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Unusual electron density profiles observed by Cassini radio occultations in Titan's ionosphere: Effects of enhanced magnetospheric electron precipitation?

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[1] The Cassini radio science facility provided 13 occultation electron density profiles of Titan during the period of 2006 and 2009. This paper presents the results of all of these occultation observations. It shows that ten of the observed electron density profiles are similar, but three are significantly different. The number of observations is relatively small for meaningful statistical conclusions, but it is shown, using the corresponding measured electron spectra, that the three anomalous profiles in the ionospheric peak regions are likely to be the result of unusually intense electron precipitation events.

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1. Introduction

[2] The ionosphere of Titan has been a topic of interest, especially since the first radio occultation measurements presented by *Bird et al.* [1997]. Numerous one-dimensional and multidimensional studies [cf. *Cravens et al.*, 2009] have been published, mostly spurred by the more recent Cassini in situ [e.g., *Wahlund et al.*, 2005; *Ågren et al.*, 2009] and remote occultation observations [*Kliore et al.*, 2008]. The Cassini Radio Science investigation (RSS) [*Kliore et al.*, 2004] has so far collected 13 individual profiles of electron density in the ionosphere of Titan from seven radio occultations from 2006 to 2009 (see Table 1). The results from the first four occultations, T12 and T14 in 2006, and T27 and T31 in 2007, have been discussed by *Kliore et al.* [2008], where T31 was first identified as being different from the other observations. In this paper, we also present the results from three additional occultations, T46 in 2008, and T52 and T57 in 2009. The electron density profiles derived from all Titan occultations are plotted in Figure 1.

[3] In Figure 1, the "normal" profiles are plotted in green, and the unusual "disturbed" profiles from T31 and T57 are plotted in red. The rest of the paper will look at and discuss the possible mechanism(s) that may cause the anomalous profiles.

2. Description of the Unusual Observations

[4] In Figure 1, the profiles from the normal observations are more or less similar in appearance, with the main electron density peak occurring near 1200 km, and peak densities of about 1×10^3 to 2×10^3 cm^{-3}. They also do not exhibit prominent secondary peaks above or below the main peak, and their baseline fluctuation noise is moderate (see Table 1). In Table 1, the baseline fluctuation is the standard deviation of a straight-line fit to the to the free space baseline of the electron density profile that is used to remove a bias and rate term from the inverted data, LST is the Local Solar Time at the longitude of the measurement, and the ram angle is the angle between the vector from the center of Titan to the tangency point of the radio line of sight and the direction of the magnetospheric ram.

[5] In contrast, the unusual profiles have a nonuniform appearance, having main peak densities varying from about 2.3×10^3 to 3.4×10^3 cm^{-3}. In addition, the baseline fluctuations are higher (see Table 1).

[6] These differences between the normal and unusual observations can be seen better in Figure 2, which shows the averaged normal observations (green), as well as the averaged unusual ones (red); the difference between the two averages is shown in blue.

[7] In Figure 3, all of the RSS observations of peak electron density are compared with results from the Cassini Radio and Plasma Wave Science (RPWS) Langmuir probe results [*Ågren et al.*, 2009]. It is obvious that the normal RSS observations, which are clustered around the terminator, agree very well with the RPWS near-terminator measurements. In contrast, the peak densities from the disturbed measurements, which also have

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Table 1. Cassini Titan Ionosphere Radio Occultations

Observation	Date	Latitude[a] (deg)	Solar Zenith Angle[a] (deg)	Ram Angle (deg)	Local Solar Time (h)	Dawn/Dusk	Peak Altitude (km)	Peak Electron Density (cm^{-3})	Sun-Earth-Probe Angle (deg)	Baseline Sigma (cm^{-3})	Peak Density Sigma (cm^{-3})
T12N	20 Mar 2006	−14.3	95.0	74	5.1	Dawn	1216	1011[b]	132	174	172
T12X		−36.3	87.5	87	18.2	Dusk	1176	2052		205	209
T14N	20 May 2006	−19.8	95.8	100	5.0	Dawn	1186	1483	73	173	144
T14X		−21.3	85.7	66	18.2	Dusk	1279	1856		157	117
T27N	26 Mar 2007	−74.6	92.2	94	2	Polar	1260	1365	138	90	103
T27X		60.6	90.0	61	7.3	Polar	1236	1416		109	91
T31N	28 May 2007	−75.4	92.3	98	23.6	Polar	1239	2485	78	553	378
T31X		74	88.2	78	9.7	Polar	1220	2917		289	277
T46N	3 Nov 2008	−33.3	92.3	137	18.4	Dusk	1161	1178	58	81	103
T46X		33.4	87.7	43	6.4	Dawn	1140	1926		153	131
T52N	4 Apr 2009	80.1	88.1	80	17.3	Polar	1178	1896	155	45	75
T52X		−25.5	88.4	37	17.9	Dusk	1181	1924		49	37
T57N	22 Jun 2009	76.3	88.6	100.2	6.8	Polar	1099	3055	81	862	651

[a]At the main peak altitude.
[b]Because of insufficient free space baseline, the peak electron density for T12N is likely to have been underestimated. For this reason it is not used in Figures 1, 4a, 4b, and 4d.

been made near the terminator, are significantly higher, similar to the RPWS measurements taken on the dayside.

3. Possible Geometrical Explanations

[8] In order to find a plausible explanation for the obvious differences between the normal and unusual occultations, we have made plots showing possible effects of latitude, magnetospheric ram angle, and the Sun-Earth-Probe (SEP) angle on the peak electron density for each observation. These are shown in Figures 4a, 4b, and 4c.

[9] In Figure 4a, no relationship is found between the magnitude of the main electron density peak and latitude. Although the T31 and T57 unusual observations occur at high latitudes, other ("normal") high-latitude observations (e.g., T27) do not show any peak density enhancement.

[10] In Figure 4b, the possible dependence of the peak electron density on the magnetospheric ram angle is investi-

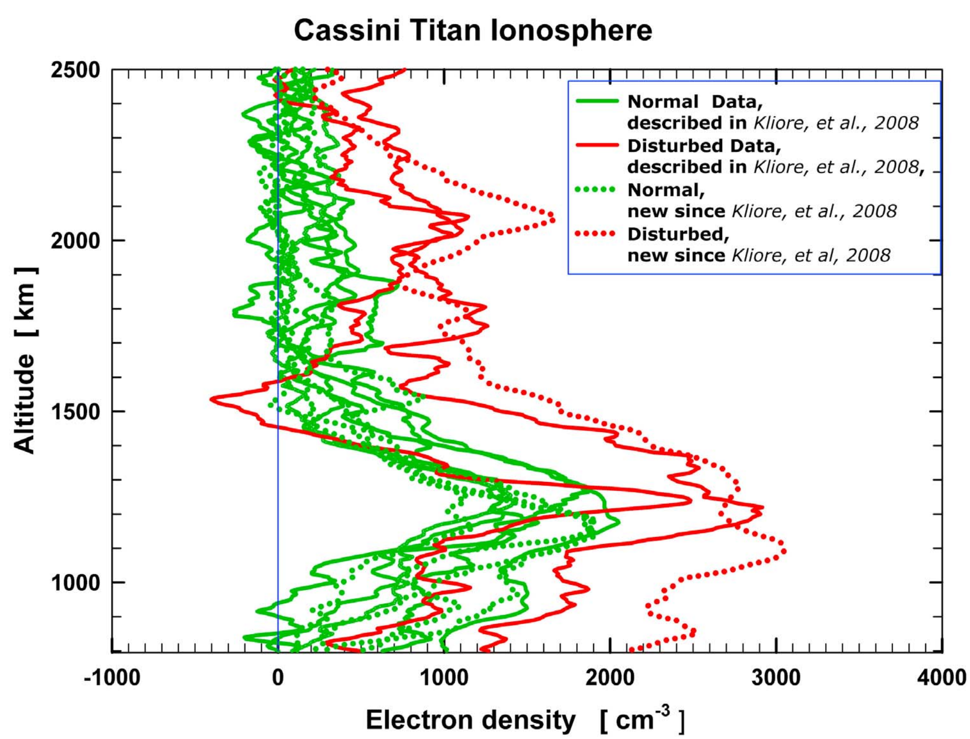

Figure 1. All electron density profiles from Cassini radio occultations. The green curves represent the normal and the red ones the disturbed observations. The data reported by *Kliore et al.* [2008] are shown as solid curves, and the new data acquired since then are dotted.

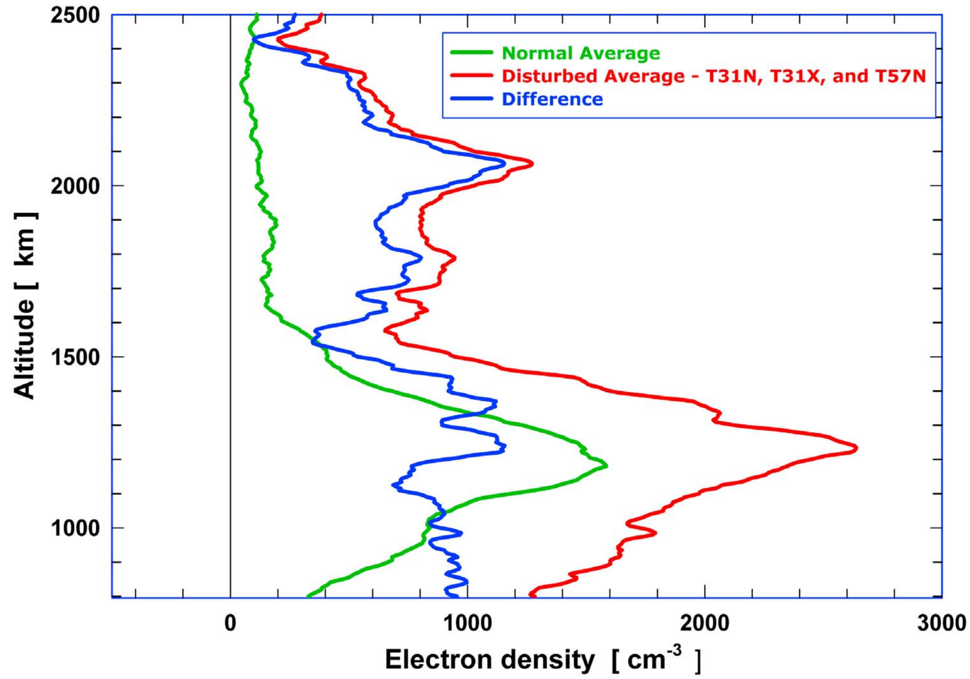

Figure 2. Averaged normal (green) and disturbed (red) observations, along with the difference between them (blue).

gated. Ram angle is defined here as the angle of the observation with respect to the nominal magnetospheric flow direction. One might expect that the effect of magnetospheric electron ionization would depend on the ram angle, but no such effect is seen in the normal observations, and the unusual observations occur at ram angles close to 90 degrees (i.e., flanks).

[11] Another property that distinguishes the unusual observations from the normal ones is the baseline fluctuation noise. This is ordinarily produced by solar plasma effects when the radio line of sight passes close to the Sun, which occurs at low SEP angles, typically below 30 deg. None of the observations, including the unusual ones, occurred at low SEP angles, and so the significant increase in the baseline fluctuation noise in the case of the unusual observations seen in Figure 4c cannot be attributed to low SEP angle.

[12] Finally, in Figure 4d we attempted to compare the magnitude of the main peak electron density with some measure of the magnetospheric energetic electron flux. Here we used Cassini Low Energy Magnetospheric Measurement System (LEMMS) data kindly supplied by D. G. Mitchell (private communication, 2010) to obtain very rough estimates of the electron flux for each of our observations. The resulting plot in Figure 4d is not intended to prove a dependence of peak electron density on electron impact ionization, but it does show a positive correlation, and it was the impetus for the work described below.

4. Possible Effects of Unusual Magnetospheric Electron Flux

[13] The presence of an intermittent low-altitude peak, near 500–600 km, was discussed in our earlier paper [*Kliore et al.*, 2008]. *Cravens et al.* [2008] found that ion precipitation is a good potential explanation for these densities. There have also been suggestions that meteoric ablation can cause such low-altitude ionization [*Molina-Cuberos et al.*, 2001]. In this paper we limit our discussions to the enhanced ionization in the main ionospheric region, between about 900 and 1400 km.

[14] There have been numerous suggestions in the past that magnetospheric electron precipitation can make a contribution to the dayside ionosphere of Titan in the region around the ionospheric peak. However, it was believed that ionization by precipitating electrons is in general relatively small compared to solar photoionization on the dayside [*Cravens et al.*, 2008; *Ågren et al.*, 2009]. In a recent paper *Rymer et al.* [2009] showed, using data from the CAPS Electron Spectrometer (ELS) [*Young et al.*, 2004] and the MIMI LEMMS instruments [*Krimigis et al.*, 2004], that the electron fluxes observed in the environment of Titan are highly variable. The time of the T31 and T57 observations corresponds to the occasions when the CAPS and MIMI electron flux measurements indicated the presence of relatively high intensity electron flux with a bimodal energy spectrum. Other measurements, when Titan was in Saturn's magnetosphere, referred to as "lobe spectra," indicated significantly lower fluxes [*Rymer et al.*, 2009], as did the bimodal spectra observed during orbits such as T46 and T47. This may be just sheer coincidence and not statistically significant, but it is interesting to note.

[15] Here we take the measured electron fluxes corresponding to T31 and T57 (as well as the lobe flux corresponding to T8 as a representative "lobe" spectrum) and calculate the corresponding electron production rates. The detailed spectrum for T31 is shown by *Rymer et al.* [2009], so we only show the measured spectra corresponding to

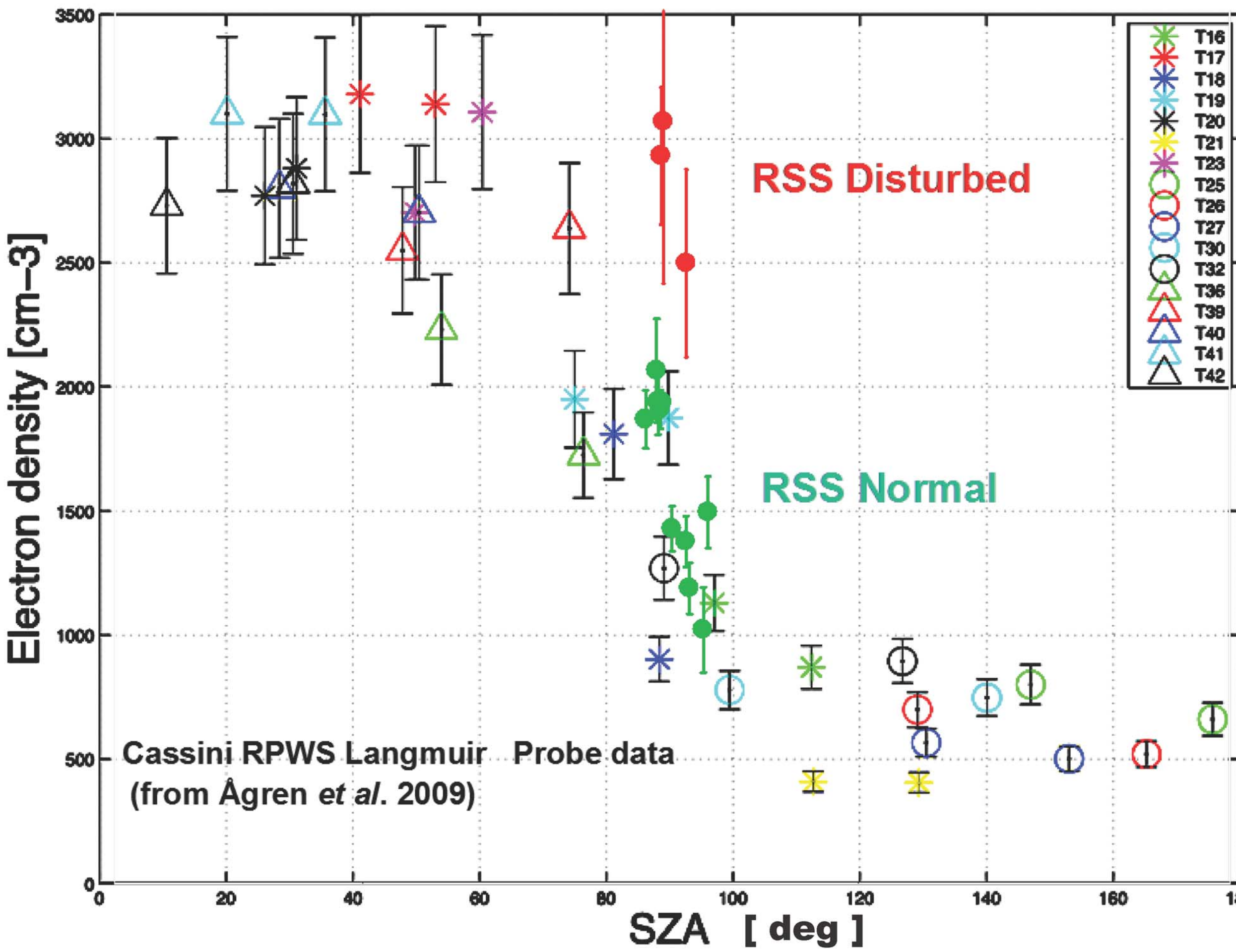

Figure 3. Peak densities from the Cassini Radio Science investigation (RSS) compared to those obtained by the Cassini Radio and Plasma Wave Science (RPWS) Langmuir probe taken at a wide range of solar zenith angles (reproduced from *Ågren et al.* [2009]), showing that the RSS peak densities from the disturbed measurements are significantly higher than the RPWS measurements near the terminator, while the normal ones are in good agreement.

T57 and T8 in Figures 5a and 5b, respectively. The CAPS-ELS measures electrons in the range of 0.6 eV–28 keV and the MIMI-LEMMS instrument measures electrons from 12 keV to >5 MeV. The data are 5 min averaged, during this time the CAPS-ELS actuated through 180 degrees with a field of view that includes that of MIMI-LEMMS.

[16] In this paper we do not present any quantitative calculations concerning actual electron trajectories along realistic field lines (that will be the topic of a follow-up paper, M. S. Richard et al., Data-model comparisons for the ionospheric peak region of Titan, in preparation, 2011), but only wish to establish the feasibility that the unusual/anomalous ionospheric densities in the region around the peak are likely to be the result of electron precipitation. We know that electrons follow magnetic field lines, which are typically draped around the ramside of Titan [e.g., *Ma et al.*, 2006]. However, in order to simplify our calculations, as we are only interested in establishing the feasibility of electron impact ionization as a potential source, we assume that the electrons move radially inward and calculate the electron flux deposition. We cover an electron energy range of 1 eV to 190 keV and use cross sections from the work of *Gan et al.* [1992] and *Cravens et al.* [2008]. We use the neutral atmosphere parameters given by the T5C1 case of *Robertson et al.* [2009] multiplied by a factor of 3 to take into account the revised INMS calibration [*Bell et al.*, 2010]. In order to arrive at electron densities from these calculated production rates, we simply take the square root of the production rate divided by the effective recombination rate, thus we need to know/assume a value for this electron-ion recombination coefficient, which we estimated to have a rather high value of 1×10^{-6} cm^3 s^{-1} [see *Schunk and Nagy*, 2009], making our choice rather conservative. It has been shown [e.g., *Ma et al.*, 2006] that chemical equilibrium conditions prevail below about 1400 km in Titan's ionosphere, and thus we can ignore transport in our region of interest. The resulting electron densities, corresponding only to the measured electron fluxes, assuming radial deposition, are shown in Figure 6. As indicated before, a realistic deposition along draped magnetic field lines would result in the peak production moving up in

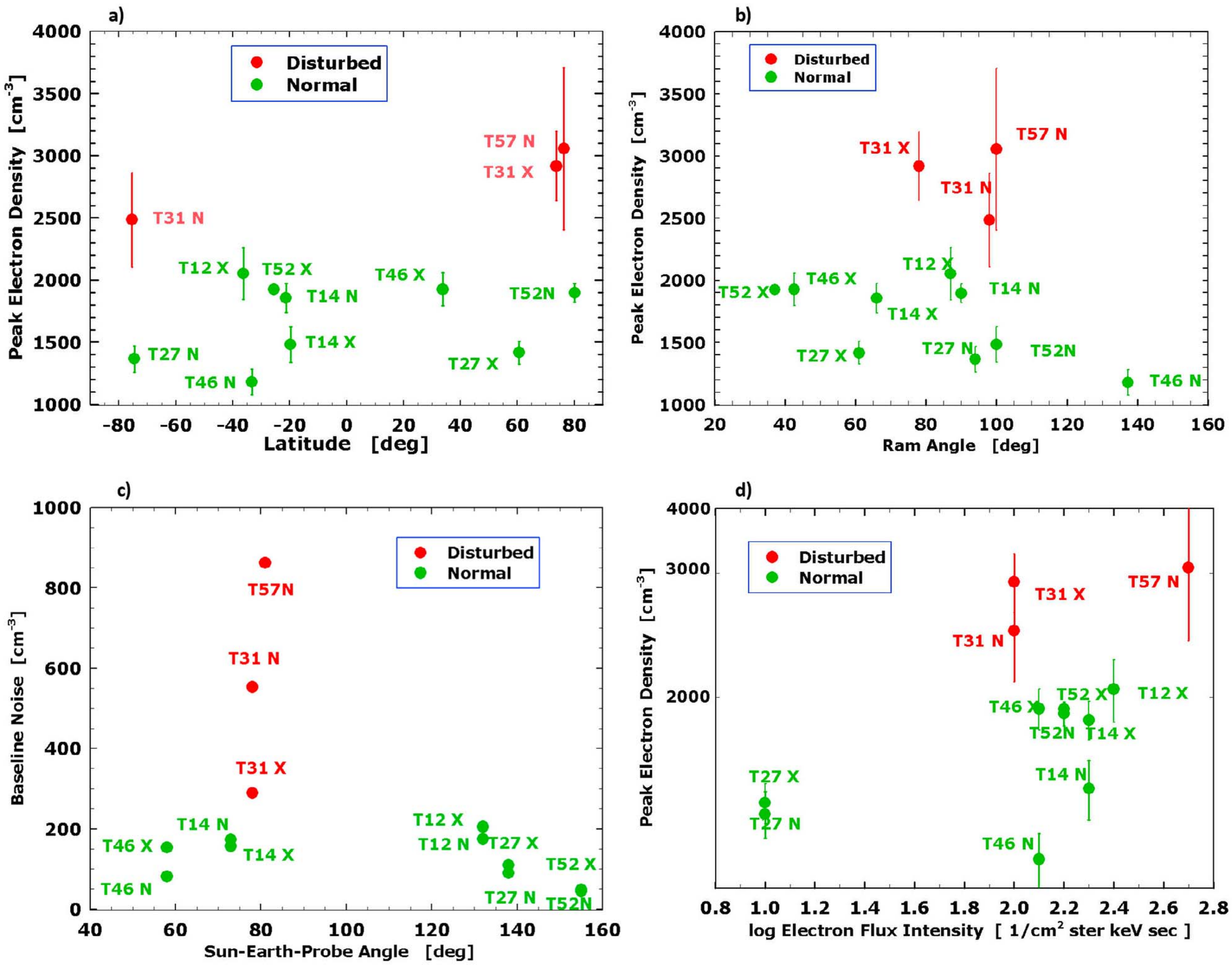

Figure 4. (a) Observed peak electron density versus latitude; (b) observed peak electron density versus magnetospheric ram angle; (c) observed baseline fluctuation noise versus Sun-Earth-Probe angle; and (d) observed peak electron density versus magnetospheric electron flux. The normal observations are plotted in green and the disturbed ones are plotted in red.

altitude and dropping sharply at the lower altitudes. Our intention here is not to come up with a quantitative answer, but only to show that precipitation by the measured electron fluxes corresponding toT31 and T57 lead to densities of around 1×10^3 cm^{-3}, of the right order of magnitude for the measured differences shown in Figure 2. Also note that the "lobe" electron flux, corresponding to T8 leads to significantly lower densities.

5. Discussion and Conclusions

[17] In this paper we presented a summary of all the ionospheric profiles obtained so far by means of radio occultations from Cassini. These observations have given us 13 electron density profiles from the near terminator region of Titan. Given the relatively small number of occultation opportunities the conclusions to be drawn have limited statistical significance, but they still provide some useful insights. The peak electron densities were found to be between about 1 to 2×10^3 cm^{-3}, except for both inbound and outbound T31 and the inbound T57 orbits, for which these densities exceeded the average from the other orbits by about 1×10^3 cm^{-3}. These two unusual orbits correspond to high northern and southern latitudes, as well as ram angles near 90°, but "normal" densities can also be found at these high latitudes and ram angles (see Figures 4a and 4b). This suggests that the cause for these increased electron densities may lay somewhere else. Impact ionization by precipitating magnetospheric electron fluxes has been suggested to be very important for the nightside and thought to make some contribution, even on the dayside. Thus it seemed logical to examine this source of ionization for the near terminator region.

[18] We have shown here that the measured fluxes corresponding to these two unusual orbits in question are a good potential ionization source that can go a long way toward explaining the observed increased densities in the ionospheric peak region. More rigorous and detailed calculations, taking into account magnetic field topology and other interaction effects, will be needed to confirm that magnetospheric electrons/ions are indeed responsible for the observed increases in

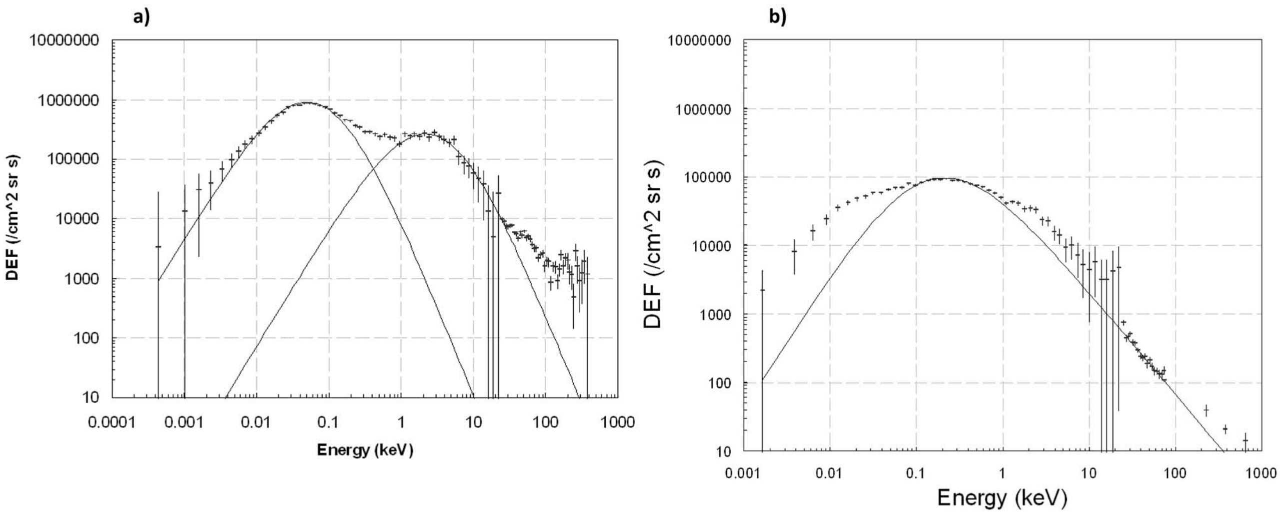

Figure 5. (a) Black dashes show combined, differential electron flux (DEF) measured by the CAPS-MIMI electron instruments inbound during T57 at 17:00 UT day of year (DOY) 173 2009. The data have been corrected for positive spacecraft potential and background radiation. The black solid lines are kappa fits to the data appropriate to (1) temperature = 30 eV, density = 80,000 m^{-3} (cold component), and (2) temperature = 1300 eV, density = 3500 m^{-3} (hot component). (b) Black dashes show DEF measured by the CAPS-MIMI electron instruments inbound during T8 at 03:10 UT DOY 301 2005. The data have been corrected for positive spacecraft potential and background radiation. The black solid line is a kappa fit to the data with temperature = 160 eV and density = 26,000 m^{-3}.

the ionospheric electron densities. These calculations must also look at the "normal" orbits to quantify the electron precipitation contribution for these cases. Clearly more observations are needed to get a better statistical indication of ionospheric variability at Titan. A clue to this question can be found in the work of *Ågren et al.* [2009], which presents Langmuir probe peak electron density observations as a function of solar zenith angle (SZA), as shown in Figure 3. Looking at the near terminator values presented by *Ågren et al.* [2009], one finds three data points within the 85°–95° SZA range. All three of these show peak densities below 2000 cm^{-3} (the values are approximately 850, 1250 and 1850 cm^{-3}). This range of values

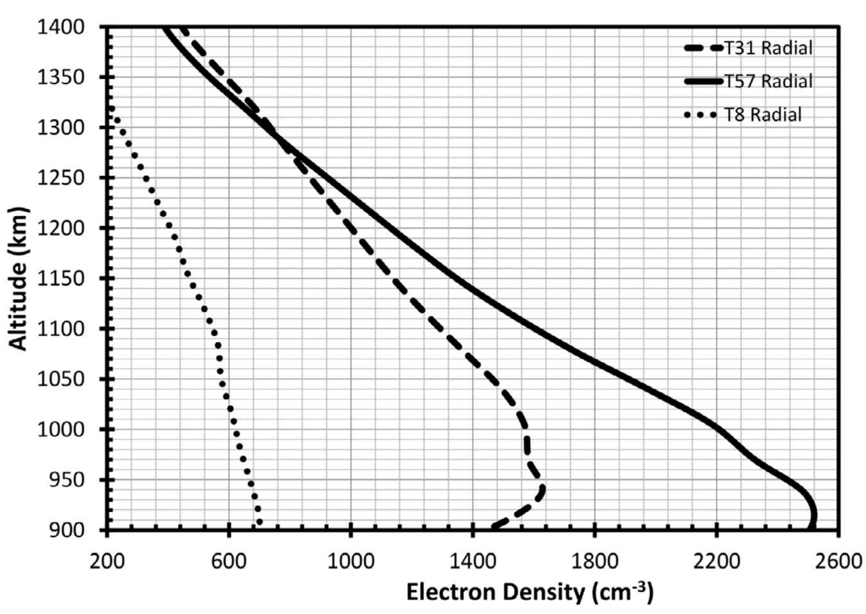

Figure 6. Electron density profile calculated from the observed magnetospheric electron fluxes for T8, T31, and T57 using a simple photochemical ionosphere model.

is consistent with the profiles that we have denoted as “normal” occultation densities. The Langmuir probe measurements correspond to independent observations, during different orbits, adding confirmation to the conclusion that the data from T31 and T57 are indeed unusual.

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