Structure of Titan's ionosphere: Model comparisons with Cassini data

I.P. Robertson a, T.E. Cravens a,*, J.H. Waite Jr. b, R.V. Yelle c, V. Vuitton d, A.J. Coates e, J.E. Wahlund f, K. Ågren f, K. Mandt b, B. Magee b, M.S. Richard a, E. Fattig a

a Department of Physics and Astronomy, Malott Hall, University of Kansas, Lawrence, KS 66045, USA
b Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78284, USA
c Lunar and Planetary Laboratory, University of Arizona, P.O. Box 210092, Tucson, AZ 85721, USA
d Laboratoire de Planétologie de Grenoble, BP 53, 38041 Grenoble Cedex, France
e University College London, Mullard Space Sciences Laboratory, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK
f Swedish Institute of Space Physics, Box 537, SE-751 21 Uppsala, Sweden

ARTICLE INFO

Article history:
Received 14 November 2008
Received in revised form
17 July 2009
Accepted 21 July 2009
Available online 29 July 2009

Keywords:
Titan
Ionospheres
Atmospheres
Chemistry
Composition
Dayside

ABSTRACT

Solar extreme ultraviolet and X-ray radiation and energetic plasma from Saturn's magnetosphere interact with the upper atmosphere producing an ionosphere at Titan. The highly coupled ionosphere and upper atmosphere system mediates the interaction between Titan and the external environment. New insights into Titan's ionosphere are being facilitated by data from several instruments onboard the Cassini Orbiter, although the Ion and Neutral Mass Spectrometer (INMS) measurements will be emphasized here. We present dayside ionosphere models and compare the results with both Radio and Plasma Wave–Langmuir Probe (RPWS/LP) and INMS data, exploring the sensitivity of models to ionospheric chemistry schemes and solar flux variations. Modeled electron densities for the dayside leg of T18 and all of T17 (dayside) had reasonable agreement with the measured RPWS electron densities and INMS total ion densities. Magnetospheric inputs make at best minor contributions to the ionosphere for these flybys, at least for altitudes above about 1000 km. At lower (<1100 km) altitudes, the total ion densities measured by the INMS are less than the electron densities measured by the RPWS/LP which could be due to heavy (>100 daltons) ions, which the INMS is not able to detect. Qualitatively, INMS spectra exhibit the same ion species and 12 amu family separations for the dayside ionospheres of T17 and T18 as were seen in the mass spectra measured during T5 (nightside). However, the relative abundance of high-mass (m>50) ion species is about 10 times less for the dayside T17 and T18 passes than it was for the polar nightside T5 flyby, which can perhaps be explained in several ways including differences in neutral composition, less dissociative recombination on the nightside than on the dayside (due to lower electron densities and affecting heavier ion species more than lighter ones), and transport of longer-lived high-mass species from day-to-night.

1. Introduction

Solar radiation and energetic particles from Saturn's magnetosphere interact with neutrals in Titan's atmosphere, producing an ionosphere. The electron density profile in Titan's ionosphere was measured by Voyager 1 in 1980 using the radio occultation technique (Bird et al., 1997). Prior to the Cassini mission a large number of models of the ionosphere and its composition were created (Keller et al., 1992; Banaszkiewicz et al., 2000; Galand et al., 1999; Fox and Yelle, 1997; Wilson and Atreya, 2004; Cravens et al., 2004). The Langmuir probe (LP) part of the Radio and Plasma Wave Spectrometer (RPWS) instrument measured in-situ electron densities and temperatures in Titan's ionosphere during the Ta (and Tb) close encounter in October 2004 (Wahlund et al., 2005). During this first flyby the Ion and Neutral Mass Spectrometer (INMS) measured densities of important neutral species in the upper atmosphere, including N 2 (95%) and CH 4 (5%) (Waite et al., 2005). But the INMS open source ion (osi) mode was not operated during this encounter and the ion composition was not measured. During the Ta flyby, the spacecraft entered the atmosphere and ionosphere on the dayside, crossed the terminator at closest approach (at an altitude of 1176 km and solar zenith angle of 91.1°), and continued onto the nightside (Waite et al., 2005). Comparisons between a theoretical model of the ionosphere and the measured electron densities demonstrated that most of the dayside ionosphere is produced by photoionization by solar radiation (Cravens et al., 2005; Galand et al., 2006).

The first measurements of the ionospheric composition at Titan were made by INMS during the T5 Cassini flyby in April 2005 (Cravens et al., 2006). This flyby took place entirely on the
not required for the model to produce electron densities in the short-lived ion species (Cravens et al., 2009). Pre-Cassini models did investigate the role of impact ionization by energetic electrons from Saturn's outer magnetosphere transported along magnetic field lines as an important ionization source (cf., Atreya, 1986; Gan et al., 1992; Cravens et al., 2009). Cravens et al. (2008) explored the role of impact ionization by energetic ion precipitation from Saturn's magnetosphere, which might be especially important for the ionosphere detected remotely at lower altitudes (below 1000 km and down to 400 km) by the Cassini Radio Science (RSS) experiment (Kliore et al., 2008).

The composition of Titan's ionosphere as observed by the Cassini INMS was partly explained by the pre-Cassini chemical models (see the references listed above). For example, it was correctly recognized that HCNH+, C4H7+ and CH3+ are abundant; however, a number of other ion species were seen in the measured mass spectra (Cravens et al., 2006) but were not predicted to be present with significant abundances (e.g., species at mass numbers 18 and 30). Vuitton et al. (2006, 2007) re-examined Titan's ion-neutral chemistry and introduced many new ion species (e.g., CH2NH2+ at m = 30), as well as new minor neutral species which have low abundances, yet have effects on the ion chemistry. Krasnopolsky (2009) created a photochemical model of Titan's atmosphere and ionosphere using a coupled ion and neutral chemistry, as did De La Haye et al. (2008) earlier, and obtained reasonable results when compared to Cassini data. Hörst et al. (2008) created a photochemical model demonstrating that O2 deposition is probably at the origin of the O-bearing species observed on Titan. Ågren et al. (2007) and Cravens et al. (2009) quantitatively analyzed the ionosphere using electron transport codes and ion chemistry schemes for T5 conditions, demonstrating that magnetospheric electrons are able to reproduce the observed ionospheric structure on the nightside.

The current paper presents INMS data and some model comparisons for the ionosphere both on the dayside and on the part of the nightside close to the terminator (i.e., solar zenith angles, SZA, up to \( \approx 105^\circ \)). INMS data from the T17 and T18 Titan flybys are presented, as well as some comparison data from the RPWS/LP experiment. The RPWS data were presented and described by Ågren et al. (2009). The T17 flyby took place on September 7, 2006, and was entirely on the dayside (SZA from 31° to 71° for altitudes below about 1600 km) and the T18 flyby took place on September 23, 2006, and was on both the day and nightside (SZA ranging from 75° to 104° for altitudes less than 1600 km, with a SZA at closest approach of about 90°). The Ta ionosphere is also revisited in this paper. Both the ion composition and the vertical and horizontal structure of the ionosphere will be explored in the paper. Only ionization due to solar radiation is included in the model calculations carried out for this paper because we found that for the T17 and T18 ionospheres, magnetospheric particle precipitation was not required for the model to produce electron densities in agreement with measured values.

2. Description of the model

The theoretical model of Titan's ionosphere that we use to interpret the Cassini data has evolved over many years and was described by Keller et al. (1992, 1994), Gan et al. (1992), Keller et al. (1998), and Cravens et al. (2004, 2005, 2009). The model includes three main components: (1) a code that accounts for (primary) ion production (and photoelectron production) due to the absorption of solar radiation, (2) an electron transport code that determines the secondary ionization rate due to impact ionization by photoelectrons, and (3) an ion chemistry code that takes the total ion production rates for "primary" species and determines ion densities versus altitude and solar zenith angle. For the current paper, a photochemical code is used for the third component and ion transport effects are neglected. Depending on the ion species this limits the reliability of the model results for altitudes exceeding about 1500 km where plasma transport is expected to be important (Cravens et al., 1998; Ma et al., 2006, 2007, 2009; Cui et al., 2009a). Our model only predicts ion densities and requires as inputs the densities of neutral species. The neutral atmosphere model(s) used for this paper are mainly derived from INMS neutral density measurements. Negative ion chemistry is not included. We will now briefly describe each model component as applied to the T17 and T18 cases.

2.1. Titan's neutral upper atmosphere for T17 and T18

The INMS in its closed source neutral (csn) mode has measured densities of many neutral species on a number of Cassini flybys. For the energy deposition and main ion production the two major species (N2 and CH4) are most important. The INMS-measured N2 and CH4 for Ta, T17, and T18 were used as model inputs as appropriate. The chemical model also requires densities of minor neutral species and where possible we used INMS data. However, our model requires densities over a large altitude range and we needed to extend the INMS density profiles by fitting them to the density curve of the same species from a theoretical model (Toulblanc et al., 1995a,b). Note that in the current paper our emphasis is not on the minor neutrals themselves but on their effects on the ionosphere, and a more general photochemical model including neutral chemistry would need to take into account recent developments (e.g., Lavvas et al., 2008; Vuitton et al., 2008; Krasnopolsky 2009). We attached the neutral densities to an altitude grid, starting at 725 km, increasing by 10 km intervals and ending at 3005 km, although our main altitude range of interest is from about 960 to 1700 km. For example, Fig. 1 shows the neutral density profiles for C2H2. From an altitude of 900 km up, the shape of the neutral density curve is similar for each model. Consequently, the shape of the Toulblanc curve was used to extend INMS observed neutral densities beyond the observation altitudes.

For the photoionization and electron transport codes we used 19 "minor" neutral species, in addition to molecular nitrogen and methane. The minor species densities from the INMS are supplemented in two ways: (1) using densities deduced from the ion chemistry for the T5 flyby by Vuitton et al. (2006, 2007),...
and (2) from the Toublanc et al. photochemical model. We organized the minor neutral densities in two different ways, as described below. This approach follows to a large extent how we modeled the nightside ionosphere for the T5 flyby (Cravens et al., 2009). Note also that densities can vary from egress to ingress, but because the derivation of minor neutrals from INMS data is thought to be more reliable during ingress, we only used measured ingress neutral densities. Part of this reliability is due to stickiness to the ante-chamber wall during the egress leg of the flyby and also due to chemical reactions taking place during that time (Cui, 2008; Cui et al., 2009b). Our two different cases of neutral densities are as follows.

1. **Case C1**: The ingress densities for N₂ and CH₄ measured by the INMS are used. The minor neutral densities are all derived from the Vuitton et al. (2006, 2007) mixing ratios for the T5 flyby for an altitude of 1100 km. Although these mixing ratios were for nightside conditions (T5), they should still provide some guidance for neutral composition for a dayside flyby. The densities for altitudes other than 1100 km are found by scaling the relative Toublanc et al. (1995a,b) curve to fit the Vuitton et al. density at 1100 km. If a species was not given by Vuitton et al. we used values from INMS if available (the derivation of these minor densities is described in case B1). Finally, Toublanc et al. (1995a,b) density profiles were directly used for the five species still left after this procedure (NH, CO, C₃H₂, C₄N₂, and CH₃).

2. **Case B1**: The same N₂ and CH₄ densities were used as in the C1 case (i.e., INMS). However, densities of most minor species were derived from the measured INMS neutral mass spectra for the relevant flybys using a spectrum deconvolution technique to unravel the “cracking pattern” as described by Magee et al. (2009), Waite et al. (2005) and Cui et al. (2009b). In many cases this procedure provided mixing ratios for altitudes near 1100 km, and at other altitudes we again used the relative altitude variations from Toublanc et al. For a few species only the mixing ratios obtained by Vuitton et al. for T5 were available. Since the minor neutrals can only be derived accurately during ingress at present, we only use the ingress data for the major species in all our runs to maintain consistency.

Note that we had separate B1 and C1 cases for each flyby we modeled. Density profiles for a few neutral species for the B1 case and T18 are shown in Fig. 2. Also see Table 1.

The determination of T17 minor INMS neutral densities is carried out over a limited low altitude region during the inbound leg of the flyby. It was only possible to obtain one data point in some cases, and the remaining data along our altitude grid points were determined by fitting the Toublanc et al. (1995a, b) curve for that minor neutral to this one data point, introducing a large uncertainty. Our approach to the densities of minor neutrals used in our ionospheric model has its limitations. A more careful consideration of the minor neutral composition is ultimately needed for all flybys including those on the dayside. For example, a Vuitton et al. type analysis should be part of such an effort. Note that Vuitton et al. (2009) reported on such an analysis for T40. This is a significant task with many uncertainties and for the current paper we will employ the atmosphere models just described.

2.2. **The solar extreme ultraviolet and soft X-ray flux and photoionization**

Ions and photoelectrons are generated when atmospheric neutrals absorb solar photons with energies exceeding the relevant ionization potentials (cf., Schunk and Nagy, 2000). We used two solar flux models, although we adjusted the wavelength bins in these models (our model uses 320 bins). For one case we used the SOLAR2000 (version 2.34) irradiance model (Tobiska et al., 2000) for wavelengths exceeding 4.2 nm. For lower wavelengths, we used a solar corona collisional model spectrum tuned to soft X-ray observations made by the Yohkoh observatory as described by Acton et al. (1999). Solar conditions for the day of the T17, T18, and Ta flybys were adopted, although we did not correct for the Sun-to-Titan time lag. For the Ta flyby we adopted F10.7 = 136.7, for T17 we used F10.7 = 86.7, and for T18 we used F10.7 = 70.4.

In order to test the sensitivity of our ionospheric model to our choice of solar flux model, we also used the EUVAC solar flux model (Richards et al., 1994a, b). The EUVAC model generates fluxes at larger wavelength bin sizes than our model, so we interpolated these fluxes to our bin-structure. And the EUVAC spectra did not extend to wavelengths as low or as high as we used (EUVAC ranged from 50–1050 Å; the Tobiska model allowed us to use a range from 2 to 1306 Å), so we adopted either Acton or SOLAR2000 fluxes to supplement these spectra. The solar flux spectra used in our model for the T18 flyby are shown in Fig. 3. The SOLAR2000 and EUVAC fluxes agree reasonably well except in the 100–300 Å range where the EUVAC fluxes are a bit higher.

Given neutral densities in the atmosphere and an incident solar flux, altitude profiles for ion production rates and photoelectron production rates (which depend on electron energy) can be found using wavelength-dependent photoabsorption and photoionization cross sections (see Keller et al., 1992; Cravens et al., 2004). The solar zenith angle (SZA) is another important parameter because the opacity of the atmosphere to incoming solar radiation at a given wavelength and altitude depends on this angle.

Some of the photoelectrons generated by photoionization are sufficiently energetic to ionize neutrals. Photoelectrons are produced over a large range of energies (less than 1 eV up to hundreds of eV) but typical energies are in the range 10–30 eV. The energy deposition and transport of these electrons were taken into account with a two-stream electron transport code including both elastic and inelastic electron impact cross sections. The transport is constrained by the magnetic field lines draped around Titan and we adopted a draped field-line geometry with parabolic-shaped field lines (see discussion in Cravens et al., 2009) for this purpose. However, most photoelectrons are
produced below an altitude of $\approx 1400$ km where they deposit their energy locally (cf., Gan et al., 1992). The total ion production rates determined with and without photoelectron transport are almost the same. Coulomb collisions with the thermal electron population are taken into account, but mainly affect the photoelectron energy distribution for energies less than 10 eV or so.

In the 2-stream code, initially developed by Nagy and Banks (1970) for the terrestrial ionosphere, electrons are allowed to move in both directions along the magnetic field (defined as upward flux, $F^s(E_s)$, and downward flux, $F^d(E_s)$, where $s$ is the distance traveled along the field line). This code was previously used to model the dayside ionosphere for the Ta flyby (Cravens et al., 2004, 2005) and the nightside ionosphere for the T5 flyby, in which precipitating magnetospheric electrons were imposed as an upper boundary condition (Cravens et al., 2009). For the current paper we do not include magnetospheric electron inputs. We only considered photoionization and the 2-stream code was only used to determine the effects of photoelectrons (i.e., secondary ionization). We found (as will be shown later) that there is sufficient solar illumination even out to a solar zenith angle of about $105^\circ$ to produce the observed ionosphere at the altitudes of those observations.

Fig. 4 shows calculated and measured photoelectron fluxes for the T18 flyby for an outbound (i.e., dayside) altitude of 1210 km. For this case, the C1 neutral densities and the Tobiska SOLAR2000 solar fluxes are used. The electron spectrum measured by the CAPS ELS instrument is also shown. The spacecraft potential for T18 at this time was estimated to be about $-1.5$ V. The CAPS spectrum shown in Fig. 4 was shifted by 1.5 eV in order to compensate for this potential. Overall, our modeled photoelectron fluxes agree quite well with the fluxes measured by CAPS. The disagreement at very low energies is partly due to the large (0.5 eV) bin size in our model. The structure in the spectra near 25–30 eV is well-known (e.g., Nagy and Banks, 1970; Gan et al., 1992) and is associated with the photoabsorption of photons at the strong solar HeII resonance line at 30.4 nm (see Fig. 3).

Fig. 5 shows ion production rates (the sum of both primary and secondary production rates) versus altitude for several ion species. Opacity effects were accurately determined only for ion species resulting from ionization of the major species, $N_2$ and CH$_4$ (including production of $N_2^+$, N$^+$, CH$_4^+$, CH$_3^+$, CH$^+$, and H$^+$). The optical depths for the other species were derived only at about 30 nm and were not determined as a function of wavelength; however, the ionization associated with the major neutral species strongly dominates all the ion chemistry.

The production rates in Fig. 5 are for the C1 neutral densities and the Tobiska SOLAR2000 solar flux. A solar zenith angle (SZA) of 80.5$^\circ$ was used corresponding to an altitude of 1210 km on the outbound leg of the T18 flyby. The ion production rates have maxima near an altitude of 1050 km for this SZA. The highest production rate, not surprisingly, is for $N_2^+$, followed by the production rates for N$^+$, CH$_3^+$ and CH$_3^+$.

Fig. 6 shows primary and secondary production rate profiles for $N_2^+$ at a 1208 km outbound altitude (SZA = 80.5$^\circ$) for T18. The secondary production is due to electron impact ionization by the photoelectrons produced by the photoionization of neutrals. Note that no magnetospheric electrons were included for this study—all the ionization is associated in one way or the other with the absorption of solar radiation.

The primary ionization clearly dominates near the peak and at higher altitudes, whereas secondary ionization (impact ionization by photoelectrons only, not by magnetospheric electrons) dominates at lower altitudes (i.e., on the ”bottom side”). The “ledge” in the ion production rates evident in Figs. 5 and 6 at an altitude of 800 km is associated with absorption of the soft X-ray
2.3. Photochemical model of Titan’s ionosphere

Many ionospheric models have been constructed for Titan (see the introduction) and each of these models has a different emphasis—some on the chemistry and others on the transport effects. Our photochemical model is very similar to what we used for our T5 nightside ionosphere study (Cravens et al., 2009), although obviously the primary ion sources and the neutral atmospheres used are different. Our photochemical model only solves for the ion composition and currently has 73 ion species. Approximately 600 ion–neutral chemical reactions are included as well as electron-ion dissociative recombination reactions. We think that we have included the key chemistry for at least the major ions with mass numbers less than 100, but much work remains to be done on the ion–neutral chemistry, particularly at the higher mass numbers. The number of neutral species adopted was 38 but our model does not solve for the densities of these neutral species. The Keller et al. (1992, 1998) studies were the starting point for our ion chemistry, but we now include most of the new ion chemistry described by Vuitton et al. (2006, 2007) as needed to explain the ion composition measured by the INMS during the T5 flyby (Cravens et al., 2006, 2009). In particular, Vuitton et al. described how nitrogen-bearing species such as CH$_3$NH$_2$ are created. The chemistry is complex and the reader is referred to the Vuitton et al. papers or to the book Titan after Cassini-Huygens (to be published in 2009 or 2010).

The altitude range of the model is 725–2725 km, although above about 1500 km transport processes begin to be important (e.g., Ma et al., 2006) and a photochemical model becomes increasingly inaccurate; and below about 960 km in-situ Cassini data are not available.

Dissociative recombination coefficients depend on the electron temperature, $T_e$ (cf. McClain et al., 2004, 2009) with the recombination coefficient decreasing as some power of $T_e$ (roughly $T_e^{-1/2}$ typically). We use temperatures measured by the RPWS/LP experiment (cf., Wahlund et al., 2005) for the three Cassini flybys that we considered. Measured electron temperatures are about $T_e$ = 600–1200 K below an altitude of 1500 km or so, but $T_e$ increases rapidly at higher altitudes (Wahlund et al., 2005). Fig. 7 shows the measured inbound and outbound T17 and T18 electron temperatures used in our models.

Ion production rates strongly depend on the solar zenith angle and for each flyby we ran our model for a large number of solar zenith angles corresponding to the location of the spacecraft. Cravens et al. (2005) published the results of similar calculations in order to determine electron densities for the Ta flyby. The Ta ionosphere was also strongly dominated by photoionization. The modeled results were compared with electron densities measured by RPWS and very reasonable agreement was obtained. Since that time the chemical model has been improved, mainly due to the chemistry introduced by Vuitton et al. (2006, 2007) but the details of the chemistry do not appear to have a strong effect on the total ion density (i.e., on the electron density).

At lower altitudes in most planetary ionospheres ion–neutral collisions and high neutral densities limit the flow of plasma, so that chemistry dominates the density structure. However, at sufficiently high altitudes such that chemical lifetimes exceed transport times, chemical processes alone are not sufficient to predict ionospheric density profiles (cf., Schunk and Nagy, 2000). This is also true for Titan (e.g., Cravens et al., 1998; Ma et al., 2006; Cui et al., 2009a). A proper consideration of transport requires plasma codes (e.g., MHD) that include the magnetic field as well as plasma sources and sinks, and such codes have not been run with the hundreds of chemical reactions that are needed to fully understand the complex ion composition. The Ma et al. MHD code (and model of the magnetospheric interaction with Titan) only includes 7 ion species as well as some rudimentary chemistry. For Ta conditions Ma et al. (2006) demonstrated that transport effects are more important than chemistry above an altitude of roughly 1400–1500 km. Cravens et al. (2009) made some empirical estimates of transport times (i.e., distance scale divided by flow speed) for the T5 ionosphere by determining the thermal and magnetic pressures from Cassini data and then adopting either a rough vertical length scale (100 km) or horizontal length scale (500 km). The Cravens et al. transport time estimates were lower limits in that it was assumed that the magnetic and thermal pressure gradient forces were in the same direction, which is not always the case. Cravens et al. also estimated chemical lifetimes for several ion species for T5. For example, CH$_3$ mainly reacts with C$_2$H$_2$, C$_2$H$_4$, and H$_2$ and the lifetime is the inverse of the sum of the rate coefficients times the densities of these neutral species. Cravens et al. concluded, in agreement with the Ma
et al. (2006) MHD model results, that transport effects start to become important for altitudes above about 1400–1500 km. Using these same methods we have estimated chemical and transport times versus altitude for the T18 outbound (dayside) ionosphere (shown in Fig. 8). Transport effects should at least be considered above about 1300 km for long-lived species and above about 1500 km for short-lived species.

3. Cassini measurements: INMS and RPWS/LP

The introduction provided a brief review of Cassini ionospheric measurements but we provide a few more details here. The INMS measures both neutral and ion species with charge to mass ratios (m/q) ranging from 0.5 to 8.5 daltons and from 11.5 to 99.5 daltons, using a radio-frequency quadrupole mass analyzer. In its open source ion (osi) mode, ions enter a narrow aperture before being guided to the mass analyzer (see the instrument descriptions by Kasprzak et al., 1996, and Waite et al., 2004). The osi instrument mode was used to measure the composition of Saturn’s ring ionosphere (Waite et al., 2005) as well as Titan’s T5 ionosphere (Cravens et al., 2006).

In this paper, we emphasize measurements of the composition of the dayside ionosphere as measured by the INMS in its open source mode, but we will also compare our model results to the ionospheric electron densities measured by the Langmuir probe (LP) part of the Cassini radio and plasma wave spectrometer (RPWS) experiment (see Wahlund et al., 2005; Ägren et al., 2009; Gurnett et al., 2004). The sum of all ion densities should equal the electron density due to quasi-neutrality unless significant densities of negative ions are present (this is a possibility below about 1000 km—Coates et al., 2007). The INMS only measures species with mass to charge ratios up to 99.5 daltons and does not measure negative ion species, both of which can affect the validity of this statement in practice.

4. Results of the ionospheric model and comparisons with cassini data—the Ta flyby

Cravens et al. (2005) generated electron densities from an earlier version of the ionospheric model and compared these densities with the density time history measured by the RPWS/LP experiment (Wahlund et al., 2005). Since INMS only measured neutral densities and ion composition was not measured during this flyby, the modeled results could only be compared with RPWS measurements. Cravens et al. considered several cases including: (a) ionization just from solar radiation and (b) ionization both from solar radiation and from precipitation of 100 eV magnetospheric electrons. Cravens et al. previously concluded that on the inbound leg of the trajectory (on the dayside) the solar source was dominant, but on the outbound leg (on the “near” nightside) solar radiation was still important, but the magnetospheric source made some contribution. Our current model has many more ion species and additional chemistry in comparison with this earlier study, as well as slightly different solar flux inputs. To reconsider Ta, we adopted the same neutral densities as used by Cravens et al. (2005). The electron densities produced by our updated model are almost the same as those presented by Cravens et al. (2005). The new model’s densities are slightly higher (about 10%) near the time of −80 s (before closest approach). And again it seems that some small extra source of ionization (i.e., magnetospheric) might be needed on the nightside beyond SZA = 100°. But overall the Cravens et al. (2005) conclusions for the Ta ionosphere stand.

5. Model and data—the T18 flyby

The T18 flyby took place on September 23, 2006, during which the Cassini spacecraft traveled over the north polar region of Titan, entering the atmosphere on the nightside at a latitude of ~63° north and 25° west longitude. Closest approach (CA) was at an altitude of 960 km and was at high latitudes near the terminator.

5.1. T18—total ion density and electron density

Fig. 9 shows both measured and modeled total ion (or electron) densities versus time for the T18 flyby. The electron density measured by the RPWS/LP and the total ion density (i.e., sum of densities of all ion species up to 99.5 Da) measured by the INMS are shown. The spacecraft not only changes its altitude during the flyby but the solar zenith angle changes too. We display the densities versus time in order to emphasize that altitude is not the only relevant variable; in fact near closest approach (CA) solar zenith angle is a more important
variable. For T18, Cassini moved from the nightside, through the terminator, and onto the dayside.

Both the RPWS/LP and INMS density time histories exhibit two maxima—the first on the nightside at $z \approx 1150$ km and $SZA \approx 99^\circ$ and the second on the dayside at $z \approx 1140$ km and $SZA \approx 82^\circ$. The dayside peak has a density ($n_{\text{e}} \approx 2100$ cm$^{-3}$), about twice the nightside peak density ($n_{\text{e}} \approx 1000$ cm$^{-3}$). The INMS and RPWS/LP peak densities and also the topside (i.e., altitudes above the peak) densities all agree within about 50%, except on inbound for times between $-275$ and $-375$ s (with respect to closest approach). In this time interval (altitudes of about $1350$–$1700$ km) on the nightside, it is possible that the plasma could have been flowing rapidly enough (i.e., in excess of roughly $300$ m/s) such that ion transmission into the INMS aperture was affected. Spacecraft potential can also affect the INMS densities. As mentioned earlier, the Cassini spacecraft can acquire an electrical charge (producing an electrical potential) which can affect ion transmission into the INMS mass analyzer for OSI measurements. The data shown in this paper, including the T18 data, were corrected for this spacecraft potential, but the corrections might not be perfect, particularly at higher values, and this introduces uncertainties into the density determinations. But, overall, the INMS and RPWS densities near and above the peaks agree reasonably well.

The INMS and RPWS density time histories each show a minimum near closest approach, but the INMS total densities are about a factor of 2.5 less than the RPWS densities near CA. The effects on INMS measurements of spacecraft potential or ion flows are not likely to be important at lower altitudes; however, it has been suggested that the densities of ion species with mass numbers exceeding $100$ amu (and not observable by INMS) could be quite high below about $1100$ km (J.-E. Wahlund, private communication; Crary et al., 2009). In particular, the IBS sensor on the CAPS instrument obtained mass spectra showing families of ion species similar to those observed by INMS but at lower mass resolution and extending to mass numbers of at least $200$ amu. Chemical models have predicted a few ion species with such high-mass numbers (e.g., Keller et al., 1998; Vuitton et al., 2008), although a detailed and complete knowledge of such chemistry is still lacking.

Another complication in the lower altitude ionosphere is the presence of negative ions. The CAPS ELS (electron spectrometer) measured densities as high as $100$ cm$^{-3}$, with mass numbers extending up to hundreds of amu (Coates et al., 2007). However, due to charge neutrality, the electron density has to be less than the total positive ion density if negative ions are present, which is the opposite of the INMS–RPWS comparison that was observed.

The results of our model are now used to interpret INMS and RPWS T18 measurements (Figs. 9 and 10). Model profiles for a number of solar zenith angles are shown in Fig. 10, as well as the spacecraft location for this flyby.

In order to produce Fig. 9, the model was run for $33$ solar zenith angles (except for the factor of 2.5 case for which fewer runs were used). The model profiles in Fig. 10 show that the density at the peak increases with decreasing solar zenith angle and that the height of the peak increases with increasing solar zenith angle—ionospheric behavior that is also found at other planets including the Earth (Schonk and Nagy, 2000). Also evident in Fig. 10 is a lower altitude density ledge located below the main peak. This ledge is produced by harder solar EUV photons and soft X-ray photons (also see Figs. 5 and 6). Cassini entered the ionosphere at high altitudes on the nightside and simultaneously moved to both lower altitudes and lower solar zenith angles, resulting in an increasing density until a time before CA of $200$ s. From this time until CA, the density decreases as the spacecraft moves to lower altitudes below the peak. From about CA until about $200$ s after CA, the density is mainly determined by the decreasing solar zenith angle as the spacecraft moves from night to day and the density increases.

The time history of the modeled electron density corresponding to that in Fig. 10 is also shown in Fig. 9 (C1-TOB blue curve). The model results and the measured densities from RPWS/LP are in reasonable agreement, although it appears that the altitude of the peak is somewhat higher for the data than for the model. The two model cases with different solar flux inputs but the same neutral atmosphere are also shown in Fig. 9 (C1-TOB for the SOLAR2000 and C1-EUV for the EUVAC). At the lowest altitudes, near CA, the EUVAC solar flux produces a modestly higher density, and in the topside ionosphere the opposite is true. The explanation is that the EUVAC solar flux is somewhat greater than the SOLAR2000 flux in the 10–20 nm part of the solar spectrum, which is absorbed in the atmosphere near $1000$ km for solar zenith angles near $90^\circ$.

The curves in Fig. 9 labeled C1-TOB and B1-TOB are for models that have somewhat different densities for minor neutral species (see Table 1), but are otherwise the same. The differences are negligible near the peak and at higher altitudes, and the differences are modest even at lower altitudes. This comparison shows that the minor neutral composition does not affect the electron density very much, although, as will be shown later, the ion composition is highly dependent on the neutral composition. Different ion species have somewhat different dissociative recombination rate coefficients, and this results in somewhat different electron densities for the two cases. Because of the large number of runs that are made to generate a single fly-through we created one additional fly-through where only solar zenith angles were run that relate to the peak electron densities and where all neutral densities (major and minor) were increased by a factor of 2.5 (B1 TOB $\times 2.5$). The peak densities are not too different but the peaks shift to higher altitudes (by an interval about equal to the neutral scale height of about $60$ km) on both inbound and outbound, as would be expected due to opacity effects. This peak shift seems to help the model–data agreement for the peak heights on both inbound and outbound (i.e., night and day, respectively).

The electron densities calculated with the photochemical model for the topside ionosphere on the outbound leg (Fig. 9) agree rather well with both the RPWS and the INMS densities up to $1800$ km in spite of the expectation that that transport should start to be important at altitudes of $1400$–$1500$ km and higher.
The transport-controlled electron density must evidently mimic the photochemical density profile (proportional to the square root of the total neutral density for the optically thin topside ionosphere).

5.2. T18-ion composition—CH$_5^+$

Dozens of ion species were measured by the INMS, and the photochemical model has 73 species. Before showing mass spectra, we present in the next few subsections altitude/time profiles for a few individual interesting species. CH$_5^+$ is mainly produced by the reaction of CH$_4^+$ with CH$_4$ and is mainly destroyed by reactions with H$_2$, C$_2$H$_2$, and C$_2$H$_4$ (cf., Keller et al., 1998). The peak densities in the models agree with the measured peak densities outbound (\( \approx 200 \text{ cm}^{-3} \)), but all model densities (including the factor of 2.5 enhanced densities) have peaks at altitudes much lower than the measured peak altitude (Fig. 11). The density for the C1 case agrees with the data near CA (i.e., 960–1000 km). The B1 and C1 model densities differ and the differences can largely be explained by the higher acetylene and ethylene abundances in the C1 model than in the B1 model. The overall poor model–data agreement for this species suggests that perhaps a key loss process is missing or that acetylene and ethylene abundances significantly exceed the B1 or C1 neutral model values. Since ion transport effects become important above an altitude of about 1500 km, the dashed vertical lines indicate these altitudes; nevertheless, because there is still agreement between RPWS and our model results, we are also showing measured and modeled results for higher altitudes or out to a time of 450 s.

5.3. T18-ion composition—C$_2$H$_5^+$

C$_2$H$_5^+$ is mainly produced by the reaction of CH$_3^+$ ions with methane with a production rate almost equal to the N$_2$ production rate. This species has several loss processes, the most important of which is reaction with hydrogen cyanide (HCN) producing another important species (HCNH$^+$). Fig. 12 shows the modeled C$_2$H$_5^+$ density and the mass 29 densities for the T18 flyby. The model–data agreement is better for this species than for CH$_5^+$, but is still not great for the “standard” B1 or C1 models for either solar flux. The best agreement between model and observations is for the B1-TOBX2.5 model case (B1 neutral atmosphere, SOLAR2000 solar flux, and overall enhanced densities). Enhancing all the neutral densities moves the peaks to higher altitudes, which helps with the agreement.

5.4. T18-ion composition—HCNH$^+$

Protonated hydrogen cyanide (HCNH$^+$) is mainly formed by chemical reaction between C$_2$H$_5^+$ and HCN. The C1 model adopts a T5 mixing ratio for the HCN neutral density, while the B1 minor densities are derived from fitting techniques applied to the observed INMS major densities (Waite et al., 2005). As shown in Fig. 13, for both solar flux cases, below about 1100 km the C1 model case gives a better fit to the observed mass 28 ion densities than does the B1 case. However, the B1 case does better than C1 near the peaks and at higher altitudes. Again, the model peaks appear to be shifted to lower altitudes in comparison with the INMS data, and enhancing all neutral densities appears to improve this situation.

5.5. T18-ion composition—CH$_2$NH$_2^+$ and a complete mass spectrum

Pre-Cassini models (e.g., Keller et al., 1998) did not predict significant abundances of ion species at a number of mass numbers that were later observed by INMS to be present in the ionosphere (Cravens et al., 2006). For example, species at mass numbers 18 and 30 were observed to be quite abundant. Mass 18 was suggested to be NH$_4^+$ produced by reaction of major ion species (e.g., HCNH$^+$) with ammonia (Cravens et al., 2006; Vuitton et al., 2006) and mass 30 was suggested to be CH$_2$NH$_2^+$ mainly produced by reaction of major species with the minor neutral
species, CH$_2$NH (Vuitton et al., 2006, 2007). Vuitton et al. deduced the abundances of this and many other nitrogen-bearing neutral species using the T5 INMS data and a photochemical model and Vuitton et al. (2009) have done this for the T40 flyby. The neutral densities of ammonia and CH$_2$NH were low enough that the INMS in its closed source mode could not measure them. Model results for the T5 ionosphere agree with INMS data for mass 30, but for our dayside models we simply adopted the mixing ratios from Vuitton et al. (2006, 2007), although this neglects any day–night and latitudinal variations in the mixing ratios of these minor nitrogen-bearing species. The Vuitton et al. approach really should be applied to the T18 (or any other) data to obtain new minor neutral densities, but this is a nontrivial task and for the current paper we use the T5 Vuitton minor neutral densities. Vuitton et al. (2009) has done this for T40.

Dissociative recombination is the main loss process for CH$_2$NH$_2$ and for similar “terminal” ion species including NH$_4^+$ and the chemical lifetimes are rather long (Cravens et al., 2009, and also see Fig. 8), although the recombination time for the T5 ionosphere (nightside) is about twice what it is for the outbound portion of the T18 ionosphere.

As can be seen in Fig. 14, all model cases overestimate the density of CH$_2$NH$_2$ in comparison with the INMS values, except right near closest approach where the C1 case is not too bad. The agreement for the outbound ionosphere and for altitudes greater than 1150 km is also not too bad for all model cases. Given that the production rate of this ion derives directly from CH$_2$NH abundances calculated to give data–model agreement for T5 at 1100 km (Vuitton et al., 2006, 2007) or other altitudes (Cravens et al., 2009, 2008), the simplest solution is to just adjust downward the density profile of CH$_2$NH. Just focusing on the outbound (dayside) ionosphere, it appears that adopting an abundance of CH$_2$NH of half what it was during T5 would be appropriate.

We have discussed only a few of the many ion species observed. Figs. 15 and 16 show complete mass spectra for the T18 flyby. All mass numbers from 1 through 99 daltons are measured by INMS, with the exception of mass numbers 9–11. If no measured or modeled density is shown in these two figures, it means that the density was lower than the minimum scale value. Fig. 15 presents a spectrum found by averaging densities for a time period on the outbound corresponding to a 24 km altitude range extending above CA (at 960 km). The model results were calculated for an altitude of 972 km on the outbound trajectory.

Fig. 16 presents a spectrum for higher altitudes (1183–1233 km) on the dayside (solar zenith angle of 80.5°). These spectra allow us to compare INMS observations to model results for all ion species with mass numbers less than 100 amu. The agreement between model densities and the INMS-measured densities is better overall at higher altitudes (Fig. 16) than it is at lower altitudes (Fig. 15), although even at higher altitudes the model does better for some species than for others. Considering species with densities greater than 10 cm$^{-3}$ at an altitude of 1200 km (Fig. 16), and not discussed previously, the model densities are a factor of 4–10 too low for mass numbers $m = 39, 40, 53$. In our model, mass 39 is mainly c-C$_3$H$_7^+$, $m = 40$ is c-C$_4$H$_8^+$, and $m = 53$ consists of C$_4$H$_8^+$ or C$_3$H$_7$CN$^+$. For $m = 40$, Vuitton et al. also have CHCNH$^+$ in their model, and our model does not, which can probably explain the problem. But the mass 53 species in our model and the Vuitton et al. T5 model are the same. C$_3$H$_7$CN$^+$ is created by reaction of major ion species with C$_2$H$_3$CN; for our dayside model we just adopted the T5 mixing ratio from Vuitton et al. for this neutral species. But the abundance of this species (too low to be measured by the INMS in its csn mode) could justifiably be adjusted upward for the dayside atmosphere. For higher mass number species near 1200 km, the biggest model–data discrepancy is for $m = 91$, which is C$_7$H$_7^+$ in our model. The source of this species in our models involves C$_6$H$_5^+$ and C$_5$H$_5^+$ (see Keller et al., 1998), but we did not include the reaction of C$_6$H$_5$ with C$_7$H$_8$ as suggested by Vuitton et al. in their T5 model. This would help boost the density at this mass number. Again, a Vuitton-type analysis is called for, but for many altitudes and not just at 1100 km as carried out by Vuitton et al. (2007).
Overall, the model–data agreement near closest approach (Fig. 15) is worse than at higher altitudes and this is especially the case for species with mass numbers greater than 50. The model density for the $m = 52$ species (mainly HC$_3$NH$^+$) is about 20 times too high at 972 km, although the agreement is not bad at higher altitudes. The main source of this species is the reaction of the major ion species with HC$_3$N. The abundance of this species adopted near 1200 km must be reasonable. The problem below 1000 km could be that the adopted mixing ratio for this species at this altitude is too high or that there is a new chemical loss process not included at all in our model. In fact, a general problem with the current photochemical model for lower altitudes is that it includes very few ion species with mass numbers exceeding 100 amu ($m = 106, 141$ are included). The CAPS IBS experiment has demonstrated that the “family” structure evident in the spectra shown in Figs. 15 and 16 extends up to at least 200 daltons (Crary et al., 2009—paper submitted to PSS). Clearly, reactions must be taking place between lower mass number species and neutrals that produce species with mass number exceeding 100 amu. Such chemistry would not only populate the higher mass spectrum, but would also reduce the densities of lower mass species (which would improve our model–data comparisons). Note though that the model electron density below 1000 km agrees rather well with the density measured by the RPWS/LP, which implies that there is a trade-off between lower and higher mass ion species and that the dissociative recombination rate coefficients for the lower and higher mass ion species cannot be too different.

6. Model and data—the T17 flyby

The September 7, 2006, T17 flyby covered a region just north of the equator and the part of the flyby with altitudes of 2000 km or less was all on the dayside. The solar zenith angle ranged from about 30° to 70°, making T17 a purely dayside flyby.

6.1. T17—total ion density/electron density

Fig. 17 shows modeled and observed electron densities for the T17 flyby. Again, the INMS “electron density” in a particular altitude is just the total density for all ion species observed in that altitude bin. The INMS observations were again corrected for the effects of spacecraft potential. The RPWS and INMS densities agree quite well except for altitudes below = 1050 km, where the RPWS densities again exceed the INMS densities. The most probable explanation is again that ion species with mass numbers exceeding 99.5 daltons are present at lower altitudes and were not measured by the INMS.

The neutral densities for the major species in the model were from the INMS closed source neutral experiment. These T17 densities were very close to the densities measured by the INMS closed source for T18 and we will not display them. For the minor species we used the T18 mixing ratios for the B1 case, as given in Table 1. We used the electron temperatures measured by the RPWS/LP experiment for T17. The RPWS T17 inbound electron temperatures differed by a factor of 3 from the RPWS T18 dayside electron temperatures at higher altitudes; the outbound electron temperatures were about the same (see Fig. 7). For instance, at 1700 km inbound the T17 temperature was about 2000 K, which was similar to the T18 outbound temperature at that altitude; however at 2500 km the T17 inbound temperature was $\sim 10^4$ K while the T18 dayside temperature was still around 2000 K. We used both the SOLAR2000 solar flux (Tobiska et al., 2000; designated in our figures as TOB) and the EUVAC solar flux adjusted for the solar conditions on the date of the T17 flyby. We only carried out high time resolution model runs for the B1-TOB case; for the other cases we sampled just a select few solar zenith angles.

Now consider the model–data comparisons. The model and observed densities are very similar above 1100 km, but at lower altitudes the model densities are significantly higher than the densities measured either by the INMS or RPWS/LP. Just as for T18, the modeled electron density profile in the topside ionosphere for T17 agrees rather well with the measured density profiles, even above 1500 km where transport effects are expected to be important.

Although the C1 neutral densities were not used in the simulations, we did do a number of model runs for B1 densities that were increased by a factor of 2.5. This change made the data–model agreement worse, even at higher altitudes where

<table>
<thead>
<tr>
<th>T18 mixing ratios</th>
<th>C1</th>
<th>B1</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$</td>
<td>0.950</td>
<td>0.948</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>0.040</td>
<td>0.040</td>
</tr>
<tr>
<td>H$_2$</td>
<td>979a</td>
<td>978b</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>393a</td>
<td>6167</td>
</tr>
<tr>
<td>N</td>
<td>65.6a</td>
<td>65.5a</td>
</tr>
<tr>
<td>NH</td>
<td>592a</td>
<td>591a</td>
</tr>
<tr>
<td>CH$_3$</td>
<td>2609a</td>
<td>2604a</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>6.84a</td>
<td>6.82a</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>0.29a</td>
<td>0.29a</td>
</tr>
<tr>
<td>C$_2$H$_6$</td>
<td>275a</td>
<td>460a</td>
</tr>
<tr>
<td>C$_2$H$_4$</td>
<td>979a</td>
<td>240a</td>
</tr>
<tr>
<td>HCN</td>
<td>196a</td>
<td>604a</td>
</tr>
<tr>
<td>ND$_3$</td>
<td>7.68a</td>
<td>7.67a</td>
</tr>
<tr>
<td>C$_2$H$_4$</td>
<td>10.2a</td>
<td>10.2a</td>
</tr>
<tr>
<td>C$_2$H$_6$</td>
<td>118a</td>
<td>29a</td>
</tr>
<tr>
<td>C$_3$H$_8$</td>
<td>43.2a</td>
<td>43.1a</td>
</tr>
<tr>
<td>C$_3$H$_6$</td>
<td>3.9a</td>
<td>5.1a</td>
</tr>
<tr>
<td>C$_4$H$_8$</td>
<td>1.26a</td>
<td>1.25a</td>
</tr>
<tr>
<td>C$_4$H$_6$</td>
<td>2.25a</td>
<td>1.09a</td>
</tr>
<tr>
<td>C$_5$H$_7$</td>
<td>29.7a</td>
<td>18.1a</td>
</tr>
<tr>
<td>C$_6$H$_7$</td>
<td>39a</td>
<td>0.95a</td>
</tr>
<tr>
<td>C$_2$N$_2$</td>
<td>1.77a</td>
<td>1.77a</td>
</tr>
<tr>
<td>C$_2$N$_2$</td>
<td>22.5a</td>
<td>22.4a</td>
</tr>
</tbody>
</table>

The major species for the two cases have very similar mixing ratios, and even the minor species abundances agree within factors of 2 or 3 for the most part.

* parts per million.

Fig. 17. Electron density versus time, altitude and solar zenith angle for the T17 flyby, which was entirely on the dayside. The electron density measured by the RPWS/LP and the total ion density measured by the INMS are shown, as are model densities for several model cases as described in the text.
there was previous agreement. To generate lower densities at lower altitudes we could use a lower ion production rate or a higher loss rate (i.e., more dissociative recombination). The data–model comparisons above 1100 km are good, so that it is unlikely that the solar flux or the ion production rates we used could be too very wrong, except perhaps at the lowest altitudes where the relevant solar flux at lower wavelengths is known to be highly variable (Tobiska et al., 2000). Perhaps the hard EUV or soft X-ray fluxes in our solar spectra for both the SOLAR2000 and the EUVAC cases are too large. However, essentially the same solar fluxes did seem to work well for T18, even at lower altitudes.

To check the second idea (increasing the loss rate), we changed the electron temperature at all altitudes from RPWS/LP values ($T_e \approx 600$–$200$ K) to $200$ K. Dissociative recombination rate coefficients decrease with temperature approximately as $T_e^{-1/2}$ and the electron density varies as $n_e \approx [P/\alpha]^{1/2}$ (where $P$ is the ion production and $\alpha$ the dissociative recombination rate coefficient) and hence $n_e$ varies roughly as $T_e^{1/4}$. The lower electron temperature should result in an electron density of about 40% lower, which is in line with the numerical results shown in Fig. 17. However, this 40% reduction is not sufficient to bring the model densities down to the measured densities. Perhaps the problem lies in the details of the ion composition. Another possibility is that the very high-mass species ($m > 100$ amu) that are thought to be important at lower altitudes (and not included in our model) have much higher dissociative recombination rate coefficients than lower mass ion species.

Fig. 18 shows the mass spectrum for T17 outbound at an altitude of 1181 km. The spectra measured by INMS on the dayside near 1200 km for T17 and T18 are very similar overall even though the latitudes for the two observations were different. Overall, at this altitude the model agrees with the T17 INMS data, although the model underestimates the densities of some species (for instance, masses 31 and 91). The agreement is better for low-mass ion species than for high-mass ion species. However, the higher density ions still have reasonably good agreement with the measured densities. Most of the discussion given earlier for the T18 dayside spectra also applies to the T17 (dayside) spectrum.

7. Comparison of INMS data for T5, T17, and T18 at 1100 km

The mass spectra measured by the INMS during T5 (high latitude nightside), T17 (low latitude dayside) and T18 (high latitude dayside) are compared in Fig. 19. Note that the measured T17 low latitude dayside spectrum near this altitude is similar to the T18 spectrum. Qualitatively, the T5, T17 and T18 spectra are similar in that the same major species (mass numbers 28, 29, 30, for example) are present, as is the “family” structure (spacing of about 12 daltons) extending up to 100 daltons. On the other hand, quantitative differences exist. The most obvious difference is that the relative abundances of all high-mass species ($m > 50$ daltons) are about a factor of 10 less for T17 and T18 than for T5.

The primary in-situ source of the ionosphere is very different for T5 (magnetospheric electron precipitation—Ågren et al., 2007; Cravens et al., 2008) than for T17 and T18 (as discussed in this paper—solar radiation) with lower ionization rates (and lower electron densities) being found on the nightside. One possible explanation for the relatively lower densities of high-mass ion species (relative to low-mass species) on the dayside compared to the nightside evident in Fig. 19 could be linked to the lower nightside electron densities. Dissociative recombination is the main loss process for higher mass species than lower mass species with high-mass species more likely to be “terminal” ion species which react much less with neutrals than do lower mass species. The chemical lifetimes of lower mass species are mainly controlled by ion–neutral reactions (see time constants in Fig. 8) and should be about the same during the day as during the night if the neutral densities are the same. In addition, higher mass species are more likely to have larger dissociative recombination rate coefficients than low-mass species. The dayside electron density at 1100 km is about a factor of 2 greater than the T5 electron density, so that dissociative recombination removes higher mass species twice as fast during the day (T17 and T18) as during the night but the densities of low-mass species remain unaffected. However, this effect alone seems unlikely to be able to account for all of the T5–T17 relative density differences evident in Fig. 19.

Differences in the minor neutral composition between the polar night (T5) and the dayside (T17 and T18) could also affect the relative densities of high-mass and low-mass ion species. Transport of ionospheric plasma might also help to explain the day–night ion composition differences. Cui et al. (2009a) used INMS data to determine average ion density profiles for the day and nightside ionospheres, and showed that the higher mass species, with longer chemical lifetimes, had smaller diurnal variations than did lower mass ion species, and this is consistent with the results shown in Fig. 19. Cui et al. (2009a) also used an ionospheric model that incorporated day-to-night transport effects, and concluded that day-to-night transport was a major source of high-mass species in the nightside ionosphere.

Fig. 18. Ion mass spectrum measured by the INMS during T17 and a mass spectrum from the model for the SOLAR2000 solar flux. The model altitude is 1181 km on the outbound with a SZA of 33.89°.

Fig. 19. Comparison of ion mass spectrum measured by INMS for T5 (nightside, polar region) (Cravens et al., 2006), for T17 (dayside, equatorial region) and for T18 (outbound, polar region). The spectra were found for data collected between altitudes of 1075 and 1125 km and all spectra are normalized to the mass 29 density.
8. Discussion and conclusions

This paper has presented ion densities versus time and ion mass spectra as measured by the Cassini ion and neutral mass spectrometer for Titan’s dayside ionosphere for two flybys. The dayside data have also been compared with the nightside T5 ionospheric data and with Cassini RPWS Langmuir probe data. In order to help interpret the dayside ion density data we used a photochemical model that included both primary and secondary ionization and a large number of ion–neutral reactions. The model did not fully address the issue of the ionospheric effects of minor neutral composition or dynamical effects, leaving plenty of room for other types of models to address these effects and to revisit the data that was presented here.

In this paper we have come to the following conclusions:

- Solar radiation is the main source of the dayside ionosphere out to solar zenith angles of about 100°, at least for the T5, T17, and T18 passes. Ionization by magnetospheric electrons was not needed in the model in order to explain the T17 and T18 data.
- Near the ionospheric peak and at higher altitudes, the total ion densities measured by the INMS agree reasonably well with the electron densities measured by the RPWS Langmuir probe for the dayside passes examined, which is consistent with the agreement found earlier on the nightside (T5).
- The INMS total ion densities are less than the RPWS electron densities near an altitude of about 1000 km and lower, and this has been attributed to the existence of chemically complex ion species with mass numbers exceeding 100 amu (not measured by the INMS).
- The overall structure of the ionosphere (location and densities of the peaks, and the shape of the profile) can be explained with a photochemical model that includes Cassini-based densities of major neutral species, electron temperatures, and both primary and secondary ionization associated with the absorption of solar radiation. This is true even at altitudes above about 1500 km, where transport effects are expected to be important.
- The ion composition measured by the INMS in the dayside ionosphere is qualitatively very similar to that measured on the nightside and at high latitudes (T5). The major ion species (e.g., CH₄, C₂H₆, HC≡N, C₂H₂NH, C₂H₆N₂, C₂H₈N...) had similar relative abundances on both the dayside and nightside, but higher mass species (m > 50 amu) had lower relative abundances on the dayside than during T5, which can perhaps be explained in several ways including differences in neutral composition, less dissociative recombination on the nightside than on the dayside (affecting heavier ion species more than lighter ones), and transport of longer-lived high-mass species from day-to-night.
- The photochemical model did a reasonable job semi-quantitatively for most species and for altitudes near 1100 km and higher, but did poorly at lower altitudes. We attribute this to missing chemistry that leads to high-mass ions (m > 100 amu) and also to our using some minor neutral abundances that are perhaps more suitable for the T5 nightside atmosphere (i.e., Vuitton et al., 2006, 2007) than for the dayside atmosphere.

Titan’s ionosphere is both chemically and dynamically complex and much future work will be needed to fully understand this ionosphere. The current paper emphasized the ion composition measured by the Cassini INMS during two flybys, T17 and T18. In the future, a more statistical approach should be undertaken and should incorporate more flybys. The data in such a study should be sorted by variables such as local time (or solar zenith angle) and latitude. Cui et al. (2009a) made some progress in this respect by considering global averages of dayside and nightside ion density profiles and Ågren et al. (2009) examined many electron density profiles measured by the RPWS Langmuir probe.

Models are needed to interpret the ionospheric data, and different models make different simplifying assumptions and emphasize different aspects of the ionosphere. For example, the De La Haye et al. (2008) model combined neutral and ionospheric chemistry. Ion–neutral chemistry was emphasized by Vuitton et al. (2007), Carrasco et al. (2007, 2008), Krasnopol’sky (2009), and by the current paper. Vuitton et al. (2009) explored negative ion chemistry in order to explain the Cassini CAPS measurements of negative ion species in the lower ionosphere (Coates et al., 2007). Primary ionization sources were considered by Ågren et al. (2007), Cravens et al. (2009), and by the current paper. Simple dynamical and/or time-dependent effects (i.e., day-to-night flow or time-dependent magnetospheric ionization) were taken into account by Cravens et al. (2009), De La Haye et al. (2008), and by Cui et al. (2009a). The global ionospheric dynamics, including how the ionosphere couples to the external magnetospheric flow, was studied by Ma et al. (2006, 2008) using a magnetohydrodynamic model with simple ion chemistry and 7 ion species. These models have all provided different and complementary insights into Titan’s ionosphere, but major gaps remain in our understanding, particularly for the high-mass ion chemistry and concerning the relative role of dynamics and chemistry.

Acknowledgements

Support from the NASA Cassini project (Grant NFP45280 via subcontract from Southwest Research Institute) is acknowledged. Model development at the University of Kansas was also supported by the NASA Planetary Atmospheres Grant NNX07AF47G. Solar Irradiance Platform historical irradiiances are provided courtesy of W. Kent Tobiska and Space Environment Technologies. These historical irradiiances have been developed with partial funding from the NASA UARS, TIMED, and SOHO missions.

References


