9-6-2018

Titan's Variable Ionosphere During the T118 and T119 Cassini Flybys

N. J. T. Edberg
Swedish Institute of Space Physics

E. Vigren
Swedish Institute of Space Physics

Darci Snowden
Central Washington University

L. H. Regoli
The University Of Michigan

O. Shebanits
Imperial College London

See next page for additional authors

Recommended Citation

Edberg, N. J. T., Vigren, E., Snowden, D., Regoli, L. H., Shebanits, O., Wahlund, J.-E., et al. (2018). Titan's variable ionosphere during the T118 and T119 Cassini flybys. Geophysical Research Letters, 45, 8721–8728. https://doi.org/10.1029/2018GL078436

Authors

N. J. T. Edberg, E. Vigren, Darci Snowden, L. H. Regoli, O. Shebanits, J.-E. Wahlund, D. J. Andrews, C. Bertucci, and J. Cui

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL078436

Special Section:
Cassini's Final Year: Science Highlights and Discoveries

Key Points:
- Large difference in ionospheric electron density is seen between T118 and T119 despite similar geometry
- The lowest density ever observed in the altitude range 1,000-1,350 km in Titan's nightside ionosphere was during T118
- Low fluxes of impact ionizing particles and ionospheric dynamics is suggested as the most probable explanation

Correspondence to:
N. J. T. Edberg,
ne@irfu.se

Citation:
Edberg, N. J. T., Vigren, E., Snowden, D., Regoli, L. H., Shebanits, O., Wahlund, J.-E., et al. (2018). Titan's variable ionosphere during the T118 and T119 Cassini flybys. *Geophysical Research Letters*, *45*, 8721–8728. https://doi.org/10.1029/2018GL078436

Received 20 APR 2018
Accepted 20 JUL 2018
Accepted article online 30 JUL 2018
Published online 6 SEP 2018

Titan's Variable Ionosphere During the T118 and T119 Cassini Flybys

N. J. T. Edberg[1], E. Vigren[1], D. Snowden[2], L. H. Regoli[3], O. Shebanits[1,4], J.-E. Wahlund[1], D. J. Andrews[1], C. Bertucci[5], and J. Cui[6,7]

[1]Swedish Institute of Space Physics, Uppsala, Sweden, [2]Department of Physics, Central Washington University, Ellensburg, WA, USA, [3]Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, USA, [4]Department of Physics, Imperial College London, London, UK, [5]IAFE, Ciudad Universitaria, Buenos Aires, Argentina, [6]School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai, China, [7]Key Laboratory of Lunar and Deep Space Exploration, Chinese Academy of Sciences, Beijing, China

Abstract We report on unusual dynamics in Titan's ionosphere as a significant difference in ionospheric electron density is observed between the T118 and T119 Cassini nightside flybys. Two distinct nightside electron density peaks were present during T118, at 1,150 and 1,200 km, and the lowest density ever observed in Titan's ionosphere at altitudes 1,000–1,350 km was during T118. These flybys were quite similar in geometry, Saturn local time, neutral density, extreme ultraviolet flux, and ambient magnetic field conditions. Despite this, the Radio and Plasma Waves/Langmuir Probe measured a density difference up to a factor of 6 between the passes. The overall difference was present and similar during both inbound and outbound legs. By ruling out other factors, we suggest that an exceptionally low rate of particle impact ionization in combination with dynamics in the ionosphere is the explanation for the observations.

Plain Language Summary Using the Cassini satellite in orbit around Saturn, we make measurements during two close passes of the moon Titan. We observe how the electron density in the uppermost part of the moon's atmosphere—the ionosphere—changes drastically from one pass to the next. We also observe unexpectedly high peaks of electron density in a specific altitude range during the first pass. The findings are attributed to low influx of charged particles from Saturn's magnetosphere as well as to increased dynamics of the plasma in the ionosphere. The study emphasizes the complexity of the physical process at play at the moon and aims at gaining further understanding of this environment.

1. Introduction

Titan, the largest moon of Saturn, is surrounded by a dense and extended ionosphere (Bird et al., 1997; Wahlund et al., 2005). The structure and variability of this ionosphere are sensitive to several factors. On the dayside of the moon, the ionosphere is created mainly through photoionization by extreme ultraviolet (EUV) radiation of the atmospheric N_2 and CH_4 (Ågren et al., 2009; Galand et al., 2010), which means that Titan's ionospheric properties will vary with the solar rotation and the phase of the solar cycle (Edberg et al., 2013; Madanian et al., 2016; Shebanits et al., 2017). Particle impact ionization also contributes and is the main ionization source on the nightside of the moon (Ågren et al., 2007; Cravens et al., 2008, 2013; Vigren et al., 2015). That the precipitation of magnetospheric electrons can vary significantly in Titan's ionosphere was demonstrated, for example, in Vigren et al. (2016). They showed examples of when the electron impact ionization rate was comparable on the nightside and dayside, for similar ambient neutral conditions, despite the lack of impact ionization from newly created photoelectrons on the nightside, which are contributing significantly to the impact ionization on the dayside. The ambient plasma conditions in Saturn's magnetosphere, and in which region of Saturn's magnetosphere Titan is located, can therefore influence the ionospheric structure of Titan significantly (Edberg et al., 2015; Luhmann et al., 2012). Another factor that is important is the topology of the ambient magnetic field, which affects the particle precipitation into Titan's ionosphere (Regoli et al., 2016). Diurnal variations, changes in the neutral atmosphere, and plasma transport also modulate especially the nightside ionosphere (Cui et al., 2009, 2010; Snowden, Yelle, Cui, et al., 2013).

The Cassini spacecraft sampled the ionosphere of Titan during 127 targeted flybys over a time period of 13 years. The flyby geometry was quite diverse around Titan, and they occurred at different Saturn local times (SLT). The ambient plasma and magnetic field properties as well as the solar EUV radiation covered a large range of values over this period, which enabled studies of Titan under various conditions. Furthermore, some flybys were designed to occur in sequences, such that the flyby geometry gradually shifted from one pass to the next. The flyby pair T118 and T119 is one such example, and in this paper we will mainly focus on these two passes to compare and study the ionospheric structure and its substantial variability. The purpose of this paper is twofold. First, we aim to report on unusual dynamics in the electron density in the ionosphere of Titan, which are interesting as such, since the magnitude of this is quite unique for T118 and T119. Second, by discussing the observations and their possible causes, we wish to encourage future modeling efforts, including, for example, time-dependent boundary conditions (such as upstream pressure, impact ionization, and neutral density), to try to reproduce the observations presented here, which would provide the community with a better understanding of Titan's ionosphere and its complexity and variability.

1.1. Instruments

We use measurements from the Radio and Plasma Waves System/Langmuir Probe (RPWS/LP) instrument (Gurnett et al., 2004; Wahlund et al., 2005) to obtain the electron density in Titan's ionosphere. We derive the electron density from the sweep mode measurements in the same way as described in, for example, Edberg et al. (2011), Shebanits et al. (2013), and references therein. These density data are compared with the density obtained from the RPWS observations of the upper hybrid frequency (F_{UH}) emission line, and they agree to within a few percent in the upper part of the ionosphere, while in the deeper part of the ionosphere there typically is a larger difference, up to a hundred per cubic centimeter. It should be noted that this discrepancy has existed throughout the mission and is not unique for these two flybys. The LP instrument measurement error is typically 10% for a density over 100 cm^{-3}.

Furthermore, we use magnetic field vector measurements from the Cassini magnetometer instrument (MAG; Dougherty et al., 2004) at a cadence of 1 min and energetic particle measurements from the Magnetosphere Imaging Instrument/Charge Energy Mass Spectrometer and Low Energy Magnetospheric Measurements System (MIMI/CHEMS and LEMMS; Krimigis et al., 2004) to obtain partial particle pressure for H^+ and W^+ (W^+ indicates water group ions) and energetic electron fluxes at Titan's location during the flybys of interest. CHEMS can measure ions with energies from 2.8 to 220 keV for H^+ and from 8.9 to 220 keV for W^+. The LEMMS instrument can measure electrons with energies above 18 keV with two oppositely directed telescopes. In this study, we use measurements taken by the lowest energy electron channel (C0, 18–40 keV) as the best available indication of the importance of electron impact ionization in Titan's atmosphere. The fluxes of these particles have been shown to be highly variable at Titan's orbit (Garnier et al., 2010; Regoli et al., 2018). There were no measurements of the lower-energy plasma (few electron volts to ~1 keV), since the Cassini Plasma Spectrometer (CAPS; Young et al., 2004) was turned off in 2012, such that we cannot assess the influence of the suprathermal plasma. However, on average in the inner magnetosphere of Saturn, an increasing amount of the plasma pressure is carried by the energetic particles when moving radially outward from Saturn such that they make up about 50% of the plasma pressure at 10 R_S (Sergis et al., 2009).

2. Observations

Below we will first describe the specific flyby geometry during T118 and T119 before presenting the measurements from these two passes. The two coordinate systems used in this paper are the Titan interaction (TIIS) coordinate system and the ecliptic coordinate system; see, for example, Edberg et al. (2015) for a description.

2.1. The T118 and T119 Flybys

The flyby geometries during T118 and T119 were quite similar. During both the T118 and T119 flybys, Titan was located at 02 hr SLT and the passes had their closest approach (C/A) on the southern nightside of Titan, as can be seen in Figure 1, and on the Saturn-averted side of Titan. Cassini approached Titan and had its inbound legs starting from the dayside of Titan, which in this case partly coincides with the magnetospheric plasma flow wake side of the moon (the angle between the wake and sun direction was 70°). The flybys took place roughly 1 month apart, on 4 April 2016 and on 6 May 2016, respectively. There is a shift of the T119 C/A toward the wake side compared to T118, but the ionospheric structure is on average not varying much on such short spatial scales in the ram-wake direction (Edberg et al., 2015). Due to part of the ionization being caused by EUV radiation, the solar zenith angle (SZA) at which measurements are performed could have an influence on

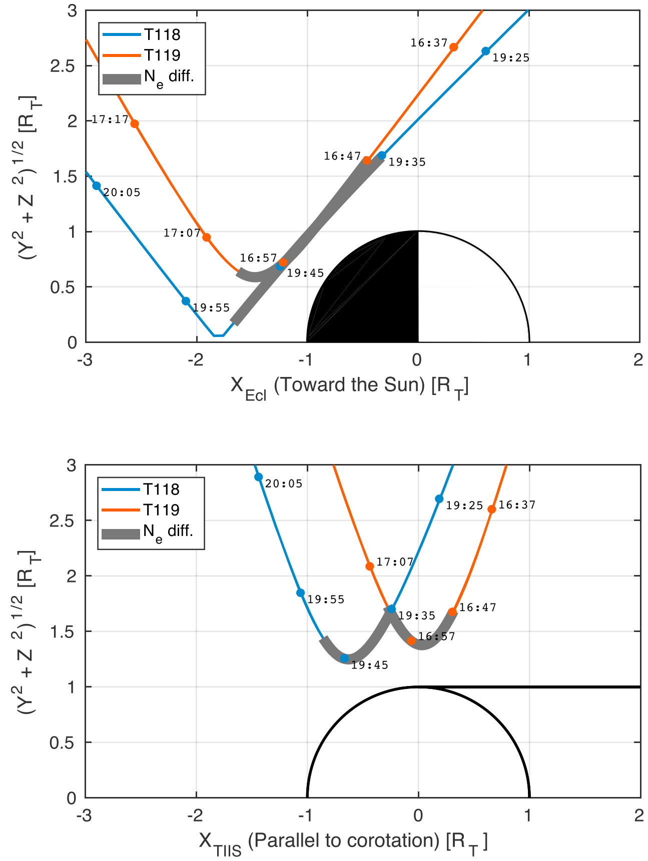

Figure 1. Flyby geometry during T118 and T119 in cylindrical (top) ecliptic and (bottom) TIIS coordinates. The thick gray lines indicate the time when a significant difference in electron density between the two passes is present. In the bottom panel, the wake behind Titan is illustrated by the horizontal black line. TIIS = Titan interaction coordinate system.

the measured density. But in this case the SZA profiles do not differ much between the two flybys, as can be viewed in the top panel of Figure 1 (the SZA variation is also shown as time series in Figure 2g further down). One difference that exists in between the two flybys is the attitude of Cassini (not shown). During T118, the LP was in the ram direction, that is, pointing in the direction of the spacecraft motion, while during T119 it was turned by about 80°. This difference should, however, not have any influence on the density measurements as long as the probe is not in the wake of the spacecraft at any time, which it is not. The thick gray bands in Figure 1 overlayed on the trajectory lines indicate where we observe very large differences in electron density between the two flybys, which will be described next.

2.2. Measurements

Figure 2 presents the data from measurements taken during the T118 and T119 flybys, centered on the time of C/A. Figures 2a–2g cover ∼25 min each, while Figure 2h covers 8 hr. Figure 2a shows the RPWS/LP sweep measurements, from which the electron density N_e is derived. The electron density from the sweeps are shown in Figure 2b together with the electron density estimate from the F_{UH} line (proportional to electron density as F_{UH} [Hz] $= 8980\sqrt{N_e}$ [cm^{-3}]) as detected by the RPWS antennas.

The two density estimates agree very well in the topside ionosphere for both passes but less so in the deepest part of the ionosphere. The electron temperature is quite similar in between the two flybys (Figure 2c). The magnetospheric energetic electron flux (Figure 2d) indicates higher fluxes during T119 than T118. Note that these electrons are too energetic to cause ionization in Titan's ionosphere proper and should rather be interpreted as (the best available) indication on what the lower-energy electron fluxes could be, assuming that they change similarly. The magnetic field data indicate very similar ambient magnetic field directions both before and after the flybys, but the B_x component differs between the flybys around C/A (Figure 2e). The bottom panels show energetic particle pressure of $H^+ + W^+$ from the MIMI instrument during a longer interval in order to capture the ambient conditions prior to and after the flybys.

What should be particularly noted in Figure 2, and which is central for this paper, is the large difference in electron density in between the two flybys in the interval of about ± 7 min around C/A (∼1,000–1,800 km). This can be seen when comparing the density estimates (Figure 2b) for the two flybys (noting again that there is also a difference between density derived from the LP and the density from the F_{UH}). The difference between T118 and T119 can also be clearly seen in the LP sweep data from Figure 2a, where there is a striking difference in both collected ion and electron current (at positive and negative bias voltage values U_{sweep}, respectively) from one flyby to the next.

To make this density difference more apparent, we plot in Figure 3 the altitude profiles of the LP measured electron density for the T118 (blue line) and the T119 (red line) flybys. From this plot it is evident that there is a significant difference in ionospheric density from the two flybys. The difference exceeds a factor of 6 at certain altitudes, for example, around 1,300–1,400 km during the outbound leg, and is typically around a factor of 2–4 throughout most of the interval.

Another central observation that occurred during the T118 flyby was that at altitudes of around 1,150 km during the inbound leg and about 1,200 km during the outbound leg of T118, the electron density had two distinct and similar peaks. The density increases during these peaks are large enough to make the density comparable again between the T118 and T119 flybys. Two broader but much smaller-amplitude peaks were observed in the altitude range 1,350–1,600 km during both the inbound and the outbound legs. We also note that local density maxima are seen on T118 at 1,150 (inbound) and 1,200 km (outbound); on T119, local density minima are seen at these altitudes. This is more pronounced during the outbound leg of T119.

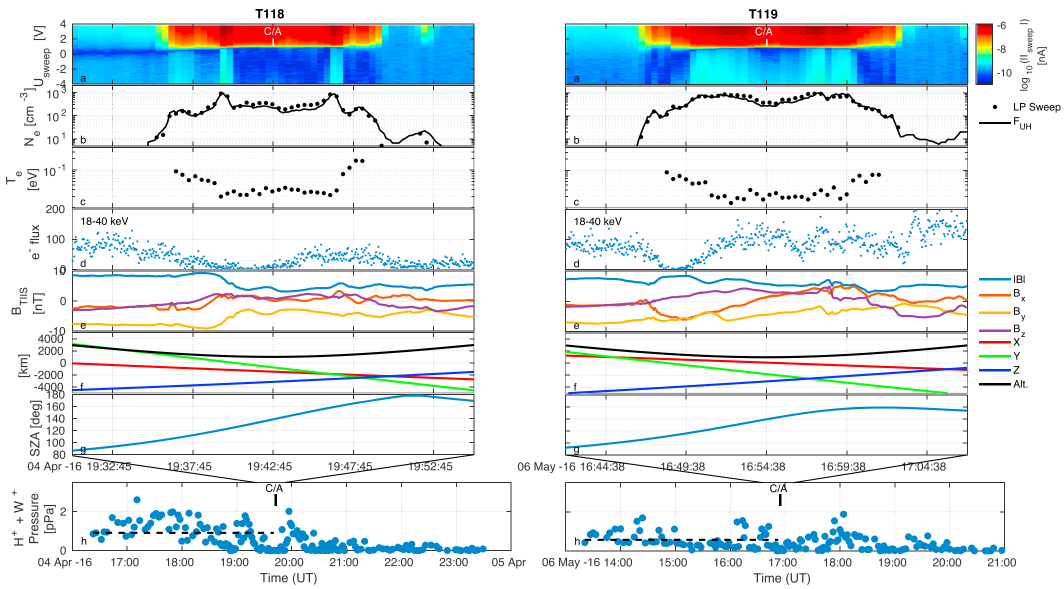

Figure 2. Time series of Cassini data from the (left) T118 flyby and the (right) T119 flyby, centered around C/A. The panels show (a) LP sweeps, (b) electron density derived from the sweeps together with the electron density estimated from the F_{UH}, (c) electron temperature from the sweeps and restricted to when the electron density is above 100 cm^{-3} (i.e., when the measurements are more reliable), (d) energetic electron fluxes in units of cm^{-2}·keV^{-1}·sr^{-1}·s^{-1}, (e) magnetic field magnitude and components in the TIIS coordinate system, (f) Cassini's position vector in TIIS as well as altitude, (g) SZA of Cassini, and (h) in a longer time interval, the ambient high energy particle pressure as measured by MIMI/CHEMS. The dashed lines indicate the mean pressure during the inbound legs. C/A = closest approach; LP = Langmuir Probe; TIIS = Titan interaction coordinate system; SZA = solar zenith angle; MIMI/CHEMS = Magnetosphere Imaging Instrument/Charge Energy Mass Spectrometer.

However interesting this coinciding dip may appear, we should state that it could simply be a coincidence arising in an otherwise dynamic ionosphere.

Also shown in Figure 3, with gray lines, are the electron density altitude profiles obtained from all of the other Cassini passes through Titan's ionosphere, for comparison. Looking at all of these profiles, there is a natural large variability in the ionospheric density spanning more than an order of magnitude for a given altitude. However, all of these profiles are gathered at a wide range of positions around Titan, at different SLT, at

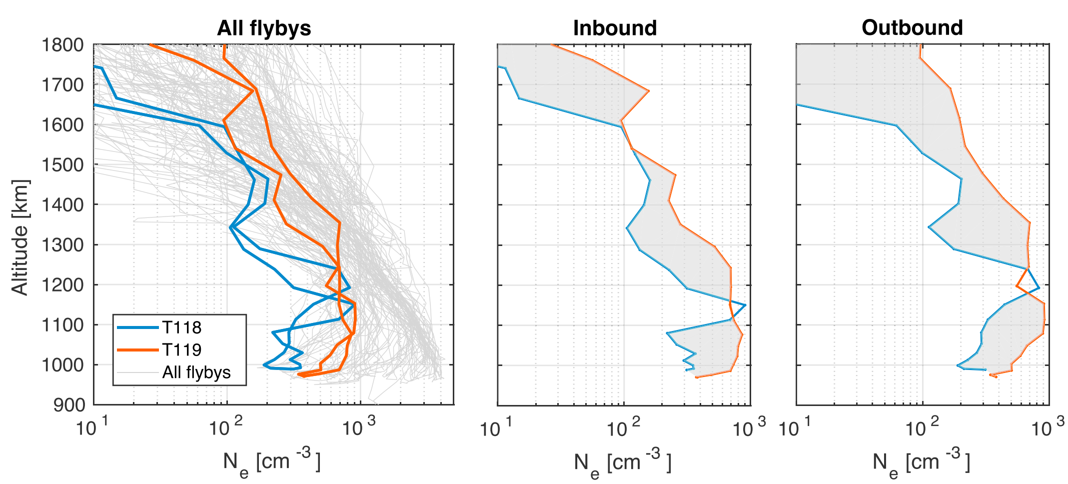

Figure 3. (left) Altitude profiles of the electron density in Titan's ionosphere as measured by the Radio and Plasma Waves System/Langmuir Probe during the T118 (blue) and the T119 (red) flybys. The gray thin lines show the electron density altitude profiles from all of Cassini's passes through Titan's ionosphere. (middle and right) The same altitude profiles again but separated into inbound and outbound leg. The gray shaded area indicates the region of large density difference between the two passes. The measurement error in density is around 10% for values over 100 cm^{-3}.

different phases of the solar cycle and during different ambient plasma conditions, which all affect the ionospheric structure of Titan (Edberg et al., 2015). What is intriguing during T118 and T119 is that all of these factors are more or less the same during the two passes: both are nightside passes, the SLT is 02 hr, the ambient conditions in Saturn's magnetosphere were typical of the northern magnetospheric lobe, although with stronger magnetic field fluctuations during T118, according to MAG data presented by Kabanovic et al. (2017). The EUV levels as observed by the Solar Dynamic Observatory/Extreme Ultraviolet Variability Experiment were similar, and no large flare was observed from space observatories. The most pronounced differences in ambient conditions between the two flybys are seen in the B_x component and the energetic particle data.

Another striking feature during T118 is that the measured electron density is very low for large parts of the ionosphere compared to all other profiles. For some altitude ranges, at about 1,200–1,350 and 1,000–1,100 km, the electron density measured during T118 were the lowest ever reported from Cassini at those altitude ranges, while the density measured during T119 seems rather normal compared to all the other profiles. The middle and right panels of Figure 3 show the data split up into inbound and outbound legs, which illustrates that the observed difference in density is present at roughly the same altitude ranges both during the inbound leg, which occurred close to the day/night terminator of the moon, as well as during the outbound leg, which occurred further in toward the nightside of the moon. At C/A, at an altitude of about 980 km, the densities seem to converge to similar values for the two flybys.

3. Discussion

In summary, the observations on the ionospheric electron density during T118 and T119 show that (i) there is an overall large difference in density between the two flybys, (ii) the density difference is present both during the inbound legs and during the outbound legs, (iii) the density during T118 was unusually low compared to all other flybys, (iv) around 1,150 and 1,200 km on the nightside of Titan two distinct electron density peaks appear in the T118 data. The altitude of these peaks changes from inbound to outbound leg, and their magnitudes are large enough to make the density comparable again between T118 and T119. These peaks are separate from the ionospheric peak created by photoionization on the dayside.

These features are important to report on since they highlight the variability of Titan's ionosphere and how that is a result of several different time-dependent physical and chemical processes at play. These all need to be taken into account in order to understand the observations. The reported difference in density between T118 and T119 is unexpectedly large given the similar trajectories; the presence of the two distinct peaks is a unique feature from the T118 flyby, to the best of our knowledge, and should, together with the overall difference between T118 and T119, stimulate interest in the community to try to model these features. Next, we will discuss possible explanations for these observations.

The fact that the electron density was unusually low during T118 means that the ionization rate was unusually low, that there was no transport of plasma to that region, that the recombination rate was increased, that significant ion outflow has occurred, that the neutral density was lower than normal, or some combination of the above.

Since most of the measurements presented in this paper were taken in Titan's nightside ionosphere, or at least at a SZA $> 90°$, the main ionization source that is at play is particle impact ionization, together with transport of plasma. The SZA could still have some effect on the electron density such that when the SZA increases, the density should decrease. The SZA profile during T118 does go up to higher values (above 160°) than during T119 on the outbound leg. However, during the inbound leg the SZA profiles are very similar and only differ by a few degrees. If we look at the flybys individually, the electron profiles are very similar on the inbound leg compared to the outbound leg, which suggests that the SZA is not important here.

In case of photochemical equilibrium, the density is expected to scale with the square root of the production rate divided by the effective recombination coefficient, so a reduction of N_e by a dividing factor of 5 would require the ratio within the square root to be reduced by a dividing factor of 25 (see, e.g., Vigren et al., 2013, for a more careful estimation of this including the relation between electron temperature and recombination coefficient). The electron temperature, as measured by LP, is quite comparable between the flybys (down to the level of the accuracy of the instrument) and not able to cause a major difference in the recombination rate.

Neutral density measurements by the Ion and Neutral Mass Spectrometer (INMS) instrument (not shown) are complicated by a data gap during T119 from 1,350 to 1,900 km for some species. During the inbound leg (the outbound INMS data can be affected by wall effects in the instrument) the neutral density values are also quite comparable and the density during T118 is actually higher below 1,100 km for especially N_2.

We can also note that the ion density derived from the LP (not shown) is generally also showing the same kind of profiles as the electron density, and the LP measurements of negative ions (Shebanits et al., 2013, 2016) do not show any distinct increases when the electron density decreases to abnormally low values during T118. This rules out any effect of dust, which could otherwise cause a depletion of free electrons as the charges attach to the dust. The possibility exists that low mass negative ions are present as discussed by Desai et al. (2017), but as we cannot confirm their presence nor determine their importance at this instance we leave that as an open issue. So neither the orbit, the electron temperature, the presence of heavy ions/dust, nor the neutral density background can explain the electron density difference between T118 and T119.

The ambient conditions during T118 were classified as northern lobe (the same as during T119) but with some higher fluctuations in the magnetic field (Kabanovic et al., 2017). These fluctuations could be indicative of Saturn's magnetospheric current sheet flapping past Titan during T118. The current sheet is typically filled with higher-density plasma compared to the lobes, which could introduce additional particle impact ionization in Titan's ionosphere. But since the measured energetic electron flux during T118 was in fact lower than during T119 (Figure 2d), which is the opposite from what is expected from sheet encounters, it seems like Titan was not located in the sheet during the T118 encounter. If we assume that the lower-energy (suprathermal) electron flux, capable of ionizing in the ionosphere, changes similarly as the high-energy electron flux and decreases during T118, then these observations give one plausible explanation for the low density during T118—the low electron flux leading to reduced impact ionization.

Furthermore, the orientation of the ambient magnetic field is very similar during both flybys with roughly $\mathbf{B} = [-2, -7, -2]$ nT (in TIIS) during the inbound leg and similar values during the outbound leg (see Figure 2e). Within Titan's ionosphere, the draping pattern is also similar for the two flybys but with some differences in especially the B_x component before C/A. A different draping pattern could mean that precipitating magnetospheric electrons or ions provide different ionization patterns in Titan's ionosphere (Regoli et al., 2016; Snowden & Yelle, 2014; Snowden, Yelle, Galand, et al., 2013), which would result in Cassini observing different densities along its path. However, how much of a difference in observed density along Cassini's path this would actually mean is difficult to estimate. Modeling this will be a challenge since the measured ambient magnetic conditions that are used as input in the models are actually very similar during the two passes, before and after the flyby. One needs to allow the field to vary during the flyby in the models to see if any changing precipitation pattern could match the observations. It is in any case a possibility that the changing draping pattern contributes, to some extent, to the density difference observed.

The distinct peaks in density during T118 at 1,150 km on the inbound leg and at 1,200 km on the outbound leg are also intriguing. They suggest a very localized plasma production regime, with low production both above and below, or transport to this specific altitude. That the peaks are present during both the inbound and outbound legs suggests that the rise in electron density is not associated with a sporadic increase in the flux of precipitating magnetospheric particles but rather that the peaks are present for at least the $\sim$ 7 min it takes from the inbound crossing to the outbound crossing. If the peaks are caused by particle impact ionization, which is a likely source in the nightside ionosphere, then it would require quite a monoenergetic beam to be able to deposit energy in such a narrow altitude range. The fact the electron density is quite comparable between the two flybys at the location of the peaks could be interpreted as the ionosphere being shielded from impact ionization outside of these peaks during T118 and that the precipitation briefly returns again during the peaks. We note again that B_x was different between the two flybys and this together with a change in trajectory could have an influence on the precipitation pattern of impact ionizing particles. Only a small change of 10–20° in geographic coordinates of the trajectory of Cassini could cause a $\sim$20% difference in precipitating ions (Regoli et al., 2018). This effect could contribute to explain the observed peaks and density difference. We also note as a point of interest that there appears to be current sheets associated with the high density peaks, both inbound and outbound. The B_x component clearly changes sign at the outer edges of the peaks by going from negative to positive on the inbound leg and in the opposite sense outbound.

Neutral density wave structures are observed in the INMS data during these flybys (not shown), which could also affect the plasma density. The vertical extent ($\sim$100 km) of the two distinct peaks in electron density during T118 are of typical wavelength for neutral waves (Cui et al., 2014; Müller-Wodarg et al., 2006). Also, the fact that the magnetospheric ram direction and the direction to the Sun are separated for these flybys (at 02 hr SLT) could result in the neutral wind direction and the magnetic forcing direction being quite different and lead to flow shear and/or stagnation layers around an altitude of ~1,300 km (Cravens et al., 2010). Above ~1,300 km transport is becoming increasingly important. Such stagnation points could possibly locally increase the electron density and is one possible, yet speculative, cause of the density peaks at 1,150 and 1,200 km.

We stated above that the ambient Saturn magnetospheric conditions were similar during the two flybys, according to MAG data. However, one measured difference was that the energetic particle pressure was about 36% higher during the inbound leg of T118 compared to the inbound leg of T119 (0.88 vs. 0.56 pPa), as shown in Figure 2h. The pressure during T118 inbound was also higher than during the outbound legs. This could possibly account for causing the larger gradient in the electron density observed in the topside ionosphere during T118, as the higher pressure compresses the ionospheric plasma. We note that the magnetic pressure and the thermal pressure are of the order of 1–10 pPa (Cravens et al., 2010). However, further down in the ionosphere, below the steep density gradient at about 1,600–1,700 km, the density during T118 is lower than during T119, which is somewhat counterintuitive: if the ionospheric plasma is compressed then the density should be increased—but this does not seem to be the case here. It could still be that the higher pressure causes more dynamics to the ionosphere and affect the transport of plasma and which would result in variable altitude profiles, as is seen during T118.

Finally, in this paper we have rather extensively discussed the difference between two particular flybys. But how does this pair of flybys compare to other pairs, or series, of flybys with similar geometry? We can briefly mention that T18-T19, T41-T42, T64-T65, and T120-T121 were sets of passes with C/A near the terminator or on the dayside and where differences less than a factor of 4 in the density profiles were observed, while during T70-T71 and T55-T59 no significant or only smaller differences in electron density were observed in the ionosphere as a whole. Therefore, it is not uncommon to observe large differences in electron density altitude profiles as reported during T118 and T119, even though the flyby geometry is similar. What is striking with T118 and T119 is that the difference in density between the two passes is so large, and that there are apparently lots of dynamical effects causing the variable profile in electron density during T118.

4. Conclusions

There is a large difference in electron density between T118 and T119, even though the flyby geometry was similar. The difference is primarily due to an unusually low density during T118 but which cause is not easily explained from our limited data set. Ruling out factors such as flyby geometry and SZA angle, effects of dust, recombination rates, and neutral density differences (but note that gravity waves are in fact present) and since the flybys were nightside passes, we can suggest that suppressed ionization from particle impacts (which is the main source of ionization on the nightside), perhaps due to a less favorable magnetic field draping pattern, is the cause of the low density during T118 and the density difference between T118 and T119. The high energy electron flux was also lower during T118 compared to T119, supporting this idea. Whether or not the lower-energy particles and their precipitating flux show a similar trend as the higher-energy electrons is not clear since, unfortunately, no measurements of lower-energy (~ 1 keV) particles were available for these flybys. We can also speculate on the fact that the dynamics in the ionosphere is increased during T118 due to the higher ambient energetic plasma pressure and the presence of neutral density gravity waves. This could perturb the transport of plasma in the ionosphere and could be partly responsible for the two distinct peaks in electron density during T118.

We conclude by stating that unusual variability is observed in Titan ionosphere during the T118 and T119 Cassini flybys, and we leave it for our colleagues in the community to try to model and reproduce these observations, including the effects of varying impact ionization, gravity waves, and ambient pressure changes.

Acknowledgments
The data from Cassini at Titan used in this work are available on the NASA PDS: https://pds-atmospheres.edu/data_and_services/atmospheres_data/Cassini/titan.html. E. V. and D. J. A. are grateful for funding from the Swedish National Space Board (Dnr 14/166 and 162/14). J. C. is supported by the National Science Foundation of China through grants 41525015 and 41774186. L. H. R.'s contribution was supported by a NASA Living With a Star grant (NNX16AL12G). N. J. T. E. acknowledges support from the Swedish National Space Board (Dnr 135/13) and The Swedish Research Council/Vetenskapsrådet (621-2013-4191).

References

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

Ågren, K., Wahlund, J.-E., Modolo, R., Lummerzheim, D., Galand, M., Müller-Wodarg, I., et al. (2007). On magnetospheric electron impact ionisation and dynamics in Titan's ram-side and polar ionosphere—A Cassini case study. *Annales de Geophysique*, *25*, 2359–2369.

Bird, M. K., Dutta-Roy, R., Asmar, S. W., & Rebold, T. A. (1997). Detection of Titan's ionosphere from Voyager 1 radio occultation observations. *Icarus*, *130*, 426–436. https://doi.org/10.1006/icar.1997.5831

Cravens, T. E., Richard, M., Ma, Y.-J., Bertucci, C., Luhmann, J. G., Ledvina, S., et al. (2010). Dynamical and magnetic field time constants for Titan's ionosphere: Empirical estimates and comparisons with Venus. *Journal of Geophysical Research*, *115*, A08319. https://doi.org/10.1029/2009JA015050

Cravens, T. E., Robertson, I. P., Ledvina, S. A., Mitchell, D., Krimigis, S. M., & Waite, J. H. (2008). Energetic ion precipitation at Titan. *Geophysical Research Letters*, *35*, L03103. https://doi.org/10.1029/2007GL032451

Cui, J., Galand, M., Yelle, R. V., Vuitton, V., Wahlund, J.-E., Lavvas, P. P., et al. (2009). Diurnal variations of Titan's ionosphere. *Journal of Geophysical Research*, *114*, A06310. https://doi.org/10.1029/2009JA014228

Cui, J., Galand, M., Yelle, R. V., Wahlund, J., Ågren, K., Waite, J. H., & Dougherty, M. K. (2010). Ion transport in Titan's upper atmosphere. *Journal of Geophysical Research*, *115*, A06314. https://doi.org/10.1029/2009JA014563

Cui, J., Yelle, R. V., Li, T., Snowden, D. S., & Müller-Wodarg, I. C. F. (2014). Density waves in Titan's upper atmosphere. *Journal of Geophysical Research: Space Physics*, *119*, 490–518. https://doi.org/10.1002/2013JA019113

Desai, R. T., Coates, A. J., Wellbrock, A., Vuitton, V., Crary, F. J., Gonzalez-Caniulef, D., et al. (2017). Carbon chain anions and the growth of complex organic molecules in Titan's ionosphere. *The Astrophysical Journal Letters*, *844*(2), L18.

Dougherty, M. K., Kellock, S., Southwood, D. J., Balogh, A., Smith, E. J., Tsurutani, B. T., et al. (2004). The Cassini magnetic field investigation. *Space Science Reviews*, *114*, 331–383. https://doi.org/10.1007/s11214-004-1432-2

Edberg, N. J. T., Ågren, K., Wahlund, J.-E., Morooka, M. W., Andrews, D. J., Cowley, S. W. H., et al. (2011). Structured ionospheric outflow during the Cassini T55–T59 Titan flybys. *Planetary and Space Science*, *59*, 788–797. https://doi.org/10.1016/j.pss.2011.03.007

Edberg, N. J. T., Andrews, D. J., Bertucci, C., Gurnett, D. A., Holmberg, M. K. G., Jackman, C. M., et al. (2015). Effects of Saturn's magnetospheric dynamics on Titan's ionosphere. *Journal of Geophysical Research: Space Physics*, *120*, 8884–8898. https://doi.org/10.1002/2015JA021373

Edberg, N. J. T., Andrews, D. J., Shebanits, O., Ögren, K., Wahlund, J.-E., Opgenoorth, H. J., et al. (2013). Extreme densities in Titan's ionosphere during the T85 magnetosheath encounter. *Geophysical Research Letters*, *40*, 2879–2883. https://doi.org/10.1002/grl.50579

Galand, M., Yelle, R., Cui, J., Wahlund, J., Vuitton, V., Wellbrock, A., & Coates, A. (2010). Ionization sources in Titan's deep ionosphere. *journal of Geophysical Research*, *115*, A07312. https://doi.org/10.1029/2009JA015100

Garnier, P., Dandouras, I., Toublanc, D., Roelof, E., Brandt, P., Mitchell, D., et al. (2010). Statistical analysis of the energetic ion and ENA data for the Titan environment. *Planetary and Space Science*, *58*(14), 1811–1822. https://doi.org/10.1016/j.pss.2010.08.009

Gurnett, D. A., Kurth, W. S., Kirchner, D. L., Hospodarsky, G. B., Averkamp, T. F., Zarka, P., et al. (2004). The Cassini radio and plasma wave investigation. *Space Science Reviews*, *114*, 395–463. https://doi.org/10.1007/s11214-004-1434-0

Kabanovic, S., Simon, S., Neubauer, F. M., & Meeks, Z. (2017). An empirical model of Titan's magnetic environment during the Cassini era: Evidence for seasonal variability. *Journal of Geophysical Research: Space Physics*, *122*, 11,076–11,085. https://doi.org/10.1002/2017JA024402

Krimigis, S. M., Mitchell, D. G., Hamilton, D. C., Livi, S., Dandouras, J., Jaskulek, S., et al. (2004). Magnetosphere imaging instrument (MIMI) on the Cassini mission to Saturn/Titan. *Space Science Reviews*, *114*, 233–329. https://doi.org/10.1007/s11214-004-1410-8

Luhmann, J., Ulusen, D., Ledvina, S., Mandt, K., Magee, B., Waite, J., et al. (2012). Investigating magnetospheric interaction effects on Titan's ionosphere with the Cassini orbiter ion neutral mass spectrometer, Langmuir probe and magnetometer observations during targeted flybys. *Icarus*, *219*(2), 534–555. https://doi.org/10.1016/j.icarus.2012.03.015

Madanian, H., Cravens, T. E., Richard, M. S., Waite, J. H., Edberg, N. J. T., Westlake, J. H., & Wahlund, J.-E. (2016). Solar cycle variations in ion composition in the dayside ionosphere of Titan. *Journal of Geophysical Research: Space Physics*, *121*, 8013–8037. https://doi.org/10.1002/2015JA022274

Müller-Wodarg, I. C. F., Yelle, R. V., Borggren, N., & Waite, J. H. (2006). Waves and horizontal structures in Titan's thermosphere. *Journal of Geophysical Research: Space Physics*, *111*, A12315. https://doi.org/10.1029/2006JA011961

Regoli, L. H., Roussos, E., Dialynas, K., Luhmann, J. G., Sergis, N., Jia, X., et al. (2018). Statistical study of the energetic proton environment at Titan's orbit from the Cassini spacecraft. *Journal of Geophysical Research: Space Physics*, *123*, 4820–4834. https://doi.org/10.1029/2018JA025442

Regoli, L., Roussos, E., Feyerabend, M., Jones, G., Krupp, N., Coates, A., et al. (2016). Access of energetic particles to Titan's exobase: A study of Cassini's T9 flyby. *Planetary and Space Science*, *130*, 40–53. https://doi.org/10.1016/j.pss.2015.11.013

Sergis, N., Krimigis, S. M., Mitchell, D. G., Hamilton, D. C., Krupp, N., Mauk, B. H., et al. (2009). Energetic particle pressure in Saturn's magnetosphere measured with the magnetospheric imaging instrument on Cassini. *Journal of Geophysical Research*, *114*, A02214. https://doi.org/10.1029/2008JA013774

Shebanits, O., Vigren, E., Wahlund, J.-E., Holmberg, M. K. G., Morooka, M., Edberg, N. J. T., et al. (2017). Titan's ionosphere: A survey of solar EUV influences. *Journal of Geophysical Research: Space Physics*, *122*(7), 7491–7503. https://doi.org/10.1002/2017JA023987

Shebanits, O., Wahlund, J.-E., Edberg, N. J. T., Crary, F. J., Wellbrock, A., Andrews, D. J., et al. (2016). Ion and aerosol precursor densities in Titan's ionosphere: A multi-instrument case study. *Journal of Geophysical Research: Space Physics*, *121*, 10,075–10,090. https://doi.org/10.1002/2016JA022980

Shebanits, O., Wahlund, J.-E., Mandt, K., Ågren, K., Edberg, N. J. T., & Waite, J. Jr. (2013). Negative ion densities in the ionosphere of Titan–Cassini RPWS/LP results. *Planetary and Space Science*, *84*, 153–162.

Snowden, D., & Yelle, R. (2014). The thermal structure of Titan's upper atmosphere, II: Energetics. *Icarus*, *228*(0), 64–77. https://doi.org/10.1016/j.icarus.2013.08.027

Snowden, D., Yelle, R., Cui, J., Wahlund, J.-E., Edberg, N. J. T., & Ågren, K. (2013). The thermal structure of Titan's upper atmosphere, I: Temperature profiles from Cassini INMS observations. *Icarus*, *226*(1), 552–582.

Snowden, D., Yelle, R., Galand, M., Coates, A., Wellbrock, A., Jones, G., & Lavvas, P. (2013). Auroral electron precipitation and flux tube erosion in Titan's upper atmosphere. *Icarus*, *226*(1), 186–204. https://doi.org/10.1016/j.icarus.2013.05.021

Vigren, E., Galand, M., Wellbrock, A., Coates, A. J., Cui, J., Edberg, N. J. T., et al. (2016). Suprathermal electrons in Titan's sunlit ionosphere: Model-observation comparisons. *The Astrophysical Journal*, *826*(2), 131.

Vigren, E., Galand, M., Yelle, R. V., Cui, J., Wahlund, J.-E., Ågren, K., et al. (2013). On the thermal electron balance in Titan's sunlit upper atmosphere. *Icarus*, *223*, 234–251. https://doi.org/10.1016/j.icarus.2012.12.010

Vigren, E., Galand, M., Yelle, R., Wellbrock, A., Coates, A., Snowden, D., et al. (2015). Ionization balance in Titan's nightside ionosphere. *Icarus*, *248*, 539–546. https://doi.org/10.1016/j.icarus.2014.11.012

Wahlund, J.-E., Boström, R., Gustafsson, G., Gurnett, D. A., Kurth, W. S., Pedersen, A., et al. (2005). Cassini measurements of cold plasma in the ionosphere of Titan. *Science*, *308*, 986–989. https://doi.org/10.1126/science.1109807

Young, D. T., Berthelier, J. J., Blanc, M., Burch, J. L., Coates, A. J., Goldstein, R., et al. (2004). Cassini plasma spectrometer investigation. *Space Science Reviews*, *114*, 1–112. https://doi.org/10.1007/s11214-004-1406-4