Planetary and Space Science 57 (2009) 1821–1827

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

On the ionospheric structure of Titan

K. Ågren [a,b,*], J.-E. Wahlund [a], P. Garnier [a], R. Modolo [a], J. Cui [c], M. Galand [c], I. Müller-Wodarg [c]

[a] Swedish Institute of Space Physics, Box 537, SE-751 21 Uppsala, Sweden
[b] Department of Physics and Astronomy, Uppsala University, SE-751 20 Uppsala, Sweden
[c] Space and Atmospheric Physics Group, Imperial College London, Prince Consort Road, London SW7 2BW, UK

A R T I C L E I N F O

Article history:
Received 5 November 2008
Received in revised form
19 March 2009
Accepted 21 April 2009
Available online 5 May 2009

Keywords:
Titan
Ionospheric physics
Ionosphere–magnetosphere interaction
Cassini
SZA

A B S T R A C T

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 ($\approx$ 350–700 K) for both dayside and nightside.

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

* Corresponding author at: Swedish Institute of Space Physics, Box 537, SE-751 21 Uppsala, Sweden. Tel.: +46 18 4715930; fax: +46 18 4715905.
E-mail address: agren@irfu.se (K. Ågren).

0032-0633/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pss.2009.04.012

atmosphere (see e.g. Molina-Cuberos et al., 2001; Cravens et al., 2008a and references therein). Photoionisation by solar radiation, with associated photoelectron ionisation, and particle impact ionisation by Saturn's co-rotating magnetosphere, with associated secondary electron ionisation, are considered to be the two main processes by which the ionosphere is created (e.g. Cravens et al., 2005; Wahlund et al., 2005; Galand et al., 2006; Ågren et al., 2007). One open question regarding Titan is the relative contribution of the ionisation sources. Ågren et al. (2007) showed 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 $\frac{2}{3}$ 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_{UH}, 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

$$I_e = I_{e0}(1 - \chi_e). \quad (1)$$

I_{e0} is the electron current given by

$$I_{e0} = A_{LP} n_e q_e \sqrt{\frac{k_B T_e}{2\pi m_e}}, \quad (2)$$

where A_{LP} 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. χ_e is given by

$$\chi_e = \frac{q_e(U_{bias} + U_{SC})}{k_B T_e}, \quad (3)$$

where U_{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_{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

$$\sqrt{T_e} n_e \left(1 + \frac{1}{T_e}(U_{SC} + U_{bias})\right). \quad (4)$$

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

$$f_{UH} = \sqrt{f_{ge}^2 + f_{pe}^2}, \quad (5)$$

where

$$f_{pe} = \frac{1}{2\pi} \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} \quad (6)$$

is the electron plasma frequency and f_{ge} is the electron gyro frequency (Stix, 1962). For the Titan flybys $f_{pe} \gg f_{ge}$, which simplifies Eq. (5) into

$$f_{UH} \approx f_{pe} \quad (7)$$

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

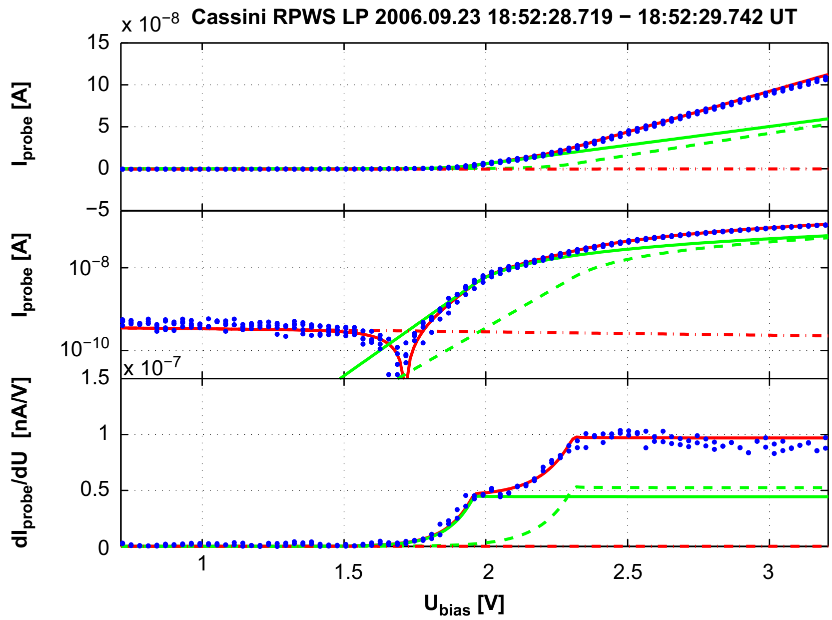

Fig. 1. The current–voltage characteristics of a sweep from flyby T18 with two electron populations. LP data are shown as blue dots. Superposed are the ion current (red dot-dashed line), two electron currents (green line and green dashed line, respectively) and the total current (red line). The *x*-axis shows applied bias voltage on the probe. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

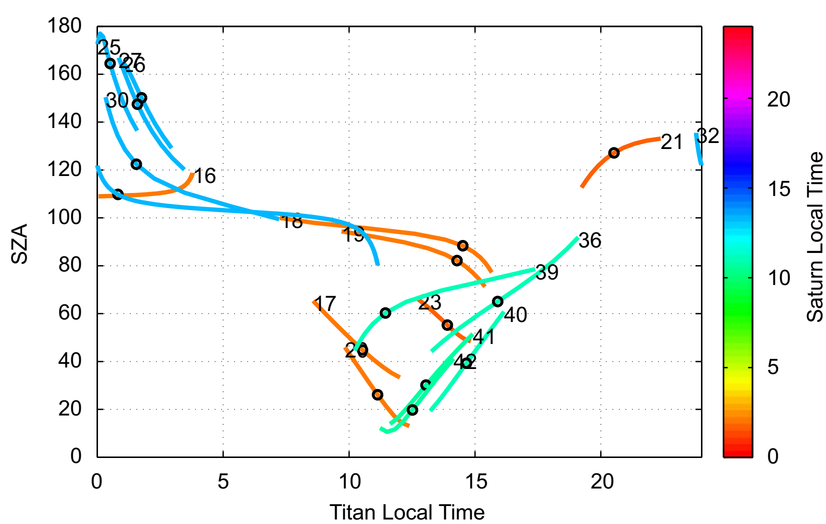

Fig. 2. Configurations of the flybys used in this study shown in terms of SZA, TLT and SLT. The number of the flyby marks the inbound leg and the circle represents the C/A. Only the part of the flyby occurring below 1400 km is shown. Three groups of flybys at SLT 2, 11 and 14 can be identified by orange, green and blue colour, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 ≈ 1200 km in the topside or exo-ionosphere (Ågren 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

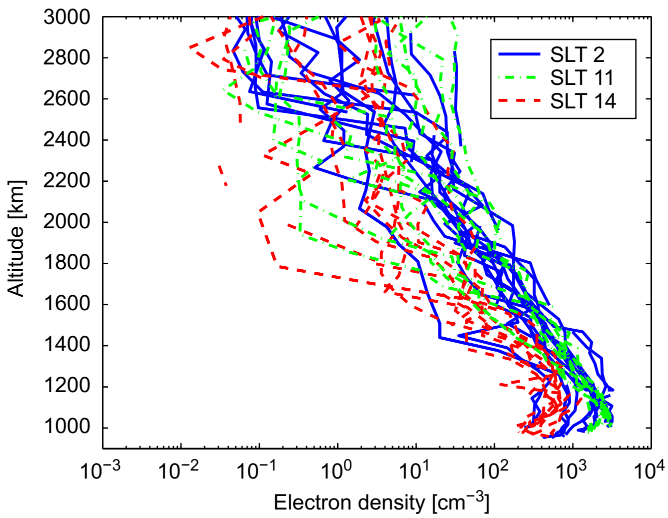

Fig. 3. Density profiles of the flybys at altitudes from C/A to 3000 km from low time resolution sweep data. The groups of SLT 2, 11 and 14 are indicated by blue continuous, green dot-dashed and red dashed lines, respectively. At low altitudes the profiles show a fairly stable density, which starts to decrease exponentially further away from Titan. Eventually a sharp drop in density down to magnetospheric values is shown, which occurs at different altitude for each flyby. Nightside flybys typically show less density than dayside flybys, but large differences within the groups can be found. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

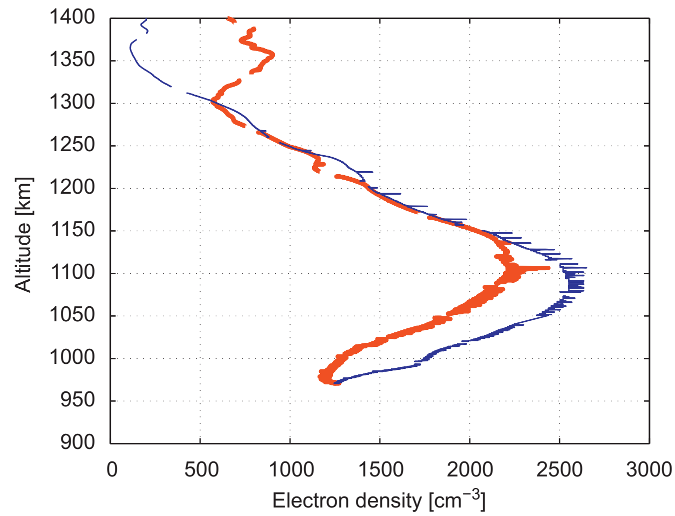

Fig. 4. Altitude profile of flyby T39 (red = inbound; blue = outbound) from the continuous 20 Hz mode data. The SZA at C/A is 60°. Data are not corrected for T_e and U_{SC}, and the spikes seen in the figure are due to instrumental interference issues. Density values do not deviate from sweep density values by more than 20%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

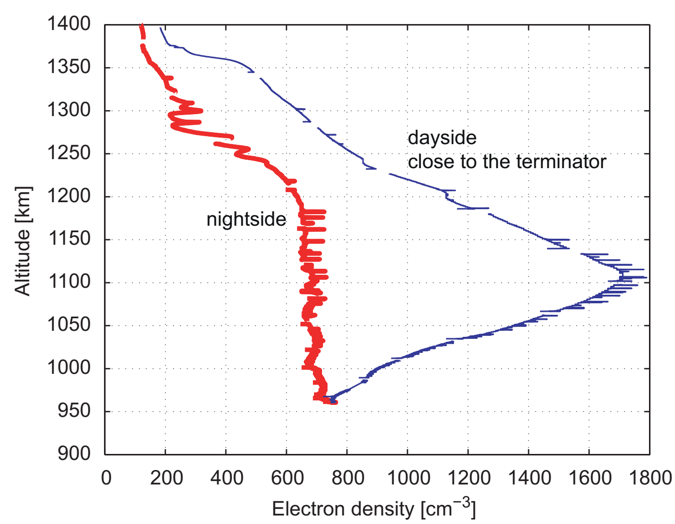

Fig. 5. Altitude profile of flyby T18 (red = inbound; blue = outbound) from the continuous 20 Hz mode data. The SZA at C/A is 88°. Similar to Fig. 4, data are not corrected for T_e and U_{SC}. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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}. 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 electron precipitation 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

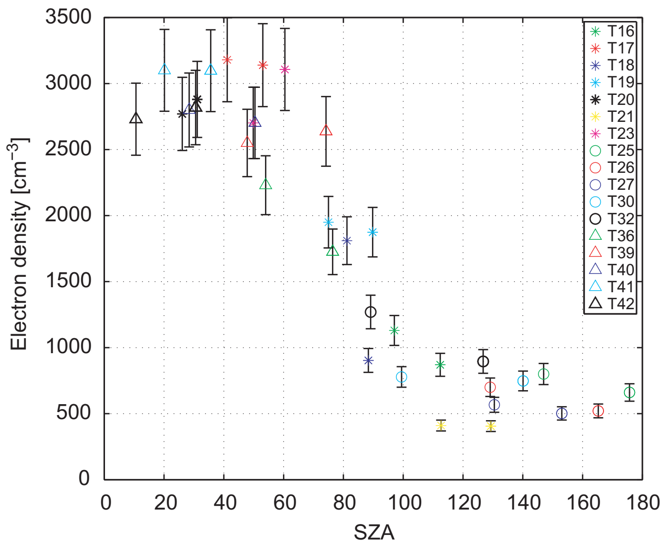

Fig. 6. The electron peak density as a function of SZA for the inbound and outbound pass of the flybys. The groups of SLT 2, 11 and 14 are marked by stars, circles and triangles, respectively. The error bars are 10% of the density value. The dayside shows on average four times more plasma than the nightside.

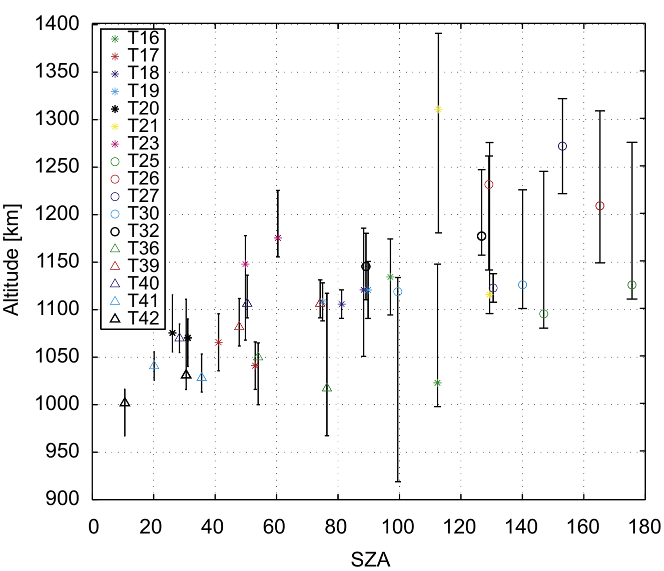

Fig. 7. The electron peak altitude as a function of SZA for the inbound and outbound pass of the flybys. The groups of SLT 2, 11 and 14 are marked by stars, circles and triangles, respectively. The error bars are set individually for each flyby, making sure that the possible peak altitudes are definitely included. For SZA $<50^\circ$ the peak altitude increases with increasing SZA.

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 precipitating magnetospheric electrons. For SZA $<50^\circ$ the trend is clear; the peak altitude increases with increasing SZA. Noteworthy is the fact that T23 (and the inbound peak of T36) falls out of this trend, suggesting that parameters other than SZA are important for the peak altitude. For SZA $>100^\circ$ the altitudes are more scattered and the error bars larger. This is related to the flatter and more structured electron density profiles on the nightside, which possibly is a consequence of that the relative contribution of the

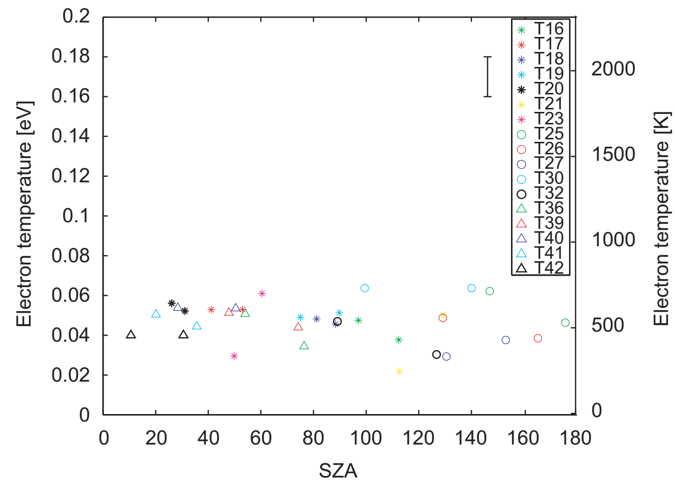

Fig. 8. The electron peak temperature as a function of SZA for the inbound and outbound pass of the flybys. The groups of SLT 2, 11 and 14 are marked by stars, circles and triangles, respectively. The error bar is shown in the upper right corner and is $\approx 20\%$ of the temperature value. A stable temperature between 0.03 and 0.06 eV is seen.

magnetospheric impacting electrons 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 $\approx 110^\circ$, 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 $\approx 10^\circ$. 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 ($\approx$ 350–700 K), i.e. within a factor of 2. However, they do not strongly depend on the SZA, 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 electrodynamics 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 ($\approx$ 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.

Acknowledgements

The Swedish National Space Board (SNSB) supports the RPWS/LP instrument onboard Cassini. The authors wish to thank the reviewers for their helpful comments which contributed to clarify and improve this article.

References

Ågren, K., Wahlund, J.-E., Modolo, R., Lummerzheim, D., Galand, M., Müller-Wodarg, I., Canu, P., Kurth, W.S., Cravens, T.E., Yelle, R.V., Waite Jr., J.H., Coates, A.J., Lewis, G.R., Young, D.T., Bertucci, C., Dougherty, M.K., 2007. On magnetospheric electron impact ionisation and dynamics in Titan's ram-side and polar ionosphere—a Cassini case study. Annales Geophysicae 25, 2359–2369.

Bertucci, C., Neubauer, F.M., Szego, K., Wahlund, J.-E., Coates, A.J., Dougherty, M.K., Young, D.T., Kurth, W.S., 2007. Structure of Titan's mid-range magnetic tail: Cassini magnetometer observations during the T9 flyby. Geophysical Research Letters 34, L24S02, doi:10.1029/2007GL030865.

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.

Coates, A.J., Crary, F.J., Lewis, G.R., Young, D.T., Waite, J.H., Sittler, E.C., 2007. Discovery of heavy negative ions in Titan's ionosphere. Geophysical Research Letters 34, L22103, doi:10.1029/2007GL030978.

Cravens, T.E., Robertson, I.P., Clark, J., Wahlund, J.-E., Waite, J.H., Ledvina, S.A., Niemann, H.B., Yelle, R.V., Kasprzak, W.T., Luhmann, J.G., McNutt, R.L., Ip, W.-H., De La Haye, V., Müller-Wodarg, I., Young, D.T., Coates, A.J., 2005. Titan's ionosphere: model comparisons with Cassini Ta data. Geophysical Research Letters 32, L12108, doi:10.1029/2005GL023249.

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

Cravens, T.E., Robertson, I.P., Waite, J.H., Yelle, R.V., Vuitton, V., Coates, A.J., Wahlund, J.-E., Agren, K., Richard, M.S., De La Haye, V., Wellbrock, A., Neubauer, F.M., 2008b. Model-data comparisons for Titan's nightside ionosphere. Icarus, 199(174), doi:10.1016/j.icarus.2008.09.005.

Cui, J., Galand, M., Yelle, R.V., Vuitton, V., Wahlund, J.-E., Lavvas, P.P., Müller-Wodarg, I.C.F., Cravens, T.E., Kasprzak, W.T., Waite, J.H., 2009. Diurnal variations of Titan's ionosphere. Journal of Geophysical Research, in press.

Fahleson, U., Fälthammar, C.-G., Pedersen, A., 1974. Ionospheric temperature and density measurements by means of spherical double probes. Planetary and Space Science 22, 41–66.

Galand, M., Yelle, R.V., Coates, A.J., Backes, H., Wahlund, J.-E., 2006. Electron temperature of Titan's sunlit ionosphere. Geophysical Research Letters 33, L21101, doi:10.1029/2006GL027488.

Gurnett, D.A., Kurth, W.S., Kirchner, D.L., Hospodarsky, G.B., Averkamp, T.F., Zarka, P., Lecacheux, A., Manning, R., Roux, A., Canu, P., Cornilleau-Wehrlin, N., Galopeau, P., Meyer, A., Boström, R., Gustafsson, G., Wahlund, J.-E., Åhlen, L., Rucker, H.O., Ladreiter, H.P., Macher, W., Woolliscroft, L.J.C., Alleyne, H., Kaiser, M.L., Desch, M.D., Farrell, W.M., Harvey, C.C., Louarn, P., Kellogg, P.J., Goetz, K., Pedersen, A., 2004. The Cassini radio and plasma wave investigation. Space Science Reviews 114, 395–463.

Gurnett, D.A., Scarf, F.L., Kurth, W.S., 1982. The structure of Titan's wake from plasma wave observations. Journal of Geophysical Research 87, 1395–1403.

Kliore, A.J., Nagy, A.F., Marouf, E.A., French, R.G., Flasar, F.M., Rappaport, N.J., Anabttawi, A., Asmar, S.W., Kahann, D.S., Barbinis, E., Goltz, G.L., Fleischman, D.U., Rochblatt, D.J., 2008. First results from the Cassini radio occultations of the Titan ionosphere. Journal of Geophysical Research (Space Physics) 113, A09317, doi:10.1029/2007JA012965.

Medicus, G., 1962. Spherical Langmuir probe in "drifting" and "accelerated" Maxwellian distribution. Journal of Applied Physics 33, 3094–3100.

Molina-Cuberos, G.J., Lammer, H., Stumptner, W., Schwingenschuh, K., Rucker, H.O., Lopez-Moreno, J.J., Rodrigo, R., Tokano, T., 2001. Ionospheric layer induced by meteoric ionization in Titan's atmosphere. Planetary and Space Science 49, 143–153.

Morooka, M.W., Modolo, R., Wahlund, J.-E., André, M., Eriksson, A.I., Persoon, A.M., Gurnett, D.A., Kurth, W.S., Coates, A.J., Lewis, G.R., Khurana, K.K., Dougherty, M., 2009. Electron density of Saturn's magnetosphere. Annales Geophysicae, submitted for publication.

Mott-Smith, H.M., Langmuir, I., 1926. The theory of collectors in gaseous discharges. Physical Review 28, 727–763.

Müller-Wodarg, I.C.F., Yelle, R.V., Mendillo, M., Young, L.A., Aylward, A.D., 2000. The thermosphere of Titan simulated by a global three-dimensional time-dependent model. Journal of Geophysical Research 105, 20833–20856.

Ness, N.F., Acuna, M.H., Behannon, K.W., 1982. The induced magnetosphere of Titan. Journal of Geophysical Research 87, 1369–1381.

Roboz, A., Nagy, A.F., 1994. The energetics of Titan's ionosphere. Journal of Geophysical Research 99, 2087–2093.

Stix, T.H., 1962. The Theory of Plasma Waves. McGraw-Hill, New York.

Szego, K., Bebesi, Z., Bertucci, C., Coates, A.J., Crary, F., Erdos, G., Hartle, R., Sittler, E.C., Young, D.T., 2007. Charged particle environment of Titan during the T9 flyby. Geophysical Research Letters 34, L24S03, doi:10.1029/2007GL030677.

Vuitton, V., Yelle, R.V., McEwan, M.J., 2007. Ion chemistry and N-containing molecules in Titan's upper atmosphere. Icarus 191, 722–742.

Wahlund, J.-E., Boström, R., Gustafsson, G., Gurnett, D.A., Kurth, W.S., Pedersen, A., Averkamp, T.F., Hospodarsky, G.B., Persoon, A.M., Canu, P., Neubauer, F.M., Dougherty, M.K., Eriksson, A.I., Morooka, M.W., Gill, R., André, M., Eliasson, L., Müller-Wodarg, I., 2005. Cassini measurements of cold plasma in the ionosphere of titan. Science 308, 986–989.

Waite, J.H., Niemann, H., Yelle, R.V., Kasprzak, W.T., Cravens, T.E., Luhmann, J.G., McNutt, R.L., Ip, W.-H., Gell, D., De La Haye, V., Müller-Wordag, I., Magee, B., Borggren, N., Ledvina, S., Fletcher, G., Walter, E., Miller, R., Scherer, S., Thorpe, R., Xu, J., Block, B., Arnett, K., 2005. Ion neutral mass spectrometer results from the first flyby of Titan. Science 308, 982–986.

Waite, J.H., Young, D.T., Cravens, T.E., Coates, A.J., Crary, F.J., Magee, B., Westlake, J., 2007. The process of Tholin formation in Titan's upper atmosphere. Science 316, 870.

Whipple, E.C.J., 1965. The equilibrium electric potential of a body in the upper atmosphere and in interplanetary space. Ph.D. Thesis, The George Washington University.