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Solar cycle modulation of Titan's ionosphere

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[1] During the six Cassini Titan flybys T83–T88 (May 2012 to November 2012) the electron density in the ionospheric peak region, as measured by the radio and plasma wave science instrument/Langmuir probe, has increased significantly, by 15–30%, compared to previous average. These measurements suggest that a long-term change has occurred in the ionosphere of Titan, likely caused by the rise to the new solar maximum with increased EUV fluxes. We compare measurements from TA, TB, and T5, from the declining phase of solar cycle 23 to the recent T83–T88 measurements during cycle 24, since the solar irradiances from those two intervals are comparable. The peak electron densities normalized to a common solar zenith angle N_{norm} from those two groups of flybys are comparable but increased compared to the solar minimum flybys (T16–T71). The integrated solar irradiance over the wavelengths 1–80 nm, i.e., the solar energy flux, F_e, correlates well with the observed ionospheric peak density values. Chapman layer theory predicts that $N_{\mathrm{norm}} \propto F_e^k$, with $k = 0.5$. We find observationally that the exponent $k = 0.54 \pm 0.18$. Hence, the observations are in good agreement with theory despite the fact that many assumptions in Chapman theory are violated. This is also in good agreement with a similar study by Girazian and Withers (2013) on the ionosphere of Mars. We use this power law to estimate the peak electron density at the subsolar point of Titan during solar maximum conditions and find it to be about 6500 cm^{-3}, i.e., 85–160% more than has been measured during the entire Cassini mission.

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1. Introduction

[2] Titan's ionosphere was first observed by radio occultation measurements from the Voyager 1 spacecraft [*Bird et al.*, 1997], but most of what is known about the ionosphere has been established following the arrival of the Cassini spacecraft. Titan is the largest moon of Saturn with a dense atmosphere and an extended exosphere filled with complex ionized organic molecules. The most abundant species in the neutral atmosphere is N_2 (98%). In the upper ionosphere $HCNH^+$ and $C_2H_5^+$ dominate [*Cravens et al.*, 2006], while there is a wealth of other minor species present, formed through the organic chemistry in the moon's atmosphere. Titan's ionosphere becomes increasingly complex due to the presence of both heavy negative ions [*Coates et al.*, 2007] and heavy positive ions [*Waite et al.*, 2007]. At the lowest levels below ~1000 km the ionosphere is dominated by heavy negative and positive organic ions [*Crary et al.*, 2009; *Coates*, 2009; *Wahlund et al.*, 2009; *Ågren et al.*, 2012; *Shebanits et al.*, 2013; *Wellbrock et al.*, 2013]. The presence of a substantial amount of negative ions implies that the ion production rate is higher than what the electron density measurements convey, since some of the negative charge is being carried by ions rather than electrons.

[3] The structure of the ionosphere has been studied extensively. *Ågren et al.* [2009] showed that the peak of the ionosphere was located in the altitude range of 1000–1400 km with an increasing altitude toward higher solar zenith angles (SZA). The electron density at the ionospheric peak altitude was about 3000 ± 500 cm^{-3} on the dayside and falling with a strong SZA dependence toward the nightside where the densities were reported to be about 400–700 cm^{-3}. As we now have more nightside passes, we can report that the average nightside ionospheric densities are closer to 1000 ± 500 cm^{-3}. The primary ionization source of Titan's atmosphere is the solar EUV flux [*Galand et al.*, 2006; *Ågren et al.*, 2009]. Impacting magnetospheric particles play a minor role in establishing the dayside ionosphere but have a larger effect on the nightside [*Cravens et al.*, 2005; *Ågren et al.*, 2007].

[4] The variability of Titan's ionospheric structure has also been studied since the arrival of Cassini. Remote

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measurements by radio occultation as well as in situ measurements have revealed that the ionospheric structure can vary significantly with time and that the electron density levels can be sporadically much higher than normal at Titan, i.e., during single flybys, likely due to increased levels of precipitating particles causing impact ionization [*Kliore et al.*, 2008, 2011; *Edberg et al.*, 2013]. Statistical studies using in situ Langmuir probe measurements have shown that although there is considerable variations in the shape of the ionospheric altitude profiles, the density and peak altitude of the ionosphere have stayed rather constant around the values stated above [*Ågren et al.*, 2009; *Edberg et al.*, 2010].

[5] From the first Titan flyby, TA, of the Cassini mission on 26 October 2004 until T71 (the 72nd close pass of Titan) occurring on 7 July 2010, it was not possible to identify any larger changes in the structure of the ionosphere in response to either solar cycle changes or seasonal changes in Titan's atmosphere. For the early parts of the Cassini mission, Titan's northern hemisphere experienced springtime, while the southern hemisphere experienced autumn (one Titan year is 29.5 Earth years). However, following Saturn equinox in 2009, the seasons started to turn, with measurable effects on the composition and structure of the neutral atmosphere [*Teanby et al.*, 2012]. In the same interval, the Sun went from the declining phase of solar cycle 23 through a deep minimum and to the rising phase of solar cycle 24. In between T71 and T83 (occurring on 22 May 2012) there were only high-altitude passes of Titan with closest approaches all above 1400 km. Hence, the ionospheric peak was not monitored for more than 1.5 years, until the T83–T88 deep flybys occurred, when the solar activity had risen toward a new maximum.

[6] In this paper we will present Langmuir probe measurements from the deep ionosphere of Titan during the recent T83–T88 Titan flybys, which indicate that a long-term change has occurred in the structure of the ionosphere. We will show evidence that this change is most likely modulated by the solar cycle.

2. Instruments and Coordinate Systems

[7] The Cassini spacecraft carries the radio and plasma wave science instrument (RPWS), in which the Langmuir probe (LP) instrument is included [*Gurnett et al.*, 2004]. The LP measures the bulk plasma parameters in the Saturn system and routinely monitors the plasma density, temperature, and bulk speed [*Wahlund et al.*, 2005]. When the LP operates in the so-called sweep mode, both the ion and the electron densities can be obtained with a 24 s cadence. The RPWS/LP measures the electron density with an error of typically within 10%, when the ionospheric density is above 100 cm^{-3} [*Wahlund et al.*, 2005; *Ågren et al.*, 2009]. Since we will investigate the effect of the solar cycle variation in this paper, it is important to note that an increased photoelectron flux, due to increased UV radiation on the LP or spacecraft, is negligible in this study. We will only investigate the ionospheric peak densities, which are much higher than any photoelectron density (or other secondaries) from the spacecraft. The measurement technique and a more detailed instrument description can be found in, e.g., *Wahlund et al.* [2005], *Ågren et al.* [2007], *Edberg et al.* [2011], or *Morooka et al.* [2011].

[8] We also make use of the solar flux measurements from the Solar EUV Experiment (SEE) on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) spacecraft in orbit around the Earth [*Woods and Eparvier*, 2006]. The TIMED/SEE instrument measures the spectral irradiance of the Sun with a resolution of 0.4 nm between 27 and 194 nm and with a resolution of 7–10 nm for wavelengths shorter than 27 nm. We use daily averages of those measurements extrapolated to the orbit of Saturn as our measure of the EUV flux throughout the paper. The extrapolation takes into account the difference in radial distance as well as the longitudinal difference between the Earth and Saturn, and the solar rotation period (27 days). The data are obtained from the TIMED-SEE website at LASP (lasp.colorado.edu/see/l3_data_page.html), and the ready routines (PLOT_SEE.PRO) that we use for extrapolating the data are available through that site. Note that the same data and the same routines have been used in a recent similar study for the Mars ionosphere, where similar results as in this paper were presented [*Girazian and Withers*, 2013].

[9] The geometry of the Cassini-Titan-Saturn system is presented in two different coordinate systems. In the Titan-centered Titan interaction system (TIIS) the x axis is parallel to Saturn's ideal corotating direction, the y axis is directed toward Saturn, and the z axis completes the right-handed system and is parallel to Saturn's spin axis [*Neubauer et al.*, 2006]. In the Titan-centered ecliptic coordinate system, the x axis points toward the Sun, the y axis is formed by the cross product of the x axis and the normal to Titan's orbital plane, and the z axis completes the right-handed system.

3. Observations

[10] Figure 1 shows the flyby geometry for all the Titan passes to date in the ecliptic reference system (Figure 1a) and in the TIIS system (Figure 1b), as well as the Saturn local time of each Titan encounter (Figure 1c). The flybys are shown in different colors since they come from different parts of the solar cycle, as will later be shown in Figure 2. The T83–T88 flybys occurred over a period of 6 months in 2012 on 22 May (T83), 7 June (T84), 24 July (T85), 26 September (T86), 13 November (T87), and 29 November (T88). They all had similar altitude of closest approach, in the range of 955–1015 km but at varying SZAs in the range 40–80°. They all occurred at approximately 13:00 h Saturn local time. Hence, these flybys are well suited for studying global long-term changes of the deep dayside ionospheric structure. The TA, TB, and T5 flybys occurred in the beginning of the mission at Saturn. TA and TB had higher closest approaches, 1174 and 1192 km, respectively, and so they are less suited for studying the deeper ionosphere of Titan. T5 was a nightside pass with closest approach of 1027 km and occurred on the dawn side of Saturn, as opposed to the dayside sector of Saturn like TA, TB, and T83–T88. Despite the unfavorable flyby geometry during TA, TB, and T5, they are important to consider here as they occurred during a different phase of the solar cycle, i.e., the declining phase of solar cycle 23, as compared to all the other flybys.

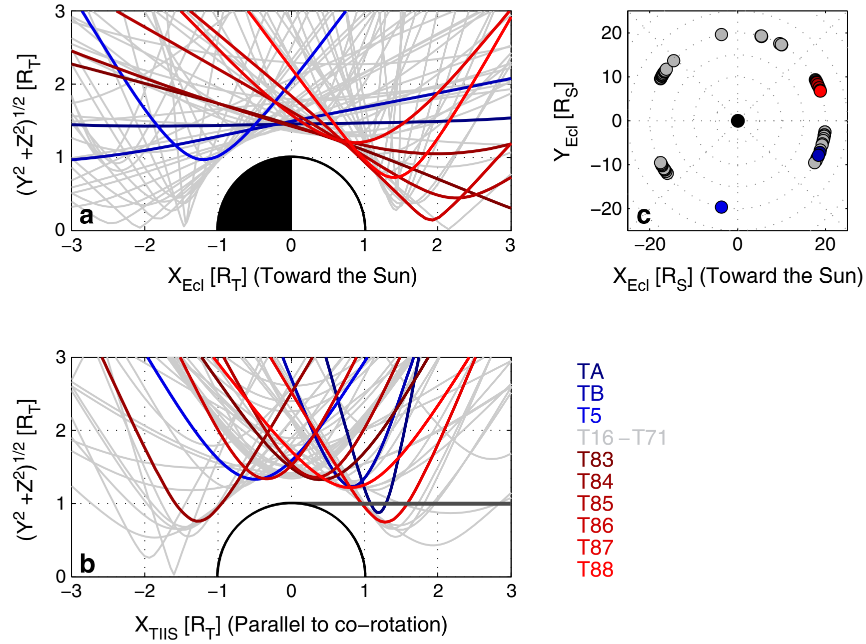

Figure 1. Flyby geometry during the TA, TB, T5 (blue), T16–T71 (grey), and T83–T88 (red) Titan flybys in cylindrical (a) ecliptic coordinates and (b) TIIS coordinates. The flybys are shown in different colors since they come from different parts of the solar cycle (see Figure 2). (c) The Saturn local time of the flybys.

3.1. The Solar Cycle

[11] In Figure 2 we show the solar spectral irradiance, I_s, at six wavelengths in the EUV range to illustrate how the solar cycle has changed during the time of our measurements. At the top of the figure we also mark the time of the ionospheric measurements from all the deep Titan passes of Cassini. From the first Cassini Titan flyby, TA, in October 2004, the Sun has gone from the declining phase of solar cycle 23 through a deep solar minimum and, by the time of the T88 flyby, probably has come close to the solar maximum of cycle 24. At the time of writing it is not clear if the Sun has reached a new solar maximum yet. During the same time period, Saturn has gone through less than a third of its 29.5 year orbit, during which it has moved outward from the Sun in its elliptical orbit by ~0.7 AU, as shown in Figure 2g. Saturn moved from being near perihelion at 9.05 AU in October 2004 to a distance of 9.78 AU in November 2012. This is important since it means that even though the solar activity has increased, Saturn and Titan have experienced less of an increase in terms of solar irradiance as it has moved farther away from the Sun. The increase in distance causes the fluxes to decrease by 17%. It is obvious that during T83–T88 we have measurements from a new phase of the solar cycle, and below we will see how this might affect the ionospheric structure.

3.2. The Electron Density in the Ionosphere

[12] Using the Langmuir probe measured electron density from the T83–T88 flybys, we show in Figure 3 the altitude profiles from each individual pass overlaid on all earlier derived altitude profiles. There is a considerable spread in the shape of the altitude profiles, partly since they cover different locations around both Titan and Saturn and partly since they were measured during different solar and magnetospheric conditions. Comparing each of the six most recent logarithmic profiles (T83–T88) to the bulk of the previous ones (T16–T71), one finds that the deeper parts of the profiles below 1100 km stand out in terms of clearly increased electron density values. These six passes stand out even further if we take into account that each pass occurred at a different SZA. To illustrate this, we plot in Figure 4a each individual peak density value ($N_{e,\text{peak}}$) as a function of SZA. There are normally two data points from each flyby, one for the inbound leg and one for the outbound leg. The peak densities from T83 to T88 are shown in red colors, and the peak values from T16 to T71 are shown in grey. A cosine fit to the T16–T71 data of the form

$$N_{e,\text{peak}} = a \cdot \cos(b \cdot \text{SZA}), \tag{1}$$

where a best fit yields $a = 3198\,\text{cm}^{-3}$ and $b = 0.65$, is included together with a 95% confidence interval. For this fit we include data from SZA < 120°. The factor a is the peak density at the subsolar point, and the parameter b is introduced to account for the fact that the ionosphere of Titan is very extended and there are photons ionizing beyond SZA = 90°. According to Chapman theory, the function describing the variation with SZA should rather be $N_{e,\text{peak}} = a \cdot \cos^{1/2}(\text{SZA})$ [*Chapman*, 1931a]. The extended ionosphere together with day to night plasma transport and contribution from particle impact ionization would make any exact theoretical fitting overly complicated. Therefore, here we choose a simple cosine fit with a variable period (the factor b) since that empirically fits the data much better and serves the purposes of this paper.

[13] Note that the peak altitude was not crossed during all flybys, so we do not have 88 inbound and 88 outbound

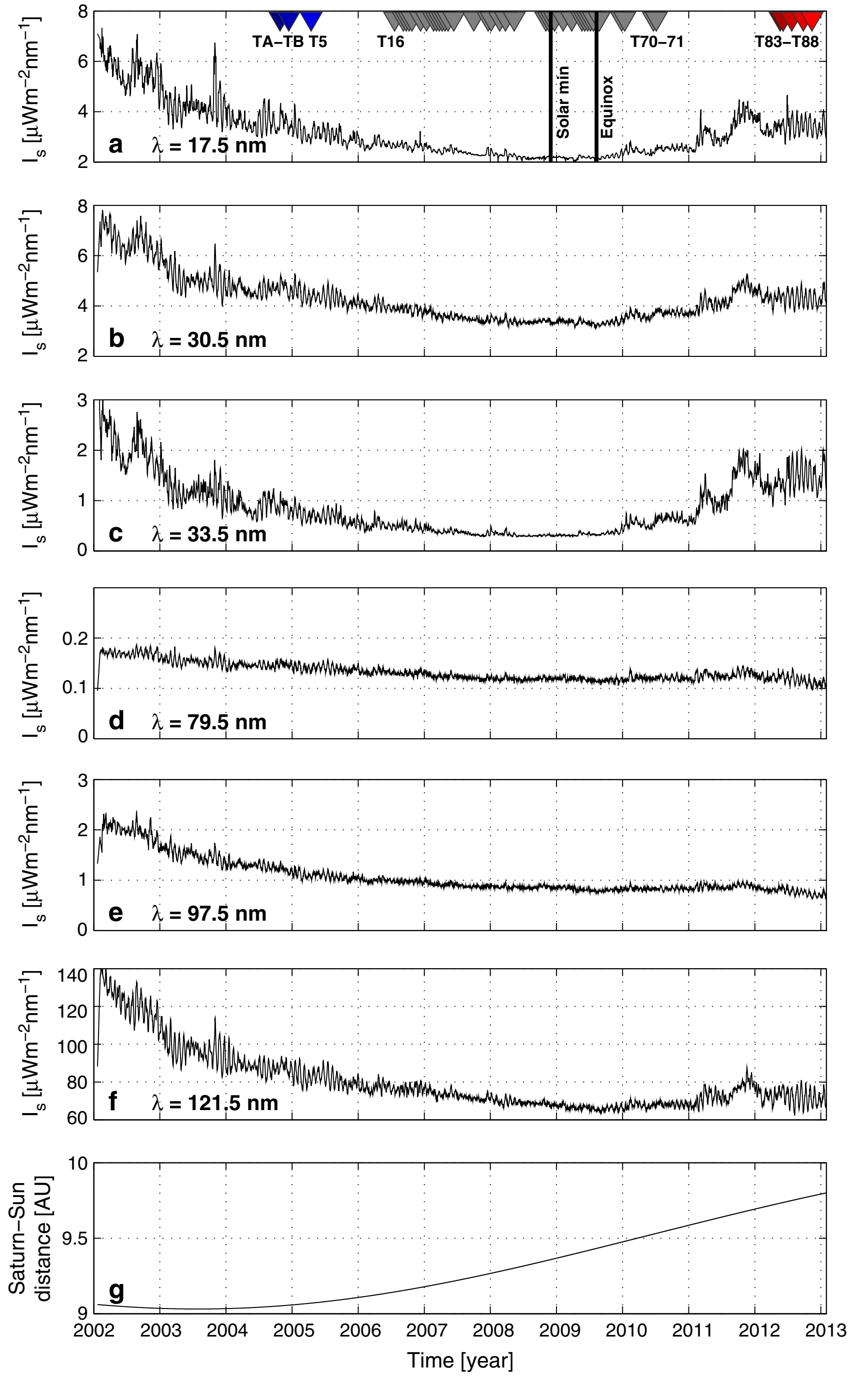

Figure 2. Time series of solar spectral irradiance measured by TIMED/SEE at six wavelengths: (a) 17.5, (b) 30.5, (c) 33.5, (d) 79.5, (e) 97.5, and (f) 121.5 nm and (g) the Saturn-Sun distance. The irradiances are scaled from Earth to the orbit of Saturn by $1/r^2$ and time shifted by the longitudinal difference between the Earth-facing and the Saturn-facing sides of the Sun. The times of the deep Titan flybys are indicated by triangles at the top of the figure.

(196 in total) ionospheric altitude profiles but rather only 84 in total. The electron densities from TA, TB, and T5 are shown in blue. During TA, TB, T85, and T88 the peak altitude was probably not reached so only the density at the closest approach during those passes are shown. The peak density during those flybys should therefore be even higher than that shown here. Nevertheless, it is evident that the maximum electron density values seen during these specific flybys are considerably increased compared to the average values. The T85 flyby is special since it took place while a solar wind pressure pulse, a coronal mass ejection (CME), impacted on Saturn's magnetosphere and compressed it to such an extent that Titan was within the magnetosheath of Saturn. This special case is studied by *Edberg et al.* [2013]. In the magnetosheath it experienced increased levels of precipitating solar wind particles during CME conditions,

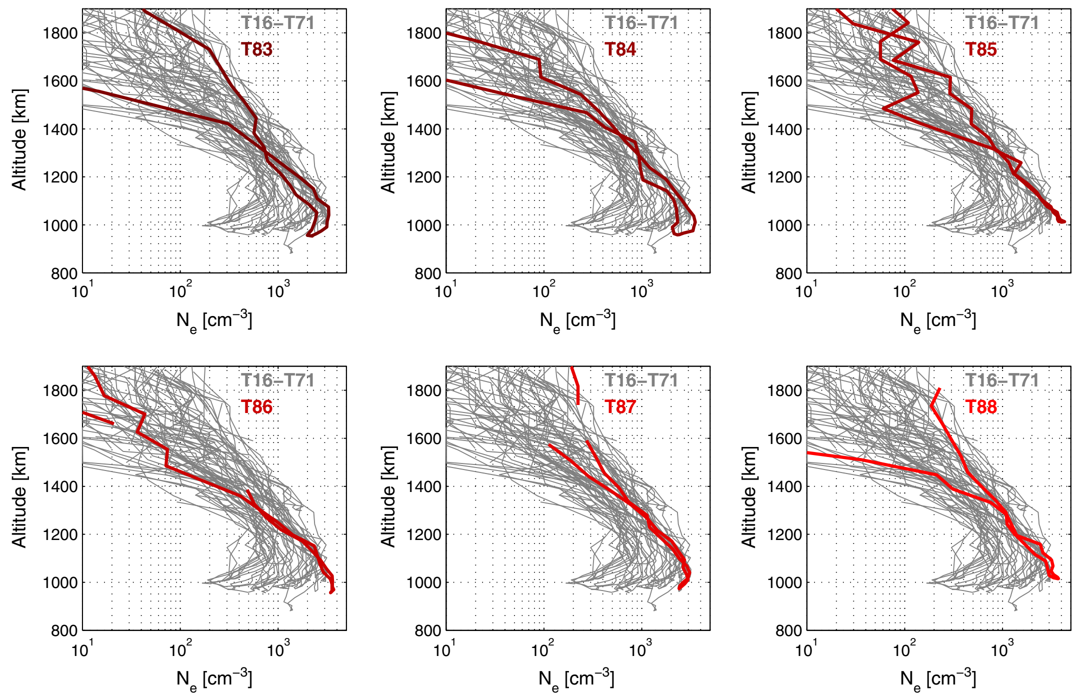

Figure 3. Langmuir probe-measured altitude profiles of the electron density from the T83–T88 flybys (colored) compared to previous profiles (grey).

which caused additional ionization. Thus, it stands out from all the other flybys in terms of electron density levels.

[14] In Figure 4b we show the altitude of the peak (or the closest approach altitude for T85 and T88) as a function of SZA, again overlaid on all previous data points for comparison. TA and TB are not included since they only reached an altitude of ~1200 km, and consequently the peak was not sampled. A least-squares fit to the data shows that the peak altitude R_{peak} is related to the SZA as R_{peak} [km] = 0.84· SZA [deg] + 1023. The lowest peak altitudes are recorded during T86 at an altitude of about 960 km. The closest approach of Cassini during T85 was at 1012 km and during T88 at 1014 km, and since the measured density was still increasing with falling altitude at these points the ionospheric peak altitudes would have been located below the closest approach altitudes.

[15] The data in Figures 4a and 4b clearly show that during T83–T88, firstly, the density at the peak altitude has increased compared to earlier, and, secondly, the peak altitude is on average lower than earlier. There is a natural spread in both density and altitude from pass to pass within all the previous data (grey points), but most of the new peak density values from the T83–T88 flybys are not even within the 95% confidence interval of the previous data. We now

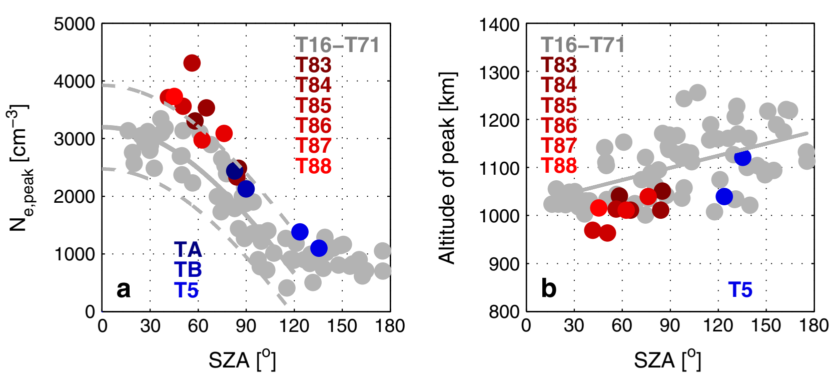

Figure 4. (a) Ionospheric peak electron density versus SZA for the T83–T88 (red), the T16–T71 (grey), and the TA–TB and T5 (blue) flybys. The TA, TB, T85, and T88 flybys did not cross the peak, and the density at the closest approaches during those passes are shown instead. A cosine fit to the values from the T16–T71 flybys for SZA < 120° is included (grey solid line) together with a 95% confidence interval (grey dashed lines). (b) Ionospheric peak altitude versus SZA for the T83–T88 (red), T16–T71 (grey), and T5 (blue) flybys. TA and TB are not included. The grey line is a best fit to the T16–T71 data. Again, for T85 and T88 the closest approach altitude is shown instead of the peak altitude.

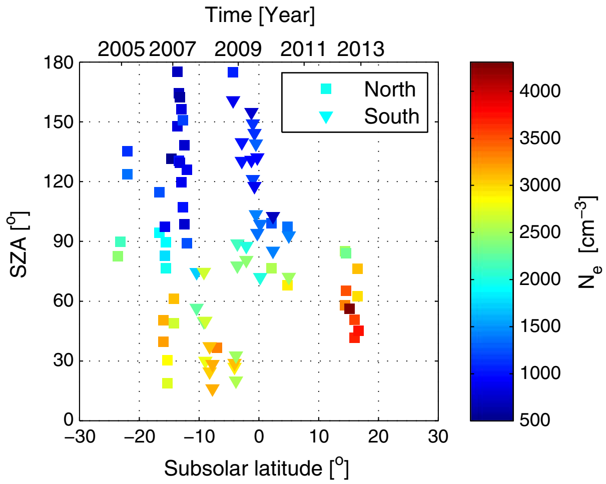

Figure 5. The subsolar latitude of Titan plotted versus the SZA angle for all ionospheric peak (or closest approach) measurements. The points are color coded by the electron density and divided into northern (squares) and southern (triangles) hemispheres measurements.

have data from six consecutive flybys, separated in time over 6 months, with continuously high values and low peak altitudes, which strongly suggest that a long-term change has occurred in the deep ionosphere of Titan. Besides the solar cycle there is also the seasonal cycle of Titan's neutral atmosphere, which could possibly be responsible for the changed ionospheric structure. We will inspect potential signatures of both cycles below.

[16] In Figure 5 we show the SZA of each data point as a function of subsolar latitude. Each data point is color coded by density and plotted either as a square, if located in the northern hemisphere of Titan, or as a triangle, if located in the southern hemisphere. High negative values ($\sim -30°$) of the subsolar latitude means that the northern (southern) hemisphere is experiencing winter (summer), and 0° corresponds to equinox. From the start of the Cassini mission the northern hemisphere has experienced springtime and is presently moving toward summer. As the change in subsolar latitude is a nonlinear measure of time, we also indicate the time (in years) on the top horizontal axis of Figure 5 for clarity. Data from the most recent flybys, T83–T88, stand out in this plot in red color as their peak densities are higher than all other for similar SZAs. These ionospheric peak values were all collected from the northern hemisphere of Titan and during subsolar latitudes of about 15°, i.e., northern spring and southern autumn. Note the gap in time to the previous deep flyby, T71, which occurred at a subsolar latitude of around 5°. If the seasonal change would be responsible for the increased density in the ionosphere, it would have been useful to have measurements from both the northern and the southern hemispheres. Since the time of the T83 flyby, we only have measurements from the northern hemisphere, and so we cannot compare for any seasonal changes between hemispheres. If the density for some reason were to increase in the northern hemisphere when moving toward summer, then one might expect that it would decrease in the southern hemisphere when moving toward winter at the same time, but we cannot test this hypothesis with the current samples. In fact, we can only state that according to our limited observations the density values during northern spring are higher than during any other season on Titan sampled so far.

[17] The other long-term cycle, the solar cycle, has a shorter period ($\sim$11 years compared to 29.5 years), and so we can more readily use our 8 years of Cassini measurements to study any potential periodic changes due to solar variation.

[18] We have seen that during T83–T88 the ionospheric electron density has increased to higher values compared to earlier flybys, and looking at Figure 2, we see that these later measurements come from a new solar maximum period of the Sun. However, the current maximum of solar cycle 24 is a very weak one and the values of the solar spectral irradiance are quite comparable to the values during the first Cassini Titan flybys, in 2004–2005, during the declining phase of solar cycle 23. As mentioned above, TA, TB, and T5 are the only flybys that we have measurements from before the Sun went into a deep solar minimum period, and so we will have to rely on these few samples for our solar cycle comparison. Looking again at Figure 4a, the data from TA, TB, and T5 are also higher than average for their respective SZAs. They nicely follow a trend of falling density with increasing SZA, still on the high end of the comparable later observations, and they seem to fit in better with the data from the T83–T88 flybys than with the rest of the data points, which came from the solar minimum era. Hence, it appears that the solar cycle variation, with its varying EUV fluxes, orders the data very nicely, and we can therefore consider it to be a likely candidate for the controlling factor of the observed increase in density of the deep ionosphere of Titan.

[19] According to Chapman ionospheric layer theory [*Chapman*, 1931a], the density at a given altitude and SZA in an ionosphere in photochemical equilibrium should be proportional to the ionizing flux as

$$N_{\mathrm{norm}} \propto F_e^k, \tag{2}$$

where N_{norm} is the electron density normalized to a common SZA, F_e is the ionizing flux, and $k = 0.5$. Here we choose the ionizing flux to be represented by the solar energy flux F_e, i.e., the solar spectral irradiance integrated over the wavelengths 1–80 nm. The fluxes used have been corrected for the difference in radial and longitudinal distance between TIMED/SEE and Saturn, as explained in section 2. F10.7 or E10.7 have previously commonly been used as a proxy for the ionizing flux in many studies at various planets, even though it has been recognized that they are in fact not so well correlated with the ionizing flux. For instance, *Chen et al.* [2011] concluded that F10.7 was not a good proxy for the EUV flux during the solar minimum of cycle 23. In a recent paper for Mars, *Girazian and Withers* [2013] studied the dependence of the peak electron density on the solar irradiance and showed that a much better measure of the ionizing flux is instead the integrated solar spectral irradiance from 1 to 90 nm. At Mars the dominating neutral species is CO_2 whose ionizing threshold is 90 nm, while the dominant species in the atmosphere of Titan is N_2, whose photoionization threshold is 79.6 nm [*Schunk and Nagy*, 2009]. The observational value of the power law exponent k was found to be 0.47 ± 0.02 by *Girazian and Withers* [2013], in good agreement with theoretical predictions. We therefore follow

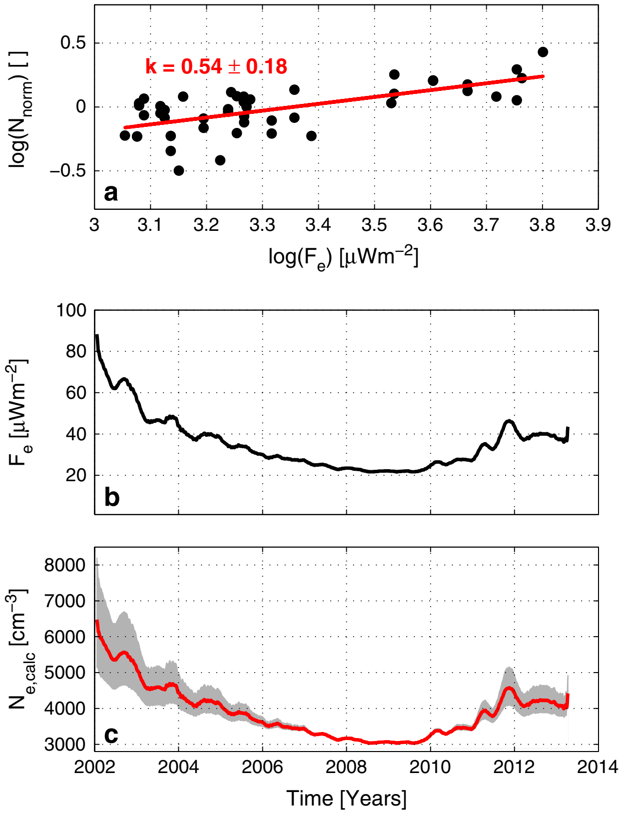

Figure 6. (a) SZA-independent peak electron density, N_{norm}, plotted versus the solar energy flux F_e. The best fit line (red) to the data has the form $\log(N_{\mathrm{norm}}) = 0.54(\pm 0.18)\log(F_e) - 1.81(\pm 0.63)$. (b) A 100 day running average of the integrated (1–80 nm) solar energy flux measured by TIMED/SEE. (c) The expected ionospheric peak electron density calculated using equation (3), the exponent k from Figure 6a, and the measured solar energy flux from Figure 6b. The shaded area corresponds to the range in density from the uncertainty interval of the power law exponent k.

their study and use the solar energy flux, in the range 1–80 nm, for our proxy of the ionizing flux. However, it should be mentioned that there are many assumptions in Chapman theory that are violated for the ionosphere of Titan, and Mars, which we discuss further in section 6.

[20] In order to find the exponent k, valid for the ionosphere of Titan, we begin by removing the strong SZA dependence from the peak density. We do this by fitting a cosine curve of the same form as equation (1) to the N_e versus SZA data but now for SZA < 90°, which yields the parameter values a = 3305 cm and b = 0.57. We divide the measured peak electron densities N_e by that curve to get a SZA-independent peak electron density, N_{norm}. In Figure 6a we show this parameter, N_{norm}, plotted against the solar energy flux, F_e, in a log-log format. We only include data sampled from SZAs < 90° now since the nightside data are not expected to be directly influenced by changing solar EUV flux. For an altitude of 1000 km above Titan the Sun continues to illuminate up to a SZA of 135°. Still, we only include data sunward of the terminator plane to remove any potential errors from the nightside ionosphere, where Chapman theory is not applicable. This excludes the T5 data, for instance. Looking at Figure 4a, the electron density seems to level out to a more constant value of about 1000 cm^{-3} past SZA= 90° and therefore this SZA value seems like a natural limit. There is a clear linear trend in the data, and a best fit yields a value for the power law exponent of $k = 0.54 \pm 0.18$. The error represents a 95% confidence interval. The value of k is in very good agreement with theory as well as with the behavior of the Martian ionosphere [*Girazian and Withers*, 2013], and the density increase seems to almost exactly follow a square-root dependence as predicted by Chapman theory. (Note that including data up to SZA = 135° adds more scatter, but the power law exponent remains roughly the same.) This provides further evidence that it indeed is the solar cycle variation that is likely responsible for the high densities during the T83–T88 flybys.

4. Peak Density During High Solar Activity

[21] Having found a clear relation between the ionospheric peak density and the solar energy flux, we can calculate what the peak density of Titan's ionosphere would be during other parts of the solar cycle, assuming that this relation holds for all solar energy flux levels. In Figure 6b we show a 100 day running average of the solar energy flux in the wavelength range 1–80 nm from 2002 until 2013. Cassini has conducted measurements of Titan's ionosphere since 2004, clearly only during medium to low solar activity if compared to the near-maximum of cycle 23 in 2002 (the EUV measurements by TIMED/SEE began in early 2002). The fluxes were considerably higher for a few years before the arrival of Cassini, and we can now estimate how high the peak electron density would have been then. We calculate the expected ionospheric peak density at the subsolar point as

$$N_{e,\mathrm{calc}} = N_0 \left(\frac{F_e}{F_0}\right)^k, \qquad (3)$$

where N_0 = 3198 cm^{-3} is taken from the fit in Figure 4a at SZA = 0°, F_0 = 23.8 $\mu\mathrm{Wm}^{-2}$ is the average value of the solar energy flux from the time between T16 and T71 (from when the data of the fit was gathered), and $k = 0.54 \pm 0.18$. In Figure 6c we show the calculated ionospheric peak density for the entire interval from which we have TIMED/SEE measurements of the solar energy flux. We also include the range from the confidence bound of the value of k, shaded in grey. The calculated peak density was considerably higher before Cassini arrived and reached values of approximately 6500 cm^{-3}. During the absolute solar maximum, which was not measured by TIMED/SEE, the peak density is likely to have been even higher.

5. Discussion

[22] Up until T71 all measurements of the ionosphere of Titan, except for TA, TB, and T5, occurred during solar minimum conditions, and it has not been possible to do any studies on the effects of the solar cycle until now. After the T71 flyby in July 2010 there was an absence of measurements of the ionosphere of Titan until the T83 flyby in May 2012. In Figure 2, we show that the measurements during

T83–88 occur during the new solar maximum period, when the higher EUV fluxes are increased.

[23] We find that the ionospheric peak electron density, from all Titan flybys, is almost exactly proportional to the square root of solar energy flux (which we use as the proxy for the solar ionizing flux). This is in very good agreement with Chapman theory [*Chapman*, 1931b] and also to the behavior of the ionosphere of Mars [*Girazian and Withers*, 2013]. As mentioned above, there are many assumptions that go into Chapman theory that are violated. It is assumed that there is a single neutral and a single ion species absorbing the ionizing flux, that the atmosphere is isothermal, and that the ionization is due to monochromatic flux as well as a plane-stratified ionosphere. However, near the peak, N_2 is the dominant neutral, $HCNH^+$ is the dominant ion, and the main loss process for the ions is dissociative recombination with an electron, the rate of which is proportional to N_e^2. This is similar to Mars (except that the dominant neutral is CO_2 and the dominant ion is O_2^+), where the many assumptions of Chapman theory are also violated, but because of a dominant neutral, a dominant ion, and loss due to dissociative recombination, it is not unreasonable to think that the peak density should be proportional to the square root of the ionizing flux. The nonmonochromatic flux means that photons with shorter wavelengths penetrate deeper into the ionosphere than those with longer wavelengths such that ionization occurs in a wider altitude range. The nonplanar stratified ionosphere means that a ray must travel a longer path through the medium, as well as photon-absorption occurring beyond the ideal terminator plane. In summary, it might not be so meaningful to compare to the ideal Chapman theory due to the many violations to its inherent assumptions. Instead, we can simply state that the square-root dependence seems to be what we observe and that the assumptions may perhaps not be so crucial, at least not for the scope of this study. It is more interesting then that the values are very comparable to the results from the ionosphere of Mars, and we observe that they behave in very similar ways to varying solar flux changes.

[24] Since the new solar maximum is a weak one and combined with the fact that Saturn has moved outward from the Sun, the solar irradiance has not varied much from the declining phase of solar cycle 23 until the maximum of cycle 24. The irradiance values during T83–T88 are comparable to the values during the TA, TB, and T5 flybys from the declining phase of solar cycle 23. The ionospheric peak densities during the latter three passes were also higher than average for similar SZAs. They exhibit similar behavior to the T83–T88 data, in that we observe a trend of falling densities with increasing SZA. When using a power law to calculate the subsolar peak ionospheric density for more normal solar maximum values, we find that the density could be as high as 6500 cm^{-3}. During the Cassini mission, the peak densities, extrapolated to the subsolar point, have only been measured to be about 2500–3500 cm^{-3}. The calculated values would hence suggest an 85–160% increase in peak electron density from solar minimum to solar maximum.

[25] T5 was studied in detail by *Ågren et al.* [2007], who showed that magnetospheric particle impacts contributed to the high plasma densities on the nightside for that pass. *Cravens et al.* [2009] also studied the T5 flyby and identified a correlation between the energetic electron flux measurements from the Cassini electron spectrometer (CAPS/ELS) and several ion species (e.g., CH_5^+ and $C_2H_5^+$). Our results here indicate that some of the high density is furthermore explainable by the fact that the measurements occurred during the declining phase of the solar cycle when there were comparably high EUV fluxes. The plasma produced on the dayside would then possibly have been transported to the nightside as described by *Cui et al.* [2010]. However, we find no trend of increasing nightside densities with increasing solar energy flux when checking for such a trend among all the nightside data.

[26] The irradiance at longer wavelengths has almost not changed at all at Saturn during this part of the solar cycle, partly due to the increasing distance between Saturn and the Sun. The heavier organic molecules in Titan's atmosphere can photoionize at longer wavelengths (e.g., CH_4 has an ionization threshold of 98.79 nm) and would be more sensitive to changes in the longer wavelengths. However, N_2 is still the dominant species and so the overall ionospheric density should be rather insensitive to longer wavelength changes.

[27] At the time of T71, Saturn had passed equinox and the northern hemisphere of Titan was still experiencing springtime. By the time of the T83 flyby, the seasons had continued to change on Titan and at the same time the solar activity had risen. Post-equinox, a buildup of atmospheric trace gases was observed in the southern hemisphere of Titan together with rapid changes in atmospheric temperatures and composition, which was interpreted as a signature of seasonal changes [*Teanby et al.*, 2012]. The ionospheric measurements of increased densities during the recent T83–T88 passes could be related to the seasonal changes observed in the neutral atmosphere through some undetermined coupling mechanisms, but we cannot determine this from the present data and it is left unclear how important this is compared to the solar cycle change.

[28] The EUV flux seems only to affect the main part of the ionosphere. The topside of the ionosphere seems to be rather unchanged to varying EUV fluxes as seen during the T83–T88 flybys. One explanation could be that when moving toward higher altitudes the role of plasma transport increases [*Ma et al.*, 2006] and becomes so dominant that the effect of an increased ion production rate is no longer discernible. Another explanation could be that the effect of magnetospheric electrons increases. In the collisional regime, in the deepest part of the ionosphere, the plasma is less affected by transport and so the effect of an increased EUV flux is apparent. If the seasonal changes were, in fact, important, then one would expect that the deeper parts of the ionosphere were affected more since the coupling to the neutral atmosphere would be stronger at lower altitudes. This will require observation over the next couple of years as the seasons slowly turn toward full summer and while the solar cycle will again move toward a new minimum.

[29] An interesting point to note is that, since the density in Titan's ionospheric peak region is sensitive to changes in the solar EUV flux, the orbital phase of Saturn is also important. Saturn's orbit is elliptic, and the distance to the Sun varies by more than 1 AU. At perihelion the solar flux is therefore 25% higher than at aphelion. Hence, there are two phases at work that are entangled: the 11 year solar cycle and Saturn's 29.5 year cycle around the Sun. The latter both modulates the seasons of the neutral atmosphere

and influences the solar flux values. If the solar maximum were to occur when Saturn was at perihelion, the structure of Titan's ionosphere might be very different from when solar maximum occurs at aphelion. Interestingly, when the Voyager spacecraft flew by Saturn in 1980 and 1981, there was also a solar maximum and Saturn was at approximately the same Sun distance as during T83–T88 (9.5 AU in 1981 compared to 9.7 AU in 2012). At the next aphelion in 2019 the solar cycle will be around solar minimum, and at the next perihelion in 2033 the Sun will be around its maximum. Unfortunately, the Cassini mission will end in 2017 and no new mission to Saturn and Titan is in sight at present.

6. Conclusions

[30] The solar cycle and the varying EUV flux strongly influence the peak electron density of Titan's ionosphere. The ionospheric peak electron densities during the T83–T88 Titan flybys are significantly increased compared to measurements from previous flybys, and the peaks are generally also found at lower altitudes than previous average values. Simultaneous with the observation of the increased densities, the Sun has risen toward a solar maximum, with increased EUV fluxes as a consequence. During the same time, the seasons have changed on Titan with observed changes in the neutral atmospheric composition and structure [*Teanby et al.*, 2012]. This may have consequences for the ionospheric structure as well through atmosphere-ionosphere coupling.

[31] Also, the orbital phase of Saturn is important for the structure of Titan's ionosphere since the distance to the Sun varies with up to 1 AU over a Saturn year, which causes a 25% variation in the ionizing flux. The ion (and electron) production rate should, according to Chapman theory, be proportional to the square root of the ionizing flux increase, and we do find a power law exponent $k = 0.54 \pm 0.18$, which is in very good agreement with theory. We have followed the procedure of *Girazian and Withers* [2013] and used the 1–80 nm integrated solar spectral irradiance as a proxy for the ionizing flux and obtained results very similar to theirs for the ionosphere of Mars.

[32] Moreover, we have used this power law to calculate the ionospheric peak electron density during higher solar activity periods and found that during the previous solar maximum the peak density should have been above 6500 cm^{-3} at the subsolar point. This is 85–160% more than what has been observed by Cassini during the solar minimum era in between solar cycles 23 and 24.

[33] It is worth noting that most of the Cassini measurements of Titan's ionosphere as well the interaction with Saturn's corotating magnetosphere have occurred during the deepest solar minimum since the Maunder minimum in the seventeenth century. The Cassini measurements used for studying Titan have all occurred during a very special era, when the ionosphere was less ionized than otherwise. We may now be moving toward a more normal era for Titan during solar cycle 24, with continuously higher ionospheric densities.

[34] We will continue to monitor the ionosphere of Titan in the coming years to see how the ionospheric structure changes. At the time of writing, the next Titan flyby that went below the average peak altitude, T91, occurred on 23 May 2013 and initial analysis showed a peak density of around 3800 cm^{-3}.

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