Model-data comparisons for Titan's nightside ionosphere

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A B S T R A C T

Solar 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. A model of Titan's nightside ionosphere will be described and the results compared with data from the Ion and Neutral Mass Spectrometer (INMS) and the Langmuir probe (LP) part of the Radio and Plasma Wave (RPWS) experiment for the T5 and T21 nightside encounters of the Cassini Orbiter with Titan. Electron impact ionization associated with the precipitation of magnetospheric electrons into the upper atmosphere is assumed to be the source of the nightside ionosphere, at least for altitudes above 1000 km. Magnetospheric electron fluxes measured by the Cassini electron spectrometer (CAPS ELS) are used as an input for the model. The model is used to interpret the observed composition and structure of the T5 and T21 ionospheres. The densities of many ion species (e.g., CH+ 5 and C2H+ 5) measured during T5 exhibit temporal and/or spatial variations apparently associated with variations in the fluxes of energetic electrons that precipitate into the atmosphere from Saturn's magnetosphere.

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1. Introduction

Solar radiation and energetic plasma from Saturn's magnetosphere ionize the neutral molecules in Titan's ionosphere, creating an ionosphere at altitudes above about 400 km (Bird et al., 1997; Wahlund et al., 2005; Young et al., 2005; Keller et al., 1992; Gan et al., 1992; Cravens et al., 2005, 2008; Galand et al., 1999; Banasikiewicz et al., 2000; Molina-Cuberos et al., 2001; Lilienstern et al., 2005a, 2005b; Agren et al., 2007; Kliore et al., 2008). Titan's neutral atmosphere consists mainly of molecular nitrogen and methane but the relatively minor amounts of many hydrocarbon and nitrogen-bearing species play an important role in the upper atmosphere and ionosphere (Waite et al., 2005b, 2007; Vuitton et al., 2006, 2007; Fox and Yelle, 1997; Keller et al., 1998). The first in situ measurements (electron densities and temperatures) of Titan's ionosphere were made during the October 2004 T5 encounter of the Cassini Orbiter by the Langmuir Probe (LP) part of the Radio and Plasma Wave (RPWS) experiment (or RPWS/LP) (Wahlund et al., 2005). Magnetic fields in the ionosphere were measured by the magnetometer experiment (Backes et al., 2005).

The T5 Cassini data plus modeling demonstrated that the observed ionosphere on the dayside could largely be explained by photoionization by solar radiation (Galand et al., 2006; Cravens et al., 2005). The current paper will focus though on the ionosphere on the nightside where the solar source obviously cannot operate. Impact ionization by energetic electrons transported along magnetic field lines from Saturn's outer magnetosphere has long been thought to be an important ionization source (cf. Atreya, 1986; Gan et al., 1992; Cravens et al., 2008, and references therein) and it has also been suggested as a source of the ionosphere observed by Cassini during T5 (Cravens et al., 2006; Agren et al., 2007). Cravens et al. (2008) also suggested that precipitation of energetic protons and oxygen ions from Saturn's magnetosphere into the atmosphere is an important source at lower altitudes (≈500–800 km) and might explain the ionosphere observed at these altitudes by the Cassini Radio Science (RSS) experiment (Kliore et al., 2008).

The first composition measurements in Titan's ionosphere were made by the Cassini Ion and Neutral Mass Spectrometer (INMS) during the outbound leg of the T5 pass in April 2005 (Cravens et al., 2006). The spacecraft remained deep on the nightside (i.e.,
solar zenith angles of \( \approx 135^\circ \)) during this time. The RPWS/LP experiment measured a substantial electron density \( (n_e \approx 1000 \text{ cm}^{-3}) \) on both the inbound and outbound legs of T5 (Agren et al., 2007); for the latter, the electron densities measured by RPWS/LP and the total ion densities measured by the INMS were in good agreement for altitudes below about 1500 km (Cravens et al., 2005). The INMS is able to measure ion species with mass numbers up to 99, and the T5 data revealed species with substantial densities for about 40–50 species. A rich and complex ion–neutral chemistry scheme was expected prior to the Cassini mission (cf. Keller et al., 1998; Fox and Yelle, 1997; Wilson and Atreya, 2004; Anicich et al., 2004) and the T5 INMS data did not disappoint. Many predicted species were indeed present (e.g., \( \text{C}_2\text{H}_2\text{C}_5 \), \( \text{C}_7\text{H}_2\text{C}_5 \), etc.) but the existence of other species was not predicted at any significant abundance by pre-Cassini models (e.g., Keller et al., 1998; Fox and Yelle, 1997; Wilson and Atreya, 2004; Coates et al., 2007a), including species at \( m = 18, 30, 54, \) and 66. Subsequent mass spectra measured during dayside Titan passes by the INMS have confirmed that relative ion composition on the day and nightsides are similar (paper in preparation).

Most of the previously unexplained “new” ion species were interpreted by Vuitton et al. (2006, 2007) as being due to reaction of major ion species with a variety of neutral nitrogen-bearing species whose abundances were low enough such that they were not measurable by the INMS (in its neutral “CSN” mode). For example, both Vuitton et al. (2006) and Cravens et al. (2006) suggested that the mass 18 species was \( \text{NH}_4^+ \) — formed by the reaction of major ion species with ammonia. And Vuitton et al. (2006) suggested that mass 30 was \( \text{CH}_2\text{NH}_2^+ \) produced by reaction of \( \text{HCNH}^+ \) with \( \text{CH}_2\text{NH} \). Vuitton et al. (2007) explained mass 66 as \( \text{C}_2\text{H}_2\text{CN}^+ \) — produced by reaction of \( \text{HCNH}^+ \) with the nitrile species \( \text{C}_2\text{H}_2\text{CN} \). The ion chemistry for heavier species may have significant implications for aerosol formation lower in the atmosphere (e.g., Waite et al., 2007). The Vuitton et al. papers focused on the chemical aspects of the T5 neutral and ion composition data. For the current paper we adopt most of the chemistry presented by Vuitton et al. and concentrate on explaining the structure and source(s) of the T5 (and T21) nightside ionosphere.

The chemical part of the model for the current paper only includes chemistry for ion species. That is, purely neutral chemistry was not included and neutral abundances for both major and minor species were adopted from INMS data or from other papers referenced later. A full understanding of the chemistry of Titan’s upper atmosphere requires a coupled ion and neutral chemical model such as the pre-Cassini model described by Wilson and Atreya (2004) and the post-Cassini model of De La Haye et al. (2008a).

Energetic electrons were observed in Saturn’s outer magnetosphere by Voyager (Schardt et al., 1984) and by both the CAPS ELS (Coates et al., 2007b) and MIMI (Krimigis et al., 2005) instruments onboard Cassini. Cravens et al. (2006) suggested that incident electrons with a broad range of energies (25 eV–2000 keV) were needed to explain the ionospheric densities measured by the RPWS/LP and INMS during T5, and this has been confirmed by detailed calculations by Agren et al. (2007). Agren et al. pointed out that the electron fluxes observed by the CAPS ELS near Titan during the T5 pass exceeded by roughly a factor of ten the fluxes needed to produce the observed ionosphere. Agren et al. also described the general magnetospheric context of the T5 pass. The spacecraft closest approach and outbound leg (where the INMS made open source ion measurements) was approximately on the ramside of Titan with respect to the magnetospheric flow.

The current paper picks up where the Agren et al. (2007), Vuitton et al. (2006, 2007), and De La Haye et al. (2008a) papers leave off. De La Haye et al. (2008a) combine neutral and ionospheric chemistry in a one-dimensional model that accounts for horizontal variations as well as temporal variations via a rotation of Titan, assuming that the upper atmosphere rotates at the same rate as the solid body. The basic model components were described by Keller et al. (1992, 1998) and by Gan et al. (1992, 1993) (but with some improvements as discussed by Cravens et al., 2004). The current paper makes detailed model comparisons for a number of individual ion species measured by the INMS for T5 and T21. The current paper also investigates the temporal/vertical structure of Titan’s nightside ionosphere in the context of the electron fluxes measured by CAPS. In particular, the paper will explore differences in ionospheric structures between “primary” ion species such as \( \text{CH}_2^+ \) and more “chemically-processed” species, such as \( \text{HCNH}^+ \). The paper will suggest that smaller-scale structure below about 1400 km can be explained by temporal and spatial variations in the incident energetic electron flux.

### 2. Magnetospheric electrons as a source of Titan’s ionosphere

The electron gas in Saturn’s outer magnetosphere is “hot” with typical thermal energies in the 100 eV–1 keV range (cf. Coates et al., 2007b; Rymes et al., 2007). Fig. 1 shows an electron spectrum from the Cassini CAPS ELS experiment for the T5 time period. The several electron populations evident in this, and similar, electron spectrographs were discussed by Coates et al. (2007b), but we will point out a few relevant features here. During times near closest approach for T5 the CAPS ELS pointed approximately along the spacecraft ram direction and pitch angles very roughly near 90° were sampled. The magnetospheric population can be located in the spectrograms near the beginning and end time periods. Substantial electron fluxes in the 100 eV–2 keV energy range are present with measurable fluxes persisting up to energies of several keV. The Cassini MIMI instrument observed electrons with energies of many tens of keV near T5 (Krimigis et al., 2005). When the spacecraft is sunlit the CAPS ELS observes spacecraft photoelectrons with energies less than about 5 eV, but for T5 this population disappeared when Cassini went through Titan’s shadow in the time period near CA. The low energy electrons near CA are secondary electrons produced in the atmosphere by electron impact ionization of neutrals by the primary incident electrons. An interesting, but not obvious, feature in Fig. 1 is the roughly 2 min time variation in the secondary electron flux (most evident for energies of a few eV or less) seen by the CAPS ELS near CA. This time period corresponds to a distance along the spacecraft track of about 1000 km.
transport requires a knowledge of the global field line topology, but field data along the spacecraft track alone cannot provide this topology (e.g., Galand et al., 2006). MHD-type modeling is also needed. For the current paper we will simply adopt 3 simple magnetic field configurations: (1) radial fields, (2) parabolic field lines with apex at the surface, and (3) parabolic field lines with apex at an altitude of 725 km. The surface parabola is the preferred configuration because for this case the field orientation near an altitude of 1100 km is close to the measured orientation.

We need to calculate electron fluxes within the atmosphere in order to find ionization rates. Upward and downward suprathermal electron fluxes as functions of altitude and energy are calculated using a two-stream electron transport method, as described by Gan et al. (1992, 1993). Both elastic and inelastic collisions with molecular nitrogen and methane are taken into account as well as Coulomb collisions with thermal electrons. A key collision process is impact ionization of neutrals which produces secondary electrons according to known differential cross sections. Secondary electrons have energies ranging from zero up to a large fraction of the primary energy, but typical energies are a few eV up to tens of eV. The electrons are allowed to go both directions along the field with an angular distribution assumed to be isotropic in each direction (fluxes: $\phi^+ (E, s)$ and $\phi^- (E, s)$, where $E$ is the electron energy and $s$ is distance along the field which is a known function of altitude $z$). A discrete energy grid was adopted with $\Delta E = 0.5$ eV at the lowest energies, increasing to 10 eV at the code’s highest energy of 5 keV.

The two-stream method was originally developed for terrestrial photoelectron transport (Nagy and Banks, 1970) and we have previously used it to find photoelectron fluxes on the dayside of Titan (Cravens et al., 2004, 2005). In this case the suprathermal electrons are produced by photoionization of neutrals by solar photons (also see Galand et al., 2006). For the current paper, photoelectrons are not considered and instead magnetospheric electrons are introduced as a boundary condition on $\phi^-$ at the “end” of the field line well outside the atmosphere. De La Haye et al. (2007a, 2007b, 2008b) discussed an application of the two-stream method to the problem of how suprathermal neutrals, produced by exothermic ion and neutral chemistry, contribute to populating Titan’s corona and neutral gas heating rates (and efficiencies) in Titan’s upper atmosphere. De La Haye et al. (2008b) calculated local-time dependent heating rate profiles, and specified the contribution of magnetospheric electrons to neutral heating, taking into account the excitation of atmospheric molecules by electron impact, electron impact ionization and dissociation, and suprathermal electron heating. Many of the electron impact cross sections used in the current paper are presented by De La Haye et al. (2008b).

The magnetospheric electron fluxes measured by the CAPS ELS for T5 or for T21 (see Figs. 1 and 2) are used as the boundary condition at the “top” of the atmosphere for the downward electron flux in our two-stream model [also see discussion in the Agren et al. (2007) paper]. However, in order to exclude any possible spacecraft photoelectrons, we set the boundary flux to zero for energies less than 10 eV. The fluxes predicted by the model for energies less than 10 eV are secondary electrons produced by impact ionization of atmospheric neutrals.

A neutral atmosphere model with densities of the major neutral species as a function of altitude is also needed for the two-stream model (Fig. 3) and is described later. The two-stream model also requires ionospheric “thermal” electron density and temperature profiles in order to determine suprathermal electron energy losses due to Coulomb collisions. We adopt RPWS/LP density and temperature values (Wahlund et al., 2005; Cravens et al., 2006; Agren et al., 2007).

Fig. 2 shows calculated electron fluxes near the top of the model atmosphere. The magnetic field line anchored at the sur-
electron flux in their modeling in order to get thermal ionospheric models of the dayside suprathermal electron fluxes by Galand et al. (2006) show good agreement between theoretical fluxes and measurements during Ta Cassini encounter agree well with spectra measured by the CAPS ELS instrument during Ta, both quantitatively and qualitatively. Both measured and calculated photoelectron spectra show the expected structure near 25 eV, associated with photoionization of neutrals by the solar HeII 30.4 nm line. Independent calculations of dayside suprathermal electron fluxes by Galand et al. (2006) show good agreement between theoretical fluxes and measured fluxes during Ta by the CAPS ELS. Dayside photoelectron flux calculations will need to be re-examined because it appears likely that the model fluxes will now be lower than the measured fluxes (after the CAPS ELS recalibration), and we are working on this now.

Models of the thermal ion and electron densities within any ionosphere require "primary" ion production rates associated with external sources such as photoionization by solar radiation, electron impact ionization, or energetic ion impact ionization (cf. Cravens et al., 2008). Ion production rates associated with suprathermal electron precipitation at a particular altitude are given by the integral over electron energy of the product of the electron flux with the ionization cross section and with the neutral density. Electron impact with N2 produces both N+ and N++ ions (about 90% and 10%, respectively) and impact with CH4 produces CH3+, CH2+, CH+, CH++, and H++ ions. Ion production from some minor neutrals such as C2H6, HCN, and CH4+ was also included in our model, but these are not important.

Fig. 5 shows N2+ and CH4+ production rates versus altitude for both T5 and T21 from 2-stream code runs for which the boundary conditions were the magnetospheric CAPS ELS spectra mentioned earlier. The production rates shown in the figure are reduced by a factor of 2.5 and are used as such in the chemical model. Production rates for other ion species were included in the chemical model, but are not shown. Ion production rates calculated for the T21 case are considerably smaller than the T5 rates, as expected since the magnetospheric electron fluxes observed by CAPS near

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**Fig. 3.** Density versus altitude profiles for several neutral species. The densities of molecular nitrogen and methane shown here were used for all the model calculations in this paper, but the minor neutral densities in this figure are just for the B4 case.

**Fig. 4.** Calculated and measured electron fluxes versus energy are shown for an altitude of 1200 km in Titan's atmosphere. The boundary electron spectrum for the model calculation was the T5 profile shown in Fig. 2.

**Fig. 5.** Production rates versus altitude for N2+ and CH4+ are shown for two cases: T5 CAPS ELS boundary electron fluxes and T21 CAPS ELS boundary fluxes, but both sets of production rates were reduced by a factor of 2.5 before being plotted.
Titan are smaller for T21 (not shown) than for T5. Fig. 5 indicates that significant ion production is present down to 800 km, well below the spacecraft CA altitude, but note that our model does not include electrons with energies greater than 5 keV and does not include energetic ion precipitation (Cravens et al., 2008), so that below about 800–900 km Fig. 5 is missing some possible sources of ionization.

At lower altitudes (z < 1100 km) the calculated ion production rates depend on the field line topology adopted but the production rates at higher altitudes are not sensitive to this topology. Only the case of magnetic field lines anchored at the surface are shown in Fig. 5. Also note that the T5 ion production rates shown here agree rather well with the production rates above 1000 km shown by Agren et al. (2007) if adjusted by the factor of 4 discussed earlier.

3. Description of the ionospheric model

Numerous models of Titan’s ionosphere have been published over the last twenty years or so (see the introduction). The basic model used in this paper was described in a series of papers (Keller et al., 1992, 1994, 1998; Keller and Cravens, 1994; Gan et al., 1992, 1993; Cravens et al., 2004, 2005). As mentioned earlier, we have now “upgraded” the chemistry in this model to include most of the chemistry (and minor neutral species) presented by Vuitton et al. (2006, 2007). Our ionospheric model has several flavors: photochemical (no time-dependence or transport), one-dimensional transport (“polar wind” type model for Titan’s wake), and one-dimensional, time-dependent MHD models. The transport versions of the models have only a few ion species and simple chemical schemes. For example, Cravens et al. (1998) published a 3-species MHD model including simple chemistry. Similarly, Ma et al. (2004) developed a 7-species three-dimensional, global MHD model with a simplified version of the Keller et al. (1998) chemical scheme. De La Haye et al. (2008a) also adopted the Keller et al. (1998) ion chemistry scheme but coupled this with a neutral chemistry scheme, and used a rotating method to account for diurnal variation of solar inputs, providing local-time dependent results at constant latitude.

Density profiles for the major neutral species as a function of altitude and position along a field line are needed for the two-stream model and for the ionospheric model. We adopted N2 and CH4 densities measured during the outbound T5 pass by the INMS in its closed source neutral (csn) mode (Waite et al., 2005a, 2005b). N2 and CH4 density profiles are extended to altitudes below the CA altitude with the Vervack et al. (2004) density profiles. Neutral density profiles for one of our several neutral model cases are shown in Fig. 3.

Table 1

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B2: INMS major and minor neutrals. Scale heights, at altitudes other than 1100 km, adjusted to achieve better results. HCN = Toublanc2. B4: CH3NH reduced by factor of 3 from B2; C2H6CN reduced by factor of 20 from B2; HCN = Toublanc2. B5: Recombination rate of HCNH+ doubled. C2/B4 altitude dependence of densities but Vuitton et al. (2006, 2007) mixing ratios adjusted to 1100 km. HCN mixing ratio is doubled from Vuitton et al. D2: Multiplied all C2 neutrals by a factor of 2.5. G5: INMS majors and most INMS minor neutrals.

A number of minor nitrile (and other nitrogen-bearing) neutral species were deduced by Vuitton et al. which we adopted for the C2 case. Vuitton et al. only reported on results at 1100 km, so for the “new” species we determined altitude profiles by adjusting the relevant minor neutral scale height to improve the ionospheric model agreement with measured INMS ion density profiles (e.g., see the ammonia/NH3+ discussion later in the paper). This is the C2 case. Note that for the “B” cases we also adopted the minor nitrile or nitrogen-bearing neutral species from Vuitton et al., but not for the other species (i.e., C2H2, C2H4, HCN, etc.). For one case (D2), we also multiplied all neutral densities (including N2 and CH4) at all altitudes by a factor of 2.5.

For the current paper we used both a photochemical ionospheric code and a time-dependent code with 71 ion species and several hundred chemical reactions. The electron density was assumed to be the sum of the densities of all ion species (i.e., quasi-neutrality is assumed). The electron temperature profile (needed for dissociative recombination rate coefficients) was taken from T5 RPWS/LP measurements (see Agren et al., 2007). Note that the temperature is $T_e \approx 500–1000$ K for most of the ionosphere. The hundreds of reaction rate coefficients needed for the chemistry are described in papers listed in the introduction and earlier in this section, and particularly by Keller et al. (1992, 1998), Vuitton et al. (2006, 2007), Anicich and McEwan (1997), and Anicich et al. (2004). Also see the discussion by Carrasco et al. (2007) on the sensitivity of Titan chemical models to uncertainties in rate coefficients.

Primary ion production is ultimately balanced by dissociative recombination. McClain et al. (2004, and references therein) dis-
cuss many of the important dissociative recombination rate coefficients. Coates et al. (2007a) described the discovery of negative ions in the lower ionosphere of Titan by Cassini. Evidently, negative ion densities can become significant below about 1000 km, but our model, focusing on higher altitudes (and also because at this moment a good understanding of the sources or sinks of negative ions at Titan does not exist), does not include negative ions.

The continuity equation for ion species \( s \) is given by

\[
\frac{\partial n_s}{\partial t} + \nabla \cdot (n_s \mathbf{u}_s) = P_s - L_s,
\]

where \( n_s \) is the density of ion species \( s \), and \( \mathbf{u}_s \) is the bulk flow velocity of ion species \( s \). \( P_s \) and \( L_s \) are the chemical production and loss rates of species \( s \), respectively. \( P_s \) includes primary production as well as production from ion–neutral chemistry. \( L_s \) includes losses due to ion–neutral chemistry and dissociative recombination. For the models presented in this paper, we neglect the transport terms (i.e., let \( \mathbf{u}_s = 0 \)). The Ma et al. (2006) global MHD calculations demonstrated that this photochemical assumption is reasonable for altitudes less than about 1450 km. For the photochemical model we solve the set of 71 equations found by setting \( \frac{dn_s}{dt} = 0 \) (that is, \( P_s = L_s \)), and for our time-dependent model we adopt time-varying primary production rates and solve the coupled 71 first-order differential equations as functions of time using a fourth-order Runge–Kutta method.

Space limitations prevent an extensive discussion of the complex chemistry operating in Titan’s ionosphere (see Keller et al., 1992, 1998; Vuitton et al., 2006, 2007; Fox and Yelle, 1997; Wilson and Atreya, 2004; De La Haye et al., 2008a; Waite et al., 2007), but a very brief summary is given in this section. The main ion species produced by electron impact ionization (\( N_2^+ \), \( N^+ \), \( CH_4^+ \), \( CH_3^+ \), etc.) were discussed earlier. Ion–neutral chemistry associated with both major neutral species and minor species (i.e., acetylene, ethylene, ethane, hydrogen cyanide, benzene, etc.) then acts to transform these “primary” ion species into a large number of complex hydrocarbon and nitrogen-bearing ion species. For example, two of the most abundant ion species predicted by pre-Cassini models (\( C_2H_5^+ \) and HCNH\(^+\)) are created via the following sequence of chemical reactions (Anicich et al., 2004):

\[
\begin{align*}
N_2^+ + CH_4 &\rightarrow CH_3^+ + N_2 + H, \\
CH_3^+ + CH_4 &\rightarrow C_2H_5^+ + H_2. \\
C_2H_5^+ + HCN &\rightarrow HCNH^+ + C_2H_4.
\end{align*}
\]

Another important reaction converts CH\(_4^+\) to CH\(_3^+\):

\[
CH_4^+ + CH_4 \rightarrow CH_3^+ + CH_3.
\] (5)

Reactions with the major neutral species (\( N_2 \) or \( CH_4 \)) are rapid so that the rate of reaction (2) almost equals the primary production rate of \( N_2^+ \) and the rate of reaction (5) almost equals the primary production rate of \( CH_3^+ \). Hence, \( CH_3^+ \), \( CH_4^+ \), and \( CH_2^+ \) ions can be considered to be primary (or almost primary) ion species. \( CH_2^+ \) is converted to \( C_2H_5^+ \) via reactions with acetylene and ethylene. \( N_2^+ \) density measurements by INMS cannot be used to assess the primary ion production rate because a much more abundant mass 28 species is HCNH\(^+\) (the most abundant species observed during T5). Reaction (4) of \( C_2H_5^+ \) with hydrogen cyanide is the main source of HCNH\(^+\) (protonated hydrogen cyanide) and the ratio of HCNH\(^+\) to \( C_2H_5^+ \) in the model output is very sensitive to the HCN density. Unfortunately, HCN cannot be accurately measured by INMS in its closed source neutral mode.

HCNH\(^+\) is chemically removed by dissociative recombination with electrons as well as by reaction with a number of rather low abundance minor neutral species, thus producing higher mass hydrocarbon and nitrogen-bearing ion species (see Fox and Yelle, 1997; Keller et al., 1998; Vuitton et al., 2006, 2007). Higher-mass ion species can also be produced by reaction of \( C_2H_5^+ \) with neutral hydrocarbon and nitrile or other nitrogen-bearing molecules.

We used our photochemical model to calculate chemical lifetimes of several ion species in different parts of the chemical scheme, and some of these are plotted in Fig. 6. The chemical lifetime for a given species is the inverse of the sum over all loss reactions of the rate coefficient multiplied by the relevant reactant abundance (i.e., density of the relevant neutral or for dissociative recombination, the electron density). Except for terminal, or almost terminal, ion species (such as \( CH_2NH_4^+ \) or \( NH_3^+ \)) these lifetimes mainly depend on the densities of the relevant neutral species acting in the loss reactions (i.e., \( N_2 \), \( CH_4 \), \( C_2H_2 \), \( HCN \), etc.). A few ion species listed in order of increasing chemical lifetime are: \( CH_4^+ \) (reaction with the major species \( CH_4 \)), \( CH_2^+ \) (reaction with \( C_2H_2 \) and \( C_2H_4 \)), \( C_2H_5^+ \) (reaction with HCN), HCNH\(^+\) (reaction with ammonia, some nitriles, and electrons), and \( CH_2NH_4^+ \) (representative of terminal ions — reaction with electrons). The transport times shown in Fig. 6 will be discussed again later. In general, except for terminal ions, the chemical lifetimes increase with altitude because the neutral reactant densities decrease with altitude. The terminal ion lifetimes (and also to a lesser extent HCNH\(^+\) lifetimes) are about a factor of 3 longer for T21 (not shown) than for T5 due to lower electron densities.

Note that the “actual” time history of the density of a species, which we determined using our time-dependent model, usually reflects the chemical lifetime, but not always. What also matters is how far down the chemical chain the species resides (see the chemical flow chart in Keller et al., 1998).
4. Comparison of ionospheric model results with Cassini data

High mass-resolution mass spectra for ion species were measured by the INMS on the outbound leg of the T5 encounter (Cravens et al., 2006). For this INMS open source ion (osi) instrument mode, ions entering the instrument aperture are deflected by a quadrupole switching lens (set to the necessary voltages) and are then guided to the radio-frequency mass analyzer, which selects ions according to their mass-to-charge ratio \( m/z \) (Waite et al., 2004, 2005a, 2005b; Kasprzak et al., 1996). The ions are then detected with a secondary electron multiplier. The field of view has a half-width of \( \approx 3^\circ \), and the instrument measures positive ions with kinetic energies appropriate for a "compensation" speed equal to the spacecraft speed (6.02 km/s in this case). Ion densities were also measured by the INMS during the T21 encounter, but (unlike T5) a high spacecraft potential existed and a large and uncertain correction factor was applied to this data set. The effects of spacecraft potential will be described in a future paper (Kasprzak et al., in preparation). Note that the INMS ion densities presented in the current paper for T5 (and now corrected for spacecraft potential) are less than about 20% different, depending on the mass number, from densities shown by Cravens et al. (2006). The current paper will show INMS data points from each 31 ms integration period available for the relevant mass number. The ion density that corresponds to 1 count is close to 0.006 cm\(^{-3}\).

The results of our photochemical model are now compared with INMS and RPWS/LP data. Several different assumptions concerning the magnetic field topology and the neutral composition were made, as discussed earlier. Table 1 lists relative neutral abundances for several model cases and for an altitude of 1100 km. Note that calculated electron density profiles do not depend much on details of the ion–neutral chemistry or on the abundances of minor neutrals, but they do depend on dissociative recombination rate coefficients and on the primary ion production rates. Fig. 7 shows electron density profiles for several model runs all with the parabolic magnetic field lines anchored at the surface and all with a factor of 2.5 reduction of the incident magnetospheric electron fluxes (from CAPS ELS). The measured and model electron density profiles agree reasonably well (within a factor of \( \approx 3 \)) particularly near 1400 km. The densities appear to be somewhat too large near 1100 km, suggesting that at lower altitudes a production rate correction factor more than a factor of 2.5 would be helpful.

Fig. 8 shows electron density profiles for just one neutral model case but for three different field line configurations. All these profiles were obtained using the factor of 2.5 incident electron flux reduction factor. The calculated densities would have been about 60% higher than measured densities at 1400 km without this factor. Note that even better model-data agreement would have been obtained at lower altitudes if a factor of 5–10 reduction in the incident electron flux had been used at lower altitudes (i.e. for higher energy incident electrons). Interestingly, the factor of 10 is the same depletion factor that looks best for the secondary electron fluxes (Fig. 4). The most dramatic differences between the 3 model density profiles are evident below 1000 km, where \textit{in situ} spacecraft data is not available.

Now we describe model-data comparisons for \( \text{CH}_3^+ \). This is an almost “primary” ion species created by reaction of \( \text{N}_2^+ \) with methane (reaction (2)) and its production rate is essentially that of \( \text{N}_2^+ \). The evident rather good agreement (except for small-scale variations) for this species indicates that the model has a reasonable \( \text{CH}_4 \) density as well as a reasonable primary production rate of \( \text{N}_2^+ \). Details of the minor neutral composition are not important. The reasonable agreement between model and data also confirms that our primary ion production rate does need a reduction factor of at least 2.5. The B4F10 case (our “standard” factor of 2.5 incident flux correction factor more than a factor of 2.5 would be helpful.)

Fig. 7. Calculated electron density versus altitude profiles are shown for the case of the parabolic magnetic field anchored at the surface of Titan and for several different model atmospheres as described in the text. A scale is also shown at the top for spacecraft time from closest approach (CA). Also shown is the electron density profile for the outbound leg of the Cassini T5 pass measured by the Langmuir probe on the RPWS/LP experiment (see Agren et al., 2007 and Cravens et al., 2006). Also shown is the total ion density profile from the INMS experiment. The vertical dashed line indicates the closest approach (CA) altitude of Cassini (1027 km).

Fig. 8. The same as Fig. 7 but the calculated electron density profiles are all from the same neutral model atmosphere case (G1). However, 3 different magnetic field line configurations were used — radial field, parabolic anchored at the surface, and parabolic anchored at an altitude of 725 km.

Fig. 9. Calculated density versus altitude profile for \( \text{CH}_3^+ \) for several model cases (different labeled lines). Also shown are the \( m = 15 \) densities measured by the INMS on T5. One sigma statistical error bars were shown for a couple of the INMS data points, but do not encompass all possible sources of error.
model) does better at higher altitudes, and the B4F20 case (factor of 5 flux reduction) does better near closest approach, again suggesting a larger flux reduction factor at lower altitudes. The model version (case C2) using all of the Vuitton et al. neutral mixing ratios also does very well. Similar conclusions are reached for CH$_4^+$ comparisons (Fig. 10). CH$_4^+$ is produced by ionization of CH$_4$ and is lost via reaction with CH$_4$, and again the model-data agreement mainly reflects on the basic primary ionization process.

Fig. 11 shows data-model comparisons for CH$_5^+$. In this case, the calculated densities are sensitive to the abundances of some “minor” neutral species (C$_2$H$_2$, C$_2$H$_4$, and H$_2$). Most of the model cases do reasonably well above about 1300 km, but at lower altitudes the agreement is not good (model densities are $\approx$5 times too high). The factor of 5 reduction model case (B4F20) does better than case B4F10 at lower altitudes. The best agreement is obtained with a model case (D2) for which C$_2$H$_2$ and C$_2$H$_4$ densities are larger. The Vuitton et al. (2006, 2007) model densities are also too high for CH$_5^+$.

We now discuss C$_2$H$_5^+$ (Fig. 12). This ion species is mainly produced from CH$_5^+$ and its abundance is very sensitive to the HCN density. Considerable differences are present between different model cases for which the HCN density differs. Again, the B4F10 and C2 models are better than the B4F20 model at higher altitudes but not at lower altitudes. We found that it was difficult to obtain simultaneous good agreement for both C$_2$H$_5^+$ and for HCNH$^+$ at all altitudes by varying the HCN altitude profiles alone. Fig. 3 shows our adopted HCN profile for case B4F10, and from Table 1 the relative HCN abundance at 1100 km is $1.34 \times 10^{-3}$.

Fig. 13 shows data-model comparisons for HCNH$^+$, an important ion species which is mainly produced by reaction of C$_2$H$_5^+$ with HCN (reaction (4)). The density of this species is sensitive to the HCN abundance. All the model cases show reasonable agreement for altitudes above 1200 km, and model C2 works best below this altitude, although none of the cases are great. The main problem is probably with the details of the HCN profile. The model case that works best for the combination of HCNH$^+$ and C$_2$H$_5^+$ comparisons is C2 but case D2 also works well.

Note that the modeled HCNH$^+$ density, as well as the electron density, falls off with altitude more slowly than the data does for altitudes above about 1450 km. Transport processes are expected to become more important than chemistry at higher altitudes (see time constants in Fig. 6) and photochemical models, such as ours, are no longer valid. Dynamical models are needed at higher altitudes, such as the multispecies MHD model of Ma et al. (2006).

An important higher-mass hydrocarbon species is C$_3$H$_5^+$. This species is mainly produced by reaction of C$_2$H$_5^+$ with C$_2$H$_4$ and it is lost via reaction with C$_2$H$_4$ and C$_2$H$_2$, producing even higher-mass hydrocarbon ion species such as C$_5$H$_9^+$. Comparisons are shown in Fig. 14.

Figs. 15 and 16 show density profiles of two terminal ion species, CH$_2$NH$_2^+$ and NH$_4^+$, respectively. The data-model agree-
ment is excellent for these species for some cases because the neutral ammonia and CH$_2$NH density profiles were designed to do just that (cf. Vuitton et al., 2006, 2007). A simple approximation (Cravens et al., 2006) to the NH$_4^+$ density is given by $[\text{NH}_4^+] \approx k[\text{NH}_3]/\alpha \approx 10^{-3}[\text{NH}_3]$, where $k$ is the rate coefficient for the reaction of any major ion species with NH$_3$ and $\alpha$ is the NH$_4^+$ dissociative recombination rate coefficient. A relative abundance of NH$_3$ of about 4 parts per million gives good data-model agreement.

Detailed altitude profiles were shown only for a few ion species in this section. Fig. 17 shows a complete comparison with INMS data of one of our calculated mass spectra (case B4) for an altitude of 1100 km. The data-model agreement is reasonable within a factor of 2 for most species ($m = 17$, CH$_5^+$ has worse agreement). Although we are essentially using the Vuitton et al. chemistry, the primary ion production rates used in the current paper are somewhat different and the minor neutral abundances are only identical for the C2 case. Note that a similar data-model spectrum comparison for C2 actually has better agreement for HCNH$^+$ than the agreement shown in Fig. 17 but worse agreement for C$_2$H$_5^+$. More details on the ionospheric chemistry can be found in the Vuitton et al. papers and also in De La Haye et al. (2008a).

What has been learned from the comparison of the INMS ion composition with the several model cases shown in this paper? First, reproducing the overall large-scale altitude variations in ion densities requires that the models have the correct minor neutral composition (e.g., HCN, C$_2$H$_2$, C$_2$H$_4$, etc.) and the associated ion–neutral chemistry. All the models shown in this paper meet this qualification. Second, the models show great variability in the factors of 2 to 3 range and depend on the details of the minor neutral composition. The details of the minor ion composition can be exploited to further understand minor neutral composition, as discussed by Vuitton et al. (2006, 2007) but this is outside the scope of the current paper. Third, the total ion density (or electron density) profile is not sensitive to the details of the minor ion or neutral composition.

All the above results were for T5 conditions but some model runs were also carried out for T21 conditions. As described earlier, magnetospheric electron fluxes measured by the CAPS ELS (and, hence, the ion production rates in the ionosphere — Fig. 5) were smaller for T21 than for T5. Calculated and measured electron densities are both shown in Fig. 18. The spacecraft potential during T21 was rather large (exceeding negative 2 V), which necessitated a large (and uncertain) INMS transmission correction (Kasprzak et al., in preparation). However, the relative ion composition measured by the INMS should be reasonably accurate. The electron densities measured by the RPWS/LP (not subject to the same spacecraft potential effects as INMS) for T21 are clearly about a factor of 4 less than the T5 densities. This is consistent with lower ion production rates for T21 than for T5 and is consistent with the lower magnetospheric electron fluxes observed by the CAPS ELS for T21. Note that in order to obtain data-model agreement, the incident CAPS electron fluxes must again be reduced by
a factor of about 2.5–10, just as for the T5 case. Fig. 18 also shows HCNH$^+$ INMS density measurements and model results.

All the ion density profiles produced by the model vary smoothly with altitude because the calculated ion production rate profiles did not exhibit much altitude variation. The measured electron density profiles (and total ion density profiles) as well as many of the individual ion density profiles are essentially smooth (HCNH$^+$ or CH$_2$NH$^+$_5, etc.), but many other ion species (CH$_5^+$, CH$_5^+$, CH$_2$H$_5^+$, etc.) exhibit significant altitude (or time or horizontal distance along the spacecraft track) variations. An examination of the chemical lifetimes (Fig. 6) indicates that “smooth profile” species have longer chemical lifetimes and structured species have shorter chemical lifetimes (R. Yelle, October 2006 DPS). The small-scale structure will be discussed in more detail in the next section.

5. Small-scale variations in the T5 ionosphere

In this paper we have displayed ion densities as functions of altitude, although Fig. 7 also has a time-scale. Cravens et al. (2006) displayed the T5 INMS densities versus spacecraft time and solar zenith angle. In fact, altitude, time, and horizontal location (partially characterized by solar zenith angle) all vary together and are “confounded” variables. The larger-scale structure of the ion densities probably does primarily depend on processes organized by altitude (as has been assumed throughout this paper), but this might not be appropriate for small-scale structure. For example, CH$_5^+$ (or C$_2$H$_5^+$) has a local density maximum and a minimum at altitudes of 1140 km and 1220 km, respectively, giving an altitude separation of about 100 km. These altitudes correspond to spacecraft times with respect to closest approach of about 155 s and 205 s, respectively. The temporal separation of the maxima and minima is about 50 s, corresponding to a distance along the spacecraft track (this is largely “horizontal”) of about 300 km using a spacecraft speed of 6 km/s. Other small-scale variations are also evident in the outbound T5 ion density data. Note that chemically longer-lived ion species do not exhibit much small-scale structure (e.g., CH$_3$NH$_3^+$) or do so only to a lesser extent (e.g., HNCH$^+$). Recall that the ionosphere is chemically controlled in this 1200 km region.

Ion production rate profiles calculated by Agren et al. (2007) for the precipitation of monoenergetic incident electrons exhibit altitude widths far exceeding 100 km, which leads us to conclude that altitude/time structures in the observed densities cannot be explained by discrete energy structures in the incident magnetospheric fluxes. In any case, the energy spectra measured by CAPS ELS outside Titan display a broad range of energies (see Figs. 1 and 2). By process of elimination, it seems that small-scale ionospheric density structures should be associated with temporal or horizontal (i.e., different magnetic flux tubes) variations in the incident magnetospheric electrons rather than being altitude structures.

As discussed earlier, primary electrons as they travel down field lines lose energy via inelastic collisions with the neutral atmosphere. The electrons also experience some scattering due to elastic collisions. Secondary electrons are created via impact ionization of atmospheric neutrals. Lower energy (few eV) secondary electrons lose energy primarily via vibrational excitation of N$_2$ and CH$_4$. Secondary electrons are evident in the CAPS ELS color spectrograph (Fig. 1) for times when Cassini was within the ionosphere (e.g., near CA). A quick examination of this spectrograph also suggests the presence of some short temporal variations in the secondary electron fluxes. Fig. 19 shows both the CAPS ELS count rate for 4.06 eV electrons and the CH$_5^+$ density measured by INMS plotted versus time. Recall that CH$_5^+$ is an “almost” primary ion species whose abundance almost directly relates to the production rate of CH$_5^+$. The CAPS ELS 4 eV electron count rate and the CH$_5^+$ density track each other quite well. A similar result (not shown) was obtained for CH$_3^+$, an ion species whose density almost directly relates to the N$_2$ production rate.

Fig. 19 strongly suggests that the incident electron flux is different for different horizontal locations which are in turn associated with different magnetic flux tubes. However, the density profiles of chemically longer-lived species do not exhibit the small-scale structure that the primary species do, which would have been the case if the electron flux at the top of each flux tube persisted at the same level for a very long time. This suggests that the incident electron fluxes not only differ from flux tube to flux tube, but that the incident electron flux on each magnetic flux tube also has some intrinsic time variation.

Fig. 19 also indicates that the secondary electron flux seen at the spacecraft increases overall by a factor of 4 or so from closest approach to a time of ~300 s after CA. Superimposed on this trend was the “periodicity” mentioned earlier, and in particular a 50% increase and decrease for times of about 150 to 250 s. For altitudes below about 1400 km, where the mean free path of low energy electrons is less than 100–200 km (i.e., the electrons are local), the secondary electron flux should be approximately independent of the neutral density and be proportional to the primary (100 eV–several keV energies) electron flux. The ion production rate depends on both the N$_2$ density and the primary electron flux. Fig. 19 thus indicates that the primary electron flux is about...
3 times greater for the flux tubes near 300 s than for flux tubes near CA. Combining that deduction with the T5 geometry shown by Agren et al. (2007), it seems possible that the flux tubes near the spacecraft location at CA had resided longer in Titan’s ionosphere than the flux tubes encountered near 300 s because these flux tubes are deeper in the atmosphere than the other flux tubes.

6. Ionospheric dynamics

The interaction of Saturn’s partially co-rotating magnetospheric plasma with Titan is quite complex due to the combination of solar and magnetospheric ionization inputs, due to the typically submagnetosonic, yet super-Alfvénic, upstream flow, due to the presence of multiple ion species, and due to the large upstream ion gyroradii (cf. Hartle et al., 1982, 2006; Ledvina and Cravens, 1998; Ma et al., 2007; Backes et al., 2005; Modolo et al., 2007; and many other references). The nominal ram direction of the magnetospheric flow during the outbound portion of the T5 encounter was on the nightside (see the schematic in Agren et al., 2007). The measured magnetic field strength was \( \approx 5-10 \, nT \) in the ionosphere, and the field was oriented at an angle of \( \approx 45^\circ \) from the horizontal, even deep within the ionosphere. Global dynamical models of the interaction (i.e., global MHD or hybrid models) for T5 have not been published to our knowledge. However, modeling of other Titan encounters (Ma et al., 2007; T9; Ta) suggests that the magnetic field should be highly draped in the ramside ionosphere (and hence be almost horizontal) at least on the dayside, whereas the field observed at T5 definitely had a significant radial component.

A full consideration of the plasma dynamics during T5 is beyond the scope of the current paper, but in this section we present some simple estimates of ionospheric plasma transport times in order to put the chemical lifetimes (Fig. 6) into context. We start by assessing the terms in a simple single-fluid MHD momentum equation (i.e., equation of motion) appropriate for the ionosphere. The Eulerian form of the single-fluid MHD equation can be written as (cf. Cravens, 1997)

\[
\rho \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \times \mathbf{B} + \rho \mathbf{g} - \rho \mathbf{v}(\mathbf{u} - \mathbf{u}_n)
\]

where \( \rho = n_i m_i \) is the mass density, \( n_i = n_e \) is the total plasma density, \( m_i \) is the average ion mass, \( \mathbf{u} \) is the bulk flow velocity, \( \mathbf{u}_n \) is the neutral flow velocity, \( p_i \) and \( p_e \) are ion and electron thermal pressures, \( p = p_e + p_i \) is the total thermal pressure, \( \mathbf{B} \) is the magnetic field vector, \( P_i \) is the ion production rate, \( g \) is the acceleration due to gravity, and \( \mathbf{v} \) is the ion–neutral momentum transfer collision frequency. \( \mathbf{J} \) is the current density.

Equation (8) is rearranged in order to obtain estimates of the plasma flow speed (\( u \)) as a function of altitude. The plasma flow within the atmosphere should normally be slow enough for the inertial terms to be neglected (i.e., left-hand side of equation), and the curvature/tension force from the \( \nabla \mathbf{B} \) term has been thrown out. We also neglect the mass-loading term (i.e., the \( \mathbf{P}_i \) term on the right-hand side of the equation). Both thermal and magnetic pressure gradients are estimated as pressures divided by length scales of \( L_p \) or \( L_B \), respectively. Estimates of “typical” vertical or horizontal scale-length scales will be introduced later. We further convert the square of the magnetic field divided by the plasma mass density to an Alfvén speed, \( V_A \), and similarly convert the thermal pressure term to a sound speed, \( V_s \). Solving for a “diffusion-like” plasma flow speed (cf. Schunk and Nagy, 2000; Cravens, 1997), we find:

\[
u \approx \left( \frac{V_A^2}{L_p} \pm \frac{V_s^2}{L_B} \pm g \right) / \rho
\]
The interaction situation for T5, in which the ram flow is “op-
posed” by a nightside ionosphere with rather low densities, seems
to have some features that differ from a dayside-ram case. The
Cassini magnetometer data indicates that the magnetic field has a
significant radial component, yet the estimated ion flow speeds deep
within the ionosphere are quite low (less than a few m/s
at 1100 km using Fig. 6 transport times), implying significant field
line draping (i.e., mainly horizontal fields). Perhaps the bulk elec-
tron flow is not tightly tied to the bulk ion flow (i.e., due to
electrical currents). That is, perhaps “Hall” effects are especially
important in the nightside ionosphere. Ma et al. (2007) showed
that Hall and regular MHD simulations gave different results in Ti-
tan’s magnetotail for T9 conditions. Note that magnetic flux tubes
are tied to the electron flow rather than the ion flow, at least as
long as the magnetic Reynolds number stays larger than unity. But
Hall effects could be important and affect magnetic flux transport
(and flux tube “hang up” times in the ionosphere) for sufficiently
large current densities, carried by a relatively low density plasma.
Simple estimates for the T5 ionosphere support this conjecture.
For $z \approx 1100$ km, electron flow speeds of $\approx 200$ m/s are needed
to carry the electrical currents that generate a 5 nT field variation
over a length-scale of 100–200 km. The horizontal convection time
for a distance of about 1000 km and 200 m/s is $\approx 1$ h, which is
much less than the horizontal ion convection time shown in Fig. 6
at this altitude. Detailed plasma simulations are needed to shed
more light on this scenario and on flux tube transport. Also note
that the magnetic Reynolds number becomes comparable to, or
less than, unity, at low enough altitudes due to Ohmic resistivity.
The magnetic field is then able to “diffuse” so that field lines are
not tied to either the electron or the ion gases (cf. Cravens, 1997).
Using Cassini T5 data we estimate that this transition altitude is at
about 1100 km for T5.

7. Discussion

The structure of Titan’s nightside ionosphere evidently does not
have a single simple explanation for all its features. The overall
large-scale trends of the measured ion densities between altitudes
of 1027 km and about 1500 km appear to be mainly altitude-
related features that can be explained by: (1) ion production rates
(and their altitude dependence) due to precipitation of suprather-
mal electrons with an incident spectrum like that observed by
the CAPS ELS instrument in the nearby magnetosphere of Saturn
(albeit with a roughly factor of 2–10 reduction), and (2) chem-
ical losses associated with ion–neutral chemical reactions and/or
dissociative recombination reactions with altitude-dependencies
that are associated with the vertical distributions of many neu-
tral species (i.e., major species such as $N_2$ and $CH_4$, as well as
minor species such as HCN, C$_2$H$_2$, NH$_3$, etc.). For altitudes above
about 1400–1500 km, an examination of time constants indicates
that transport as well as chemistry starts to control the ioni-
spheric structure (see Ledvina and Cravens, 1998; Ma et al., 2007;
Agren et al., 2007).

The smaller-scale structure (unlike most of the larger-scale
trends) evident in chemically short-lived ion species profiles ap-
ppears to be horizontal or temporal structures. The correlation of
the densities of “primary” ion species with secondary electron
fluxes observed by CAPS strongly suggests that the small-scale
variations are related to differences in the incident suprathermal
electron fluxes coming from the magnetosphere at different loca-
tions/times across the nightside of Titan. Given that we adopted
a factor of 2.5–5 electron flux reduction for the overall struc-
ture, this suggests that at some locations the flux reduction factor
should be either greater or less than this by another factor of 2
or so. However, it also seems that the incident electron flux at
the “top” of each magnetic flux tube cannot be entirely steady,
or all ion species (chemically short-lived and long-lived) would
exhibit the same small-scale variations, yet species like HCN$^+,
$ have much smoother profiles than species like CH$_3^+$. The incident
magnetospheric fluxes must both vary from flux tube to flux tube
and must also have some “intrinsic” temporal variation with time
scales greater than the chemical lifetime of species like CH$_3^+$
yet
less than the lifetime of species like NH$_2^+$ or HCN$^+$. An exami-
nation of Fig. 6 suggests that an “intrinsic” flux time scale for the
incident magnetospheric electrons of roughly 1000 s might do the
job for the 1000–1350 km region.

What is the explanation for the temporal (or horizontal) vari-
ations in the incident magnetospheric electron flux? What is re-
ponsible for the factor of 2.5–10 reduction in the required inci-
dent electron fluxes relative to unperturbed outer magnetospheric
values? Answering these questions requires a detailed understand-
ing of how Saturn’s magnetic field and the outer magnetosphere
interact with Titan, and in particular, how suprathermal electrons
participate in this process. Such an understanding does not yet ex-
ist but results presented in this paper can perhaps provide some
insight.

Electrons with keV or less energies are tied to magnetic field
lines (gyroradii of $\approx 10–20$ km for 5–10 nT magnetic fields)
for altitudes above about 900 km. Below this altitude the electron-
neutral collision frequency exceeds the gyrofrequency and elec-
trons become “unmagnetized.” Magnetic flux tubes pushed into
Titan’s atmosphere by the interaction with the external flow act
as conduits for the transport/precipitation of magnetospheric elec-
trons. On the other hand, energetic magnetospheric ions are not
very sensitive to the magnetic field topology near Titan (cf. Ledvina
et al., 2005; Cravens et al., 2008). Suprathermal electrons mov-
ing along field lines that thread deep enough into the atmosphere
lose energy via collisional excitation and ionization of neutrals, so
that the suprathermal electron fluxes are attenuated. Some frac-
tion of the incident electrons are also scattered back out of the
atmosphere due to elastic collisions and lower energy electrons
(secondary electrons for the nightside and solar-produced photo-
electrons on the dayside) escape from Titan’s atmosphere out into
Saturn’s magnetosphere.

Electrons in Saturn’s magnetosphere are trapped by Saturn’s
approximately dipole magnetic field (with stretching in the plas-
mash, etc., as described by the Cassini MAG team — Dougherty
et al., 2005), bouncing between mirror points closer to the planet.
A magnetic flux tube has a finite electron content, and if such a
flux tube becomes attached to Titan’s atmosphere, then the whole
tube should gradually become depleted with a time scale of the
bounce period (for electrons of a given energy) within Saturn’s
magnetic field, unless processes such as cross-field diffusion can
replenish the flux tube over the same time-scale. Gan et al. (1993)
investigated this scenario using a two-stream electron interaction
model for Titan (Gan et al., 1992). Gan et al. carried out a series
of 2-stream calculations in which the downward electron flux at
the upper boundary was set equal to the calculated upward flux at
earlier times with a time delay equal to the electron bounce time
at the relevant electron speed/energy. Fig. 20 shows a schematic
of saturnian magnetic field lines being draped around Titan. The
time to the mirror point and back to Titan is $\approx 720$ s for 100
eV electrons and is about 240 s for 1 keV electrons. Parabolic
field lines (within Titan’s ionosphere) were assumed, and the apex
was moved radially inward with a convection speed that varied
linearly with radial distance. Gan et al. demonstrated that 1 keV
electron fluxes take about 500 s to attenuate a factor of 2 and
100 eV fluxes take about 1000–1500 s. The lower energy electron
fluxes (tens of eV) in the Gan et al. simulation actually increased
with time due to photoelectron production within the sunlit Titan
atmosphere, but this is not applicable to our nightside case.
Gan et al. (1993) adopted rather arbitrary assumptions about flux tube convection through the atmosphere, but qualitatively such flux tube depletion must be taking place. As discussed earlier, INMS data (and the associated model comparisons) seem to indicate that the primary electron flux varies from magnetic flux tube to flux tube, with perhaps the near-CA region being associated with the oldest and most depleted flux tubes. The intrinsic temporal variation due to depletion on a given flux tube are supported by the small scale variations seen by INMS in primary ion species but not long-lived species. In fact, it seems surprising that the electron flux depletions for magnetic tubes “hung up” in Titan’s ionosphere do not greatly exceed the factors of 2.5–10 we found with our data-model comparisons using the CAPS ELS inputs. There are several possible explanations:

1. Electrons diffuse across magnetic field lines and replenish the electron content of a magnetic flux tube attached to Titan on time scales of about 600 s.
2. The flux tube moves through Titan’s atmosphere more quickly than one might expect and is “hung up” for times less than 600 s (this would require tube speeds in the atmosphere of \( \approx 1 R_T / 600\) s or 4 km/s, which is an extremely large velocity (note that 100 m/s or much less would be expected from the dynamics for altitudes below 1200 km so).
3. The backscattered electron flux (see Fig. 2) might be much larger than our model predicts so that the electron content in a flux tube can last for several bounce periods (although this would also reduce the flux that actually makes it into the atmosphere).
4. For the long-lived chemical species, some plasma might be flowing from the dayside and help support larger densities than the “immediate” ion production rates would imply (this idea is discussed more in the next paragraph), but this would not help with the short-lived species or with the atmospheric suprathermal electron model-data comparisons (i.e., Fig. 19).

We used the time-dependent version of our ionospheric model to investigate how the ionosphere responds to time-varying primary ion production rates. We present just one case here for an altitude of 1200 km. The initial conditions are from the chemical model (factor of 2.5 depleted production rates and case B4), and then the time-dependent version of the model is run for an altitude of 1200 km. The initial conditions are from the photochemical model (factor of 2.5 depleted production rates and case B4), but with an exponential decay (with time constant \( \approx 600\) s) between a time of 10000 s and 15000 s. At a time of 15000 s the “standard” production rates were re-introduced but with an extra factor of 10 reduction factor.

8. Conclusions

Model-data comparisons presented in this paper suggest that the overall, large-scale structure can largely be organized in terms of altitude and that the density profile of a given ion species depends on: (1) the distribution of neutral densities for both major (N\(_2\) and CH\(_4\)) and minor (HCN, C\(_2\)H\(_2\), etc.) neutral species, and (2) the altitude-dependent primary ion production rates (e.g., for N\(_2^+\), N\(_3^+\), CH\(_2^+\), CH\(_3^+\), etc.) that result from impact ionization by electrons precipitating from Saturn’s magnetosphere. Success was obtained for both T5 and T21 for ion production rates consistent with electron energy spectra measured by the Cassini CAPS-ELS instrument in the nearby magnetosphere, but the incident electron fluxes had to be reduced by a factor of about 2.5 to 10 (the larger reduction being for the lowest altitudes near 1027 km). A factor of \( \approx 8\) was needed to obtain good agreement between the theoretical suprathermal electron fluxes at 1200 km and the ones measured by the CAPS ELS at that altitude.

We now make a few summary comments on the ion composition results of the paper. Several model cases with different minor neutral compositions were considered in this paper. We learned that the ion density structure observed on the nightside of Titan by INMS can be explained for larger length/altitude scales within factors of 2–3 accuracy. But achieving better accuracy requires a careful assessment of the minor neutral composition and knowledge of the ion-neutral chemistry, which is beyond the scope of the current paper. Two other limitations of the current study are that we did not present results for mass numbers greater than the 100 Dalton upper limit of the INMS, and we did not include negative ions. Some ionospheric models have included some positive ion species with mass numbers well beyond 100 Daltons (e.g., Keller et al., 1998; Vuitton et al., 2007) and the Cassini CAPS instrument measured (as yet unpublished) ion mass spectra beyond 100 Daltons, but our understanding of this high-mass chemistry is still poor. Similarly, the Cassini CAPS ELS detector observed negative ions in the lower Titan ionosphere (Coates et al., 2007), but our understanding of the associated chemistry is almost nonexistent (cf. Waite et al., 2007).

Smaller-scale (i.e., \( \Delta z \approx 100–200\) km or time-scales of 100 s or so) structures evident in chemically short-lived ion species (but not long-lived species) require for their explanation ion production rates and incident electron fluxes that vary by factors of 2 or so from location to location (and hence from magnetic flux tube to...
magnetic flux tube) on Titan's nightside. This was supported by the correlations shown in the paper between low energy electron fluxes measured by the CAPS-ELS instrument and the measured density of CH$_4$. The different temporal responses of short and long-lived ion species can perhaps be used as a “clock” to study the temporal history of magnetic flux tubes caught up in Titan's ionosphere. A time constant of a few hundred seconds appears to be required to explain the ionospheric structure for T5 (intermediate between the chemical lifetimes of the primary and terminal ion species in Fig. 6). And this time-scale of 600 s is approximately a bounce period in Saturn's magnetosphere for a few hundred eV electron.

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