kronocentric Solar Magnetospheric (KSM) coordinates (x axis from Saturn toward the Sun, y axis perpendicular to the rotation axis toward dusk, and the planet's spin axis in the $X-Z$ plane) together with the measurements from MAG in the Saturn centered KRTP system (R directed radially away from Saturn, θ in the meridional direction, and ϕ in the azimuthal direction). Figure 1a shows the trajectory of Cassini at Titan together with the locations of Saturn's bow shock and magnetopause. When the upstream solar wind dynamic pressure is between 0.01 and 0.1 nPa, Titan's orbit is well within the magnetosheath of Saturn on the

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[1] Swedish Institute of Space Physics, Uppsala, Sweden.
[2] Max Planck Institute for Solar System Research, Katlenburg-Lindau, Germany.
[3] University of Toulouse, UPS-OMP, IRAP, Toulouse, France.
[4] CNRS, IRAP, Toulouse, France.
[5] Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas, USA.
[6] JAXA Institute of Space and Astronautical Science, Sagamihara Kanagawa, Japan.
[7] Now at Department of Physics and Astronomy, University of Leicester, Leicester, UK.
[8] UVSQ/LATMOS-IPSL/CNRS-INSU, Guyancourt, France.
[9] Institute for Astronomy and Space Physics, Ciudad Universitaria, Buenos Aires, Argentina.
[10] The Blackett Laboratory - Imperial College London, London, UK.

Corresponding author: N. J. T. Edberg, Swedish Institute of Space Physics, Box 537, Uppsala, SE-75121, Sweden. (ne@irfu.se)

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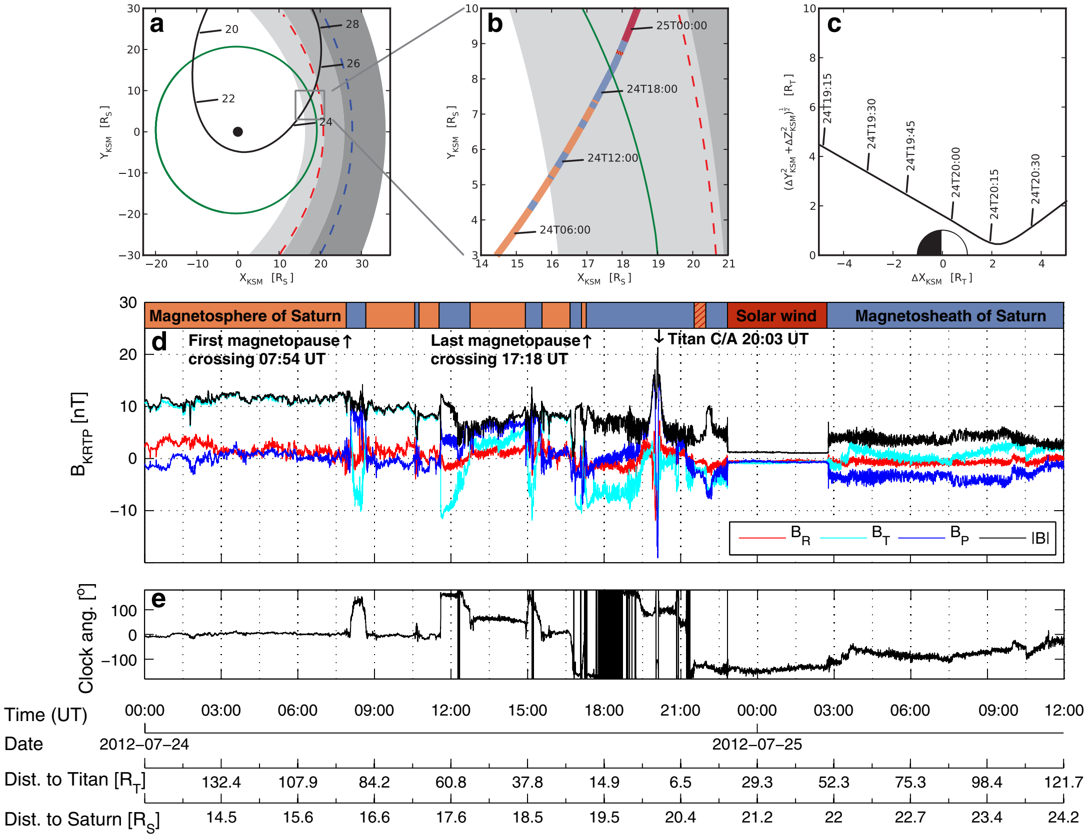

Figure 1. (a) The Cassini trajectory (black), the orbit of Titan (green), the average positions of the magnetopause (red dashed) and bow shock (blue dashed). The light gray (dark gray) shaded area show the magnetopause (bow shock) locations for an upstream dynamic pressure range of 0.1–0.01 nPa according to *Masters et al.* [2008] and *Kanani et al.* [2010]. The overlapping area is shown in medium gray. (b) A zoomed in portion of Figure 1a. The orange, blue, and red colors along the track indicate when Cassini is in the magnetosphere, the magnetosheath, or the solar wind, respectively, and are matched by the color of the bars in Figure 1d. (c) The flyby geometry shown in Titan-centered cylindrical KSM coordinates. The Sun is to the right. (d) The magnetic field data in the KRTP coordinate system and (e) the clock angle of the magnetic field as a function of time, distance to Titan, and distance to Saturn.

dayside, as indicated by the light gray shaded region taken from the model by *Kanani et al.* [2010]. Figure 1b shows a zoomed portion of Figure 1a around the C/A of the T85 flyby. The orange and blue colors along the trajectory of Cassini illustrate when MAG data indicate that Cassini is in the magnetosphere, magnetosheath, or in the solar wind, as discussed below. Figure 1c shows the flyby geometry in cylindrical KSM coordinates centered on Titan.

[7] The magnetic field measurements from the MAG instrument are shown in Figures 1d and 1e over 1.5 days around the time of the T85 flyby. As seen in Figure 1d, Cassini first measures primarily Kronian field, from before 00:00 until 07:54 UT, characterized by steady field components of a few nT and low fluctuations, and primarily a north-south orientation (clock angles near 0°). This tells us that Cassini is located well within the magnetosphere of Saturn. At 07:54 UT on 24 July Cassini crosses the magnetopause, as seen by a sudden change in the magnetic field direction together with an increase in field fluctuations, and finds itself in the magnetosheath of Saturn. This first magnetosheath encounter only lasts about 1 h. The magnetopause is crossed several times after that due to an expanding/contracting motion of the magnetopause boundary. The final crossing into the magnetosheath before the T85 flyby occurs at 17:18 UT on 24 July. This is 2 h 45 min before the C/A to Titan. Hence, both Cassini and Titan are located within the magnetosheath during the entire T85 flyby. During the flyby, the enhanced draped magnetic fields, up to 20 nT compared to 5 nT in the surrounding sheath, are clearly visible in the MAG time series. Twenty nanoteslas is higher than usual for the draped field of Titan [e.g., *Bertucci et al.*, 2008; *Edberg et al.*, 2011]. After C/A, Cassini exits the induced magnetosphere of Titan and continues to measure magnetosheath magnetic fields for about 1 h. During a short period of time (≈ 20 min, from 21:32 to 21:50 UT on 24 July), Cassini once again appears to enter the magnetosphere as the magnetopause boundary moves outward and then rapidly inward again. This short interval is somewhat harder to classify and could instead represent a brief excursion by Cassini through the bow shock and into the solar wind. From 22:50 on 24 July until 02:44 on 25 July, Cassini is, however, clearly in the solar wind, which can be seen by the weak and steady magnetic field components. The three regions that Cassini encounters (Saturn's magnetosphere, Saturn's magnetosheath, and the solar wind) during this 1.5 day interval are indicated at the top of the figure.

[8] The clock angle of the magnetic field aid in interpreting in which region Cassini is located in. While the cone

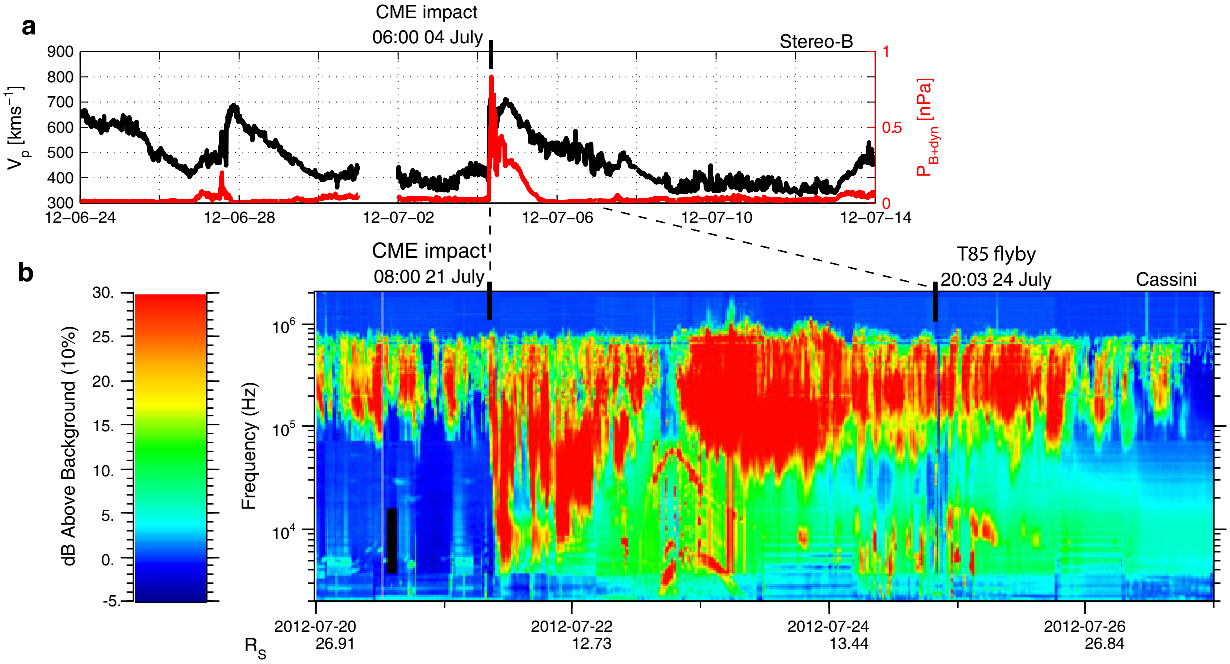

Figure 2. (a) Time series of solar wind velocity and pressure, as measured by Stereo-B, centered around the CME on 4 July. (b) Electric field emissions measured by Cassini around the time of the T85 Titan flyby, showing the periodic SKR. The impact of the CME, arriving at Saturn on 21 July, is identified by the intensification of the SKR emissions and broadening to lower frequencies.

angle (not shown) is relatively constant, the rotations of the clock angle reveal rather clearly when a new plasma region is entered. There is also a long-term trend in how the clock angle of the solar wind magnetic field changes. During the first magnetosheath encounter, after 07:54 UT, the clock angle is about 120°, while during the last interval in magnetosheath plasma, directly after the Titan encounter, the clock angle is about –120°. When continuing out into the solar wind and back into the magnetosheath again, after 03:00 UT on 25 July, the clock angle changes to negative values around –60°. A rotation of the field (predominantly in azimuthal component) is commonly seen at heliospheric current sheet crossings embedded in corotating interaction regions as well as coronal mass ejections (CME) [*Badman et al.*, 2008]. In section 2.2, we show that a CME is the major reason for why the magnetopause and bow shock are pushed in toward Saturn in the first place.

[9] The above described measurements show that Cassini and Titan are located in the magnetosheath for 2 h 45 min before Cassini passes by Titan. Titan is also very close to being located in the solar wind during the flyby since the bow shock is observed to be as close as 0.7 R_S (42000 km) from Titan in the upstream direction. Since the magnetopause was located at a stand-off distance of only 16 R_S from Saturn at 07:54 UT, it is likely that the bow shock would have been closer than normal to Saturn. It may even have passed the orbit of Titan, especially when Titan was closer to the subsolar point of Saturn, and left Titan in the unshocked solar wind.

2.2. Impact of a Coronal Mass Ejection

[10] The presence of Titan in the magnetosheath during the T85 flyby was likely caused by a coronal mass ejection (CME). Solar wind data from the Stereo-B spacecraft at 1 AU are shown in Figure 2a. On 4 July 2012, Stereo-B measured the passing of an extreme pressure pulse with velocities reaching 700 km s^{-1}, densities reaching up to 100 cm^{-3}, magnetic fields reaching 40 nT, and a pressure reaching ~1 nPa. Stereo-B was at this time about 45° ahead of Saturn in heliospheric longitude. If this high pressure pulse, a CME, would have traveled radially outward toward Saturn at a speed of 700 ± 100 km s^{-1}, it would have taken about 21 ± 3 days to reach Saturn, thus arriving sometime in the interval 22-28 July 2012. At Saturn, Cassini measurements of the SKR provide strong evidence of that having occurred. The SKR is generated through the cyclotron-maser instability driven by upward-directed field-aligned currents at auroral latitudes on Saturn. While fundamentally a periodic phenomena, the intensity of the SKR has also been shown to be strongly influenced by the upstream conditions in the solar wind, in particular the dynamic pressure, see e.g., *Badman et al.* [2008]. Figure 2b shows measurements of the SKR emission during one week around the T85 flyby. On the 21 July 2012, a significant broadening of the SKR emissions to lower frequencies occurs. This is a typical signature of a compression or relaxation of the Saturn magnetosphere [*Clarke et al.*, 2009], which is something that would have happened during a CME impact. The impact time is earlier than what is expected from the simple arrival time calculation above. However, the Stereo-B spacecraft may only have caught the limb of the CME such that it could actually have had a higher velocity at the center and therefore reach Saturn earlier.

2.3. Extreme Ionospheric Densities

[11] The magnetosheath encounter of Titan becomes further interesting since during the T85 flyby, we see the highest ionospheric electron density ever recorded at Titan.

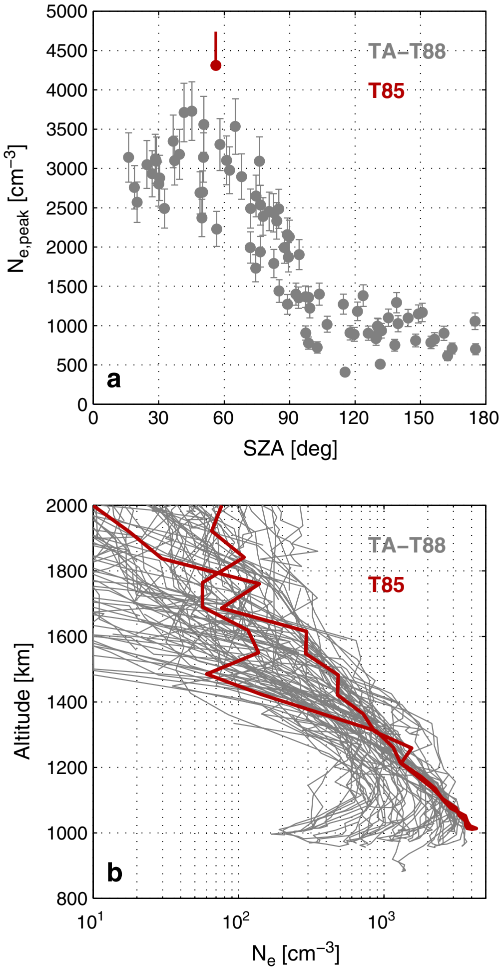

Figure 3. (a) The ionospheric peak density plotted versus SZA for all deep Titan flybys. The maximum density from T85 is highlighted in red. The error bars show the ±10 % LP measurement error [*Wahlund et al.*, 2005] and the red bar (arbitrarily chosen to be 10 %) indicate that the T85 value is only a lower limit to the unknown maximum. (b) The corresponding electron density altitude profiles.

Figure 3a shows the peak ionospheric densities from all the deep Titan flybys with the T85 value highlighted in red. Since not all of the flybys cross the peak, there are in total only 84 peak values (inbound and outbound). Figure 3b shows the corresponding altitude profiles along the Cassini trajectory. During T85, the electron density measured by the LP reaches a maximum value of 4310 cm^{-3} at an altitude of 1012 km. What makes this high value even more remarkable is that it is not the peak value of the ionosphere. The spacecraft had its C/A above the ionospheric peak, so the maximum ionospheric density must be higher than 4310 cm^{-3}. A peak altitude below 1012 km is unusually low and therefore interesting. Also, the ionospheric density has been clearly shown to increase with decreasing SZA [*Ågren et al.*, 2009]; and during T85, the ionospheric peak is sampled at a SZA of 55°. Several previous flybys have sampled the ionospheric peak at lower SZA, but none of these reach the high density values reported here during the magnetosheath encounter.

3. Discussion

[12] All of the peak ionospheric densities measured during the recent T83–T88 are higher than previous average due to the rise toward a new solar maximum, but the peak density during T85 was at least 500 cm^{-3} higher than that during any other flyby. The fact that Titan had been exposed to magnetosheath/solar wind plasma for at least 2 h 45 min prior to the flyby is one possible reason for this. Unusually high particle fluxes during a CME impact could have caused additional ionization. The Cassini Plasma Spectrometer (CAPS) instrument, which would have provided information on the particle fluxes in the relevant energy range (1–3 keV), was unfortunately not operating at this time. The Magnetosphere Imaging Instrument/Low Energy Magnetospheric Measurements System (MIMI/LEMMS) instrument, which only measures the particles with energies above 18 keV, does not reveal any significantly higher than normal fluxes during the T85 flyby (not shown).

[13] It is only in the deep ionosphere, below ~1100 km, that we see higher than normal densities, which leads us to conclude that particle precipitation is the cause of the extreme densities. Increased EUV flux should increase the density at all altitudes down to the peak. The EUV flux (lasp.colorado.edu/lisird) or the soft X-ray flux (www.swpc.noaa.gov) were not significantly enhanced at the day of the T85 flyby.

[14] We can estimate the proton fluxes required to produce the high ionospheric electron density. Using an effective dissociative recombination rate coefficient of $\alpha = 7 \cdot 10^{-7}$ $cm^3 s^{-1}$, with the LP measured electron temperature of 500 K, [*Vigren et al.*, 2013] (and assuming that we are in a photochemical regime) the peak electron density of 4310 cm^{-3} implies an ionization rate of $P \approx \alpha N_e^2 = 13$ cm^{-3} s^{-1}. The excess production rate at 1000 km required to enhance the electron density by 500 cm^{-3} above other values around solar maximum is then 3 cm^{-3} s^{-1}. Assuming typical solar wind proton energies of about 1–3 keV, they should penetrate down to 900–1000 km [*Cravens et al.*, 2008; *Luna et al.*, 2003]. The total column ion production rate needed is the scale height (about 50 km) times the excess production rate of 3 cm^{-3} s^{-1}, or $1.5 \cdot 10^7$ cm^{-2} s^{-1}. A 2 keV proton generates about 10–50 N_2^+ ions, so a proton flux of about $1 \cdot 10^6$ cm^{-2} s^{-1} is needed.

[15] A likely solar wind proton flux near Saturn is about 10^6 cm^{-2} s^{-1} (300 km s^{-1} · 0.03 cm^{-3}). It is not unreasonable to assume that the bow shock of Saturn will allow another factor of four flux enhancement, according to the Rankine-Hugoniot relations, and for CME conditions, there could be another factor of about 10, so sufficient protons should be available to produce the excess ionization rate in Titan's atmosphere. Currents could also have been set up at the magnetopause boundary, which would further increase the particle precipitation. We therefore likely have a situation where the deep ionosphere of Titan is significantly ionized by the impact of solar wind particles. However, the draped magnetic field could act to shield parts of Titan from this proton flux [*Ledvina et al.*, 2012]. The gyro radius of a 2 keV proton in a 20 nT field is 0.1 R_T. Magnetosheath electrons typically have energies of about 100 eV, which, combined with magnetic field draping, limits their contribution to ionospheric production to higher altitudes. The more energetic magnetospheric electrons should be more effective at atmo-

spheric ionization [*Ågren et al.*, 2007; *Cravens et al.*, 2008]. However, in the absence of CAPS particle data and specific model studies, electron precipitation contributions to the extra ionization cannot be excluded.

[16] The ionospheric response time to a sudden change in the ionization rate is the recombination time scale $1/\alpha N_e$ $\sim$5 min near the peak. During the T32 magnetosheath encounter, the ionospheric densities were not enhanced above normal EUV levels, perhaps due to the short period it was in the magnetosheath prior to the Cassini flyby, $\sim$10 min compared to 2 h 45 min during T85, or due to shielding from a different magnetic field topology.

4. Conclusions

[17] The maximum electron density during the T85 flyby is the highest ever recorded on Titan and reaches 4310 cm^{-3}, which is 500 cm^{-3} higher than during any other flyby. We also report that during T85, Titan is located in the magnetosheath of Saturn, following an impact of a CME on the magnetosphere of Saturn. Titan is located in the magnetosheath for at least 2 h 45 min before the actual Cassini flyby and this exposure to magnetosheath plasma, and possibly even unshocked solar wind plasma, during CME conditions likely causes the extra ionization through shocked solar wind proton precipitation.

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References

Ågren, K., et al. (2007), On magnetospheric electron impact ionisation and dynamics in Titan's ram-side and polar ionosphere - A Cassini case study, *Ann. Geophys.*, *25*, 2359–2369.

Ågren, K., J.-E. Wahlund, P. Garnier, R. Modolo, J. Cui, M. Galand, and I. Müller-Wodarg (2009), On the ionospheric structure of Titan, *Planet. Space Sci.*, *57*, 1821–1827, doi:10.1016/j.pss.2009.04.012.

Badman, S. V., S. W. H. Cowley, L. Lamy, B. Cecconi, and P. Zarka (2008), Relationship between solar wind corotating interaction regions and the phasing and intensity of Saturn kilometric radiation bursts, *Ann. Geophys.*, *26*, 3641–3651, doi:10.5194/angeo-26-3641-2008.

Bertucci, C., et al. (2008), The magnetic memory of Titan's ionized atmosphere, *Science*, *321*, 1475–1478, doi:10.1126/science.1.159780.

Clarke, J. T., et al. (2009), Response of Jupiter's and Saturn's auroral activity to the solar wind, *J. Geophys. Res.*, *114*, A05210, doi:10.1029/2008JA013694.

Cravens, T. E., et al. (2005), Titan's ionosphere: Model comparisons with Cassini Ta data, *Geophys. Res. Lett.*, *32*, L12108, doi:10.1029/2005GL023249.

Cravens, T. E., I. P. Robertson, S. A. Ledvina, D. Mitchell, S. M. Krimigis, and J. H. Waite (2008), Energetic ion precipitation at Titan, *Geophys. Res. Lett.*, *35*, L03103, doi:10.1029/2007GL032451.

Dougherty, M. K., et al. (2004), The Cassini magnetic field investigation, *Space Sci. Rev.*, *114*, 331–383, doi:10.1007/s11214-004-1432-2.

Edberg, N. J. T., K. Ågren, J.-E. Wahlund, M. W. Morooka, D. J. Andrews, S. W. H. Cowley, A. Wellbrock, A. J. Coates, C. Bertucci, and M. K. Dougherty (2011), Structured ionospheric outflow during the Cassini T55-T59 Titan flybys, *Planet. Space Sci.*, *59*, 788–797, doi:10.1016/j.pss.2011.03.007.

Galvin, A. B., et al. (2008), The Plasma and Suprathermal Ion Composition (PLASTIC) investigation on the STEREO observatories, *Space Sci. Rev.*, *136*, 437–486, doi:10.1007/s11214-007-9296-x.

Garnier, P., et al. (2009), Titan's ionosphere in the magnetosheath: Cassini RPWS results during the T32 flyby, *Ann. Geophys.*, *27*, 4257–4272.

Kanani, S. J., et al. (2010), A new form of Saturn's magnetopause using a dynamic pressure balance model, based on in situ, multi-instrument Cassini measurements, *J. Geophys. Res.*, *115*, A06207, doi:10.1029/2009JA014262.

Kliore, A. J., A. F. Nagy, T. E. Cravens, M. S. Richard, and A. M. Rymer (2011), Unusual electron density profiles observed by Cassini radio occultations in Titan's ionosphere: Effects of enhanced magnetospheric electron precipitation? *J. Geophys. Res.*, *116*, A11318, doi:10.1029/2011JA016694.

Ledvina, S. A., S. H. Brecht, and T. E. Cravens (2012), The orientation of Titan's dayside ionosphere and its effects on Titan's plasma interaction, *Earth Planets Space*, *64*, 207–230, doi:10.5047/eps.2011.08.009.

Luhmann, J. G., et al. (2008), STEREO IMPACT investigation goals, measurements, and data products overview, *Space. Sci. Rev.*, *136*, 117–184, doi:10.1007/s11214-007-9170-x.

Luna, H., M. Michael, M. B. Shah, R. E. Johnson, C. J. Latimer, and J. W. McConkey (2003), Dissociation of N_2 in capture and ionization collisions with fast H^+ and N^+ ions and modeling of positive ion formation in the Titan atmosphere, *J. Geophys. Res.*, *108*(E4), 5033, doi:10.1029/2002JE001950.

Masters, A., N. Achilleos, M. K. Dougherty, J. A. Slavin, G. B. Hospodarsky, C. S. Arridge, and A. J. Coates (2008), An empirical model of Saturn's bow shock: Cassini observations of shock location and shape, *J. Geophys. Res.*, *113*, A10210, doi:10.1029/2008JA013276.

Vigren, E., et al. (2013), On the thermal electron balance in Titan's sunlit upper atmosphere, *Icarus*, *223*, 234–251, doi:10.1016/j.icarus.2012.12.010.

Wahlund, J.-E., et al. (2005), Cassini measurements of cold plasma in the ionosphere of Titan, *Science*, *308*, 986–989, doi:10.1126/science.1109807.