On the ionospheric structure of Titan

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ABSTRACT

In this study we present data from 17 Titan flybys showing that solar photons are the main ionisation source of Titan’s dayside atmosphere. This is the first comprehensive study of Solar Zenith Angle (SZA) dependence of the electron number density and electron temperature at the ionospheric peak. The results show on average four times more plasma on the dayside compared to the nightside, with typical dayside electron densities of around 2500–3500 cm$^{-3}$ and corresponding nightside densities of around 400–1000 cm$^{-3}$. We identify a broad transition region between SZA 50° and 100°, where the ionosphere of Titan changes from being entirely sunlit to being in the shadow of the moon. For SZA < 50° the ionisation peak altitude increases with increasing SZA, whereas the transition region and the nightside show more scattered ionospheric peak altitudes. Typical electron temperatures at the ionospheric peak are 0.03–0.06 eV (≈ 350–700 K) for both dayside and nightside.

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1. Introduction

The Cassini spacecraft has been orbiting Saturn since 2004 and one of the principal objectives of the spacecraft is to perform several close flybys and conduct measurements of the plasma environment near Titan, the largest satellite of Saturn. The first spacecraft measurements of Titan were carried out in November 1980 when the Voyager 1 spacecraft crossed the plasma wake of the moon. Evidence of an induced bipolar magnetic tail was clearly identified (Ness et al., 1982). The partial ionisation of the neutral atmosphere creates a dense and cold ionosphere which acts as an obstacle towards the Kronian plasma flow. This conductive obstacle modifies the plasma flow and twists the magnetic field lines around the body, since the magnetic field lines diffuse slowly through the conductive ionosphere of Titan. In addition to this, shielding currents are set up that oppose the original flow. The plasma wave instrument on Voyager 1 detected several types of plasma wave emissions, such as the upper hybrid resonance emissions. From these measurements it was shown that a dense plume of plasma was flowing downstream of Titan (Gurnett et al., 1982). Furthermore, the Voyager 1 radio occultation experiment measured the electron density column content of Titan’s ionosphere and inferred a peak density of 2400 cm$^{-3}$ at an altitude of 1175 km (Bird et al., 1997). The first in situ measurements of Titan’s ionosphere were conducted in October 2004, when the Cassini spacecraft made its first close flyby of the moon and plasma densities up to 3000 cm$^{-3}$ were encountered on the dayside (Wahlund et al., 2005).

Since Cassini’s arrival at Saturn our knowledge about the planet and its moons has significantly increased. More than 40 Titan flybys have been carried out to-date and the thermosphere/exosphere and ionosphere as well as the moon’s interaction with Saturn have been studied in detail.

Titan features the most compositionally complex ionosphere in the Solar System with more than 50 ions contributing to create molecules and aerosols (Vuitton et al., 2007). The principal components of Titan’s atmosphere are N$_2$ and a few percent of CH$_4$. Measurements by the Cassini Ion and Neutral Mass Spectrometer (INMS) showed molecular hydrogen, argon and a host of stable carbon-nitrile compounds, which leads to the conclusion that Titan hosts an intricate organic chemistry in the upper atmosphere (Waite et al., 2005). Results from the Cassini radio occultation experiment found main ionospheric peaks near 1200 km with a density of a few thousand cm$^{-3}$ (Kliore et al., 2008). Moreover, Waite et al. (2007) obtained evidence for the formation of organic aerosols from simple molecules, which is shown to occur in the upper atmosphere, at altitudes around 1000 km. Another recent discovery in the ionosphere of Titan is the existence of heavy, negative ions that contribute to the complex chemistry (Coates et al., 2007). There are at least five sources that help to produce the ionosphere of Titan. Ionisation by cosmic rays, meteors and energetic ions are shown to be of high importance in the lower...
discussed the relative contribution of solar radiation versus plasma detected on the nightside, which was confirmed by that ionisation by magnetospheric electrons can account for the plasma detected on the nightside, which was confirmed by Cravens et al. (2008b). In a previous paper Cravens et al. (2005) discussed the relative contribution of solar radiation versus magnetospheric input and came to the conclusion that ionisation from solar photons contributes about \( \frac{1}{2} \) of the total ionisation for a Solar Zenith Angle (SZA) of \( \approx 80^\circ \). In this study Radio and Plasma Wave Science (RPWS) Langmuir Probe (LP) data are used to show that solar radiation is the dominant ionisation source on Titan’s dayside. The results suggest that the electron density on the dayside is on average about four times higher than the nightside density.

Prior to Cassini, no measurements of the electron temperature in Titan’s ionosphere had been conducted. However, model estimates were published that predicted a nearly constant electron temperature at the ionospheric peak of 800–1000 K, see Roboz and Nagy (1994). The RPWS/LP allows accurate estimate of this parameter. The electron temperature is dependent on e.g. electron–neutral collisions, photoelectron production in the atmosphere, ionisation sources and the magnetic field configuration. Combining model calculations with Cassini multi-instrumental dataset, Galand et al. (2006) assessed the electron energy budget in Titan’s ionosphere. They showed that the configuration of the magnetic field in Titan’s upper atmosphere determined the electron temperature during the TA flyby. In this study we show that the electron temperature remains fairly constant at the ionospheric peak, independent of the altitude and the maximum number density of this peak.

### 2. RPWS measurements

In this study we use measurements from the RPWS instrument package onboard Cassini. The RPWS consists of three electric field sensors, three magnetic field sensors, a spherical Langmuir Probe and high, medium and Wideband Receivers (WBR) for processing the data. This study is primarily based on the LP measurements, but the upper hybrid line, \( f_{\text{OH}} \), as obtained by the WBR is at times used to confirm the measurements, as the WBR and the LP provide two independent ways to estimate the electron number density, \( n_e \), when operated in Titan’s ionosphere.

The LP can be operated in two modes; sweep and continuous. In the sweep mode, the bias voltage sweeps are most often in the range from \(-4 \) to \(+4 \) V. The LP sweeps used in this study are carried out every 24 s. The total current is sampled in the vicinity of the spacecraft. The analysis of sweep data is based on a two-electron and one drifting ion component Orbit Motion Limited (OML) theory (Mott-Smith and Langmuir, 1926; Medicus, 1962; Fahleson et al., 1974). The analysis of the current–voltage curves gives estimates of several plasma parameters. For this study, the electron number density, \( n_e \), and electron temperature, \( T_e \), are of prime interest.

The total current principally consists of three components; the ion current, the electron current and the photoelectron current. In addition, currents by energetic ions and electrons and dust particles may give minor contributions but will not be included in this discussion. For a positive bias voltage, the electron current is dominant and gives a linear contribution according to

\[
I_e = Io(T_e) = Io(T_e)(1 - e^{-\frac{U_{\text{bias}}}{k_B T_e}}).
\]

\[
Io(T_e) = \frac{A \phi \sqrt{k_B T_e}}{2 \pi m_e}
\]

where \( A \phi \) is the area of the LP, \( q_e \) is the electron charge, \( k_B \) is the Boltzmann constant and \( m_e \) is the electron mass. \( \chi_e \) is given by

\[
\chi_e = \frac{q_e (U_{\text{bias}} + U_{SC})}{k_B T_e}
\]

where \( U_{\text{bias}} \) is the bias potential and \( U_{SC} \) is the spacecraft potential. As given by Eqs. (1)–(3) a fit to the sweep data will give estimations of \( n_e \), \( T_e \) and \( U_{SC} \), as the other parameters are given. Fig. 1 shows an example of a typical current–voltage characteristic curve with a superposed OML fit obtained during the T18 flyby. The uppermost panel shows the linear fit to the current, the middle panel the logarithmic fit and the bottom panel represents the first derivative of the current, \( dI_{\text{probe}}/dU \). Variations in the non-linear least square fit to the sweep voltage–current characteristics do not allow an error in the ionosphere of more than 10% in the electron density parameter and 20% in the electron temperature parameter. By using equations valid for negative bias voltage, numerous ion parameters can be derived, such as ion temperature, ion density, ion mass and ion velocity (see e.g. Whipple, 1965; Fahleson et al., 1974). However, the theory behind it will not be discussed here.

In the continuous 20 Hz mode, the electron current is sampled at a constant bias voltage (\( \approx +4 \) V) with 20 samples per second, which is proportional to

\[
\sqrt{T_e n_e} = \sqrt{1 + \frac{T_e}{T_e} (U_{SC} + U_{\text{bias}})}.
\]

By assuming that the highest electron density obtained in the continuous mode is equal to the maximum density found in the sweep mode, the high resolution data can be used to obtain information about small scale structures that the sweep data cannot show. The results presented here are based on a combination of these data sets. WBR estimates the plasma density by determining the upper hybrid emission line, which is an electrostatic resonance that occurs at

\[
f_{\text{OH}} = f_{\text{Pe}}^2 + f_{\text{Ge}}^2
\]

where

\[
f_{\text{Pe}} = \frac{1}{2 \pi \sqrt{\frac{n_e e^2}{e_0 M_e}}}
\]

is the electron plasma frequency and \( f_{\text{Ge}} \) is the electron gyro frequency (Stix, 1962). For the Titan flybys \( f_{\text{Pe}} > f_{\text{Ge}} \), which simplifies Eq. (5) into

\[
f_{\text{OH}} \approx f_{\text{Pe}}
\]

from which the electron density can be derived. However, for most deep Titan flybys the upper hybrid emission line in the ionosphere is not easily detected, and for others two plasma lines are found. This limits the usefulness of data from the receivers to confirm LP measurements. For a more detailed description of the RPWS instrument package, see Gurnett et al. (2004).

### 3. Flyby configurations

This study is based on the inbound and outbound passes of 17 flybys that occurred at different locations around Titan and for
varying solar illumination conditions. Only flybys with a closest approach (C/A) below 1200 km have been included in the study. Fig. 2 shows the configurations of the flybys in terms of SZA, Titan Local Time (TLT) and Saturn Local Time (SLT). The flybys are numbered from “T16” up to “T42”, according to the Cassini project terminology. The inbound leg is marked with the flyby number and the circle represents the C/A. This study focuses on three distinct groups, each one occurring at similar SLT: around 2, 11 and 14, respectively. For every SLT a wide range of SZA are covered, which will lead to varying results also at a given SLT. Altogether, the C/A are ranging from SZA 20–165°. Beside SLT and SZA, the ionisation is expected to depend on the ram direction. This will be discussed in the next section.

4. Results

Fig. 3 shows all the sweep derived electron density altitude profiles used in this study. When examining the profiles individually, three common regions can be distinguished, although variations can be large between flybys. The lowest region is the ionosphere surrounding the primary plasma density peak. At altitudes above \( \approx 1200 \) km in the topside or exo-ionosphere (Ágren et al., 2007), the influence of Saturn’s magnetospheric conditions becomes important, with large variations in the plasma density. From being relatively steady in the deep ionosphere, the plasma density starts to exponentially decrease with increasing altitude. The starting altitude for this
rather steady electron density around 2500–3500 cm$^{-3}$/C14 for SZA 50–100°. Continuous data are not corrected for T$_e$ range, rather than an error in the data itself. Note that the 20 Hz determination is therefore reflecting the possible variation in T$_e$ and possibly electric convection, making it very difficult to fit theoretical curves, like a Chapman profile, to the data. Instead, we have combined sweep data and high resolution data in order to individually determine the altitude extent and magnitude of the electron number density near the ionospheric peak. Furthermore, the electron temperature is determined for each profile by deriving the temperature at the altitude of the ionospheric peak. In this transition region the ionosphere of Titan changes from being totally sunlit to being in the shadow of the moon. This region is extended beyond SZA 90° as a result of Titan’s extended atmosphere (see Müller-Wodarg et al., 2000). The behaviour of the electron density for SZA 0–100° shows the importance of solar EUV ionisation in this region. The shadow side of Titan covers a region of SZA 100–180° and shows a rather constant electron density level. This could be a result of magnetospheric influence or convection of plasma from the dayside.

Fig. 7 shows the electron peak altitudes as a function of SZA. For the dayside ionosphere the ionospheric peak is found in a region between 950 km and 1250 km, whereas in the nightside ionosphere the peak altitude can vary vastly from 900 to 1400 km. However, as discussed above, this is partly a result of the extended peaks of the nightside profiles, and partly due to plasma dynamics. Comparing the peak altitudes at low SZA with those exponential decrease differs between flybys and can vary between 1100 and 1500 km. The large variation of the topside ionosphere suggests that the surroundings of Titan are very dynamic. Further away from Titan, at distances ranging from about 1800 km to 7R$_T$ (1R$_T$ = 2575 km) a sharp drop in density down to magnetospheric values around $\sim$0.1 cm$^{-3}$ is found, indicating that the spacecraft has left Titan’s plasma surroundings. However, clear signatures of magnetospheric influence can at times be seen down to $\approx$1200 km.

By inspecting each altitude profile by eye, making sure that possible peak altitudes are definitely included, we have determined the altitude of the ionospheric peak and the electron number density at the peak with error bars. Variability of the peak profiles, obviously depending on temporal variations in ionisation rate and possibly electric convection, makes it very difficult to fit theoretical curves, like a Chapman profile, to the data. Instead, we have combined sweep data and high resolution data in order to individually determine the altitude extent and magnitude of the electron number density near the ionospheric peak. Furthermore, the electron temperature is determined for each profile by deriving the temperature at the altitude of the ionospheric peak.

Figs. 4 and 5 show the high resolution density profiles of flyby T39 and T18, respectively. The spikes are not real, but due to instrumental interference issues. T39 shows a smooth, Chapman-like profile and the ionisation peaks are easily identified. T18, on the other hand, shows an extended peak on the inbound, leading to large “error” bars. The “error” bars for peak altitude determination is therefore reflecting the possible variation in range, rather than an error in the data itself. Note that the 20 Hz continuous data are not corrected for T$_e$ and U$_SC$, which means that the magnitude and to some extent the altitude of the peak can deviate from the sweep derived values.

In Fig. 6, the electron number densities at the ionospheric peaks are plotted versus SZA. The figure can be divided into three regions: the sunlit region ranging from SZA 0° to around 50°. In this region a rather steady electron density around 2500–3500 cm$^{-3}$ can be seen. Between SZA 50–100°, the electron density decreases from its maximum values to minimum values of around 400–1000 cm$^{-3}$.
at high SZA, suggests that magnetospheric electrons on average ionise at a higher altitude than solar photons, which supports the study of Cravens et al. (2005). Nevertheless, as seen in Fig. 7, individual flybys show a large variation in altitude, especially on the nightside, which possibly reflects changes in energy of the ionisation source of Titan’s dayside atmosphere. This is consistent with the recognition of a transition region from SZA 50° to 100°, which is a direct result of Titan’s extended atmosphere and possible aerosol EUV extinction. On the dayside, the variation of peak altitude with SZA is strongest and becomes less clear when moving towards darkness. Towards the nightside, ionospheric density variation with altitude becomes more complex and shows no clear peak. One possible explanation for this is that the relative contribution of the magnetospheric impacting electrons to the solar photons becomes larger compared with solar photons. If so, this means that changes in the magnetospheric conditions become more prominent. T16 and T21 both have a peak at SZA ≈ 110°, but their peak altitudes vary from 1000 km to almost 1400 km (within the error bars). As they happen at more or less the same SLT, this suggests that the ionosphere of Titan can vary substantially, also at a given SLT and SZA. Investigations of the changes in SZA between lower and upper limits of the error bars have been conducted. We estimate a maximum change for the outbound leg of orbit T30 of ≈ 10°. All other flybys show less change.

Additionally, we have derived the electron temperatures at the ionospheric peaks. Fig. 8 shows the resulting temperatures as a function of SZA. The temperatures vary between 0.03 and 0.06 eV (≈ 350–700 K), i.e. within a factor of 2. However, they do not strongly depend on the SLT, which supports the theory by Galand et al. (2006) that, even though sensitive to ionisation sources, the electron temperature is strongly affected by the configuration of the magnetic field lines.

5. Discussion

This study of the peak ionospheric densities and altitudes of Titan’s ionosphere suggests that solar photons are the main ionisation source of Titan’s dayside atmosphere. This is consistent with the recognition of a transition region from SZA 50° to 100°, which is a direct result of Titan’s extended atmosphere and possible aerosol EUV extinction. On the dayside, the variation of peak altitude with SZA is strongest and becomes less clear when moving towards darkness. Towards the nightside, ionospheric density variation with altitude becomes more complex and shows no clear peak. One possible explanation for this is that the relative contribution of the magnetospheric impacting electrons to the solar photons becomes larger. However, a recent study by Cui et al. (2009) suggests that the chemical survival of ions produced on Titan’s dayside also plays a significant role for maintaining a substantial ionosphere on the nightside, especially for long-lived species.

Nevertheless, combining the results of electron density versus SZA and peak ionisation versus SZA indicates that ionisation by magnetospheric electrons is important for the ionospheric...
structure on the nightside. In the context of this study we have not attempted to assess in more detail the magnetospheric conditions during each of the flybys except for identifying the SLT of specific flybys. Magnetospheric conditions around Saturn are known to vary even at a given SLT (Morooka et al., 2009), so some of the unexpected behaviour seen for example during T23 might be a result of magnetospheric forcing. Another example is T21 with less impacting electrons from the magnetosphere that consequently shows the least density. This could possibly be the explanation to the difference in ionisation peak altitude between T16 and T21, which was discussed earlier, but further analysis is needed to determine this unambiguously.

Note that this study has been conducted with data taken during 17 flybys occurring at only three different SLT values, with two that are rather close; SLT 11 and 14. To better assess the influence of SLT on Titan’s ionosphere we need better sampling statistics. Furthermore, for flybys on the nightside of Titan, a study of ram direction could be valuable. However, measurements by Cassini have shown that the direction of the incident co-rotating plasma can differ largely from the ideal direction (e.g. Bertucci et al., 2007; Szego et al., 2007). Such investigations need to be undertaken in the future in order to possibly separate the contribution from magnetospheric impacting electrons to plasma transport. In this study we have focused on the influence of solar radiation.

6. Summary and conclusions

We have presented data for 17 Titan flybys, adding up to a total of 34 altitude profiles of Titan’s deep ionosphere. The flybys occurred at three different SLT, with C/A ranging from SZA 20° to 165°. The ionospheric peak altitude, electron number density and temperature have been studied as a function of SZA, showing that solar photons are the main ionisation source of Titan’s dayside atmosphere. Typical dayside electron densities were found to be around 2500–3500 cm⁻³, whereas nightside densities reached around 400–1000 cm⁻³. Between dayside and nightside, a transition region between SZA 50° and 100° was identified. The wide range of this region is due to Titan’s extended atmosphere, which permits solar ionisation to influence the plasma density at SZA beyond 90°. Both the dayside and the nightside show rather constant electron densities with some fluctuations, which may be explained by magnetospheric influence. The ionospheric peak altitudes were found to follow a clear trend up to SZA 50° showing increasing peak altitudes with increasing SZA. In the transition region and on the nightside, the ionospheric peak altitudes are more scattered, which again might be explained by magnetospheric electricfields and by the fact that the contribution of the magnetospheric impacting electrons becomes larger compared with solar photons. However, the latter explanation is only valid for the transition region and not on the nightside. The electron temperatures at the ionospheric peaks were found to be very stable around 0.03–0.06 eV (≈ 350–700 K). The fact that they do not depend on SZA is coherent with the theory that electron temperature is primarily driven by the magnetic field configuration (Galand et al., 2006). Our results show that the ionosphere of Titan can vary substantially, also at a given SLT and SZA, especially on the nightside. A comprehensive study of the magnetospheric conditions and ram direction of each flyby would shed more light on the issue.

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