Energetics of Titan’s ionosphere: Model comparisons with Cassini data

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[1] Observed electron and ion temperatures in planetary ionospheres are higher than the neutral temperature. Instruments on board the Cassini spacecraft have shown this is also true for Titan. The Radio and Plasma Wave Science Langmuir Probe (RPWS-LP) (Wahlund et al., 2005) has measured electron temperatures above 1000 K. Ionospheric ion temperatures were deduced from a combined analysis of data from the Cassini Plasma Spectrometer and Ion and Neutral Mass Spectrometer (INMS) (Cravens et al., 2009). Elevated electron temperatures attributed to heating by suprathermal electrons were predicted by pre-Cassini models (e.g., Gan et al., 1992; Roboz and Nagy, 1994) and observed by the Cassini electron spectrometer. Models of the energetic electrons and ions are presented that include Cassini inputs (i.e., measured neutral densities from INMS). The results are compared between 800 and 1800 km with suprathermal electron fluxes and plasma temperatures measured by Cassini instruments emphasizing the thermal electron temperature. Using only solar inputs, the dayside model agrees well with electron temperatures measured by RPWS-LP (Ågren et al., 2009) between 1000 and 1400 km. At higher altitudes energy input from magnetospheric electrons is needed to reproduce the measured temperature. Incorporating typical magnetospheric electron fluxes into the dayside does not noticeably increase ion production near the ionospheric peak; however, effects can be seen near 1350 km. Joule heating effects are shown to be capable of contributing significantly to the ion temperature. Magnetospheric suprathermal electrons are shown to provide sufficient heating for the thermal electron population in the middle to upper ionosphere on the nightside.


1. Introduction

[2] Radio occultation data generated from Voyager 1 [Bird et al., 1997] and the Cassini Science Subsystem [Kliore et al., 2008], as well as in situ measurements made by the Cassini spacecraft (see review by Cravens et al. [2009a]), have shown that an ionosphere exists on Titan above 400 km with peak ionospheric electron densities between 900 and 1200 km depending on the conditions of Titan [Wahlund et al., 2005; Young et al., 2005; Keller et al., 1992, 1998; Gan et al., 1992; Cravens et al., 2004, 2005, 2008; Galand et al., 1999; Banaszkiewicz et al., 2000; Molina–Cuberos et al., 2001; Lilensten et al., 2005a, 2005b; Ågren et al., 2007; Kliore et al., 2008]. On the dayside of Titan, photoionization of the neutral atmosphere from solar irradiance is usually the dominant source of the ionosphere above 800 km [Robertson et al., 2009; Cravens et al., 2004, 2005]. Electron impact ionization of the neutral atmosphere by energetic electrons from Saturn’s outer magnetosphere has been shown in models to adequately reproduce the nightside ionosphere in some cases, e.g., T5 (flybys are labeled in chronological order, such as Ta, Tb, Tc, and then T followed by a sequential number) [Cravens et al., 2006, 2009b; Ågren et al., 2007].

[3] Titan’s neutral atmosphere is primarily composed of nitrogen and methane with a few minor hydrocarbon and nitrile species [Waite et al., 2005, 2007; Vuitton et al., 2006, 2007; Magee et al., 2009]. In situ measurements of the ion composition were first conducted by the Ion–Neutral Mass Spectrometer (INMS) on the Cassini spacecraft on the outbound leg of the T5 flyby of Titan [Cravens et al., 2006]. The temperature of the neutral atmosphere is estimated to be between 145 and 160 K [Waite et al., 2005; Vervack et al., 2004; Shemansky et al., 2005; De La Haye et al., 2007].

[4] Titan has no intrinsic magnetic field, and data from the Voyager 1 encounter with Titan [Hartle et al., 1982; Neubauer et al., 1984] showed that Saturnian magnetic field lines drape around Titan. Cassini observations of the magnetic interaction with Titan have confirmed this [cf. review by Sittler et al.,]
2009]. It has been shown that the magnetic field line topology is important for models of Titan’s ionosphere and its energetics [Roboz and Nagy, 1994; Gan et al., 1992; Cravens et al., 2005, 2009b; Robertson et al., 2009; Galand et al., 2006]. The details of the field topology are less important for the energetics than the degree to which the field lines connect different altitudes.

[5] Thermal electron temperatures were first measured in the ionosphere during the Cassini Ta flyby of Titan by the Langmuir Probe (LP), part of the Radio and Plasma Wave Science (RPWS) experiment [Wählund et al., 2005]. Temperatures and densities of ionospheric thermal electrons (that is, electrons with energies less than about 1 eV) were measured by RPWS/LP with temperature values measured to be between 400 and 1200 K [Agren et al., 2009]. Energetic suprathermal electrons with energies ranging from 10s of eV for photoelectrons to MeV for electrons in Saturn’s magnetosphere were also measured by the Cassini Plasma Spectrometer (CAPS) [Coates et al., 2007] and the MIMI instrument (Magnetospheric Imaging Instrument) [Krimigis et al., 2005] both in Titan’s ionosphere and in the nearby Saturnian magnetosphere. Prior to the Cassini mission Gan et al. [1992, 1993] modeled ionospheric suprathermal fluxes using a two-stream method originally constructed by Nagy and Banks [1970] for the terrestrial ionosphere. Post-Cassini models of suprathermal electron fluxes using this general approach have been discussed for the nightside [Cravens et al., 2009b] and the dayside [Galand et al., 2006; Robertson et al., 2009].

[6] Prior to the Cassini mission a one-dimensional heat transport (along the magnetic field lines) model of electron temperatures was developed by Gan et al. [1992], and a one-dimensional electron and ion temperature model was created by Roboz and Nagy [1994]. In both of these models the energy equation for thermal electrons was solved. Roboz and Nagy [1994] indicated that the electron temperatures \( T_e \) above 1000 km had reached a steady state. [7] Post-Cassini, Galand et al. [2006] presented an electron energetics model (thermal energy equation and suprathermal electron transport equation) for Titan and compared modeled electron temperatures with data for the first pass of the Cassini spacecraft through Titan’s upper atmosphere (i.e., the Ta encounter). Note that subsequent Cassini passes, or encounters with Titan, are labeled Tb, Tc, T1, T2,..., although the current paper focuses on just two passes (T5 and T18) as described later. The energetics model of Galand et al. [2006] generated temperatures at two locations (near 1200 and 1350 km) on two separate magnetic field lines using independent solutions of the energy equation. Galand et al. [2006] also noted that the electron temperature along a radial field line was too low by several hundred K because heat from the upper atmosphere is readily conducted to lower altitudes where the cooling rate is large. No comparisons or temperatures were provided below 1200 km. The post-Cassini electron energetics model of Ma et al. [2009] demonstrated that structure of the magnetic field lines at Titan is very complex and that the magnetic field produced by MHD models does not generally agree with magnetometer data at lower altitudes below 1300 km or so [Ulusen et al., 2010]. This suggests that usefulness of using detailed field line topology from MHD models in ionospheric energetics models is limited. In this paper we adopt rather simple field-line topologies in order to explore how basically radial versus horizontal field configurations affect the electron energetics.

[8] Crary et al. [2009] recently showed a measured global average ion temperature altitude profile. The profile has a temperature minimum of about 110 K around 1250 km, and an approximate temperature of 260 K is reached at an altitude of 1600 km. Crary et al. [2009] compared data from the CAPS Ion Beam Sensor (CAPS-IBS) and INMS to generate ion fluxes as a function of energy that were fit to a Maxwellian distribution. The width of the peak ion flux is related to the thermal velocity of the ion species and hence the temperature of the ions. In order to obtain their global average results, data was collected from 14 flybys of Titan with varying solar zenith angles and at varying Saturn local times.

[9] The works of Gan et al. [1992], Roboz and Nagy [1994] and Galand et al. [2006] are the only works to date that present detailed calculations of the electron temperature at Titan. Gan et al. [1992] showed with their pre-Cassini model that solar ionizing radiation is the dominant source of electron heating on the dayside. Galand et al. [2006] used horizontal magnetic field lines (that is, field lines with a strong component parallel to Titan’s surface) in their model and also found that solar radiation was sufficient to explain the measured temperatures near the terminator. The subject of nightside and non-Ta dayside electron temperatures has yet to be explored in the literature.

[10] The goal of the paper is to use parametric equations for electron and ion temperatures in a model in conjunction with Cassini data in order to see if the observed electron temperatures, which are much greater than the neutral temperature, can be explained. We present the results of a coupled suprathermal electron transport model and a thermal electron and ion energetics model. Temperature profiles versus altitude between 800 and 1800 km are calculated for electrons and ions and for the dayside (T18) and the nightside (T5). Comparisons are drawn between the model results and the measured electron and ion temperatures, and the effects of model geometry and magnetospheric inputs are examined.

2. Relevant Experimental Data

[11] Cassini data from the outbound legs of T5 (nightside case with a solar zenith angle of 137° near closest approach and with Titan near 5.27 Saturn Local Time (SLT)) and T18 (dayside case near the terminator with solar zenith angles between 80° and 90° and with Titan near 2.27 SLT) are used for model inputs and for comparison with our model output (i.e., \( T_e \), \( T_i \), and suprathermal electron flux values).

2.1. Cassini Plasma Spectrometer (CAPS)

[12] The CAPS instrument [Young et al., 2005] includes an electron spectrograph (ELS) used for measuring energetic electrons in the magnetosphere of Saturn and in the ionosphere of Titan. Suprathermal electron fluxes measured by this instrument will be used for model comparison. This instrument also includes an ion beam sensor (IBS) that measures the flux of ions as a function of their kinetic energy and direction. Crary et al. [2009] used this sensor for their comparisons with INMS mass spectra in the ionosphere and for their determination of the ion temperature.
For additional information see Young et al. [2005] and Coates et al. [2007].

2.2. Ion–Neutral Mass Spectrometer (INMS)

The INMS instrument is a radio-frequency quadrupole mass spectrometer. It is capable of measuring both the ion and neutral composition of the ionosphere for neutrals and ions with a mass to charge ratio of 0.5 to 8.5 Daltons and from 11.5 to 99.5 Daltons. For more information see Kasprzak et al. [1996] and Waite et al. [2004]. The neutral density profiles we need for our model are based on INMS data (also see Cravens et al. [2009b], Robertson et al. [2009], Cui et al. [2009], and Magee et al. [2009]).

2.3. Cassini Radio and Plasma Wave Spectrometer (RPWS)

The Cassini RPWS/LP instrument is a Langmuir Probe (LP), which measures electron densities ($n_e$) and temperature ($T_e$). Details on this instrument can be found in Wahlund et al. [2005], Ågren et al. [2009], and Gurnett et al. [2004].

3. Model Description

Our model is essentially taken from the models of Gan et al. [1992, 1993] and Cravens et al. [2008]. Magnetic field line topologies are chosen such that the field orientation at the spacecraft location is in general agreement with magnetometer observations for each flyby (see Figure 1) [Dougherty et al., 2004; Backes et al., 2005; Bertucci et al., 2009; Cravens et al., 2010]. Parabolic field lines were used to approximately simulate the draping of Saturn’s magnetic field around Titan. A generic sketch of parabolic field lines is shown in Figure 2. The radius of curvature at the apex point, or anchor point, where the parabola intersects the line of symmetry in Figure 2 and is closest to the center of Titan, is the distance from the apex point to the center of Titan. This configuration gives a parabola with monotonically increasing radial distances with increasing angle from the apex. See Figure 3 for an example of altitude versus the distance along a magnetic field line for a case with its apex point at an altitude of 960 km. The model uses grid spacing of 35 km along magnetic field lines [Gan et al., 1992, 1993; Cravens et al., 2004] for the suprathermal electron flux calculations and also for the calculation of thermal electrons and the ion temperatures from the coupled electron and ion energy equations.

[16] The main neutral species in the model are nitrogen and methane. A primary photoelectron population is created as the result of photoionization of these neutrals by solar extreme ultraviolet (EUV) and solar X-ray radiation. The
SOLAR2000 flux model [Tobiska et al., 2000] is used to provide inputs from solar radiation, as described by Robertson et al. [2009], and the reader is directed to that paper for details including a plot of the solar flux versus wavelength.

[17] The thermal population of electrons, heated by Coulomb collisions with the suprathermal electron population of magnetospheric or atmospheric origin, is considered. We use a two-stream electron transport code to calculate suprathermal electron fluxes along magnetic field lines and their code-generated thermal electron heating rate. Electron and ion temperatures for the thermal electron and ion species are calculated by solving the coupled electron and ion energy equation that includes heat transport via heat conduction, local heating sources/sinks, and dynamical terms.

[18] The current code works in one dimension along magnetic field lines, but is not strictly one-dimensional in altitude as the field lines are curved. For this model the field line configuration will serve as a path for suprathermal electrons and photoelectrons and will influence how much of the atmosphere a particle will potentially interact with. Thermal conductivity along the field lines allows heat to be transported in the ionosphere between different altitudes and, in particular, potentially from higher altitudes down to lower altitudes where the higher neutral densities result in higher collision frequencies and greater cooling. If the magnetic field is horizontal (i.e., nonradial), at least for a significant extent along the field line, then little heat will be transported between altitudes.

[19] The temperature model gives its results in terms relative to the neutral temperature \(T_i - T_a\). For comparison purposes with the Crary et al. [2009] paper, the neutral temperature is set at 150 K.

3.1. Two-Stream Model and Electron Heating Rates

[20] The two-stream electron transport method was originally used to calculate suprathermal electron fluxes in the terrestrial ionosphere [Nagy and Banks, 1970] and has previously been used in models of both the energetics and composition of Titan’s ionosphere [Gan et al., 1992; Cravens et al., 2009b; Robertson et al., 2009]. This method derives from a gyrotrropic distribution function averaged over a gyroperiod [cf. Schunk and Nagy, 2009]. As photoelectrons and magnetospheric electrons move along field lines they may scatter in a new direction or ionize a neutral thus creating another electron. This secondary electron must then also be tracked along the field line. Monte Carlo simulations have shown that considering only two streams, one up and one down [cf. Schunk and Nagy, 2009, and references therein] is usually sufficient in the ionosphere. The two-stream equation for suprathermal electron fluxes up and down a magnetic field line is as follows (see Nagy and Banks, 1970):

\[
\frac{d\Phi^\pm}{ds} = \frac{\pm 1}{(\cos \theta)} \sum_k n_k [\sigma_e^k + \beta_e^k \phi^\pm] + \frac{\pm 1}{(\cos \theta)} \sum_k n_i \beta_i^k \sigma_e^k \Phi^\pm
\]

where \(\Phi^+\) and \(\Phi^−\) are the electron fluxes away and toward the apex point as a function of the energy of the electron, \(E\), and the distance along the field line, \(s\). The number density of the \(k\)th neutral species (i.e., \(N_2\) or \(CH_4\)) is represented by \(n_k\). The total electron scattering cross-section for elastic collisions with the \(k\)th species is represented by \(\sigma_e^k\). The electron backscatter probability for elastic collisions with the \(k\)th species is given by \(p_e^k\). The electron production rate in the range \(E\) to \(E + dE\) and at a given location, due to photoionization by solar radiation, is denoted by \(q\). That is, \(q\) is the primary photoelectron production rate as a function of energy and location. The suprathermal electron production rate in the energy range \(E\) to \(E + dE\) due to electrons at higher energies that undergo inelastic collisions is the cascading production rate, denoted \(q^c\). This production rate also includes the secondary electrons produced by primary electron impact ionization of neutrals. The average cosine of the pitch angle is assumed to be 1/2 (i.e., isotropic upward and downward distributions).

[21] The electron impact elastic ionization, excitation, and Coulomb cross-sections for \(N_2\) and \(CH_4\) were taken from Gan et al. [1992]. Electron fluxes as a function of energy were calculated by solving the above equations as described.
by Gan et al. [1992]. The fluxes as functions of distance along the magnetic field line are assumed to be symmetric about the apex of each parabola. The energy grid consists of discrete energy bins starting with a bin size of 0.5 eV and increasing to 200 eV at the maximum energy in the code of 5 keV. A sample flux for the dayside case is given in Figure 4. The photoelectron peak at an energy of 25 eV is due to the strong solar HeII resonance line at 30.4 nm [Nagy and Banks, 1970; Gan et al., 1992; Robertson et al., 2009].

Suprathermal and secondary electrons are transported up and down magnetic field lines in this model and, through Coulomb collisions, provide heating to the thermal electron population. This heating rate is computed along the field line from the apex of the parabola. For electrons, the dynamical terms (i.e., those terms depending on the bulk flow velocity, \( \mathbf{u}_s \)) are not important and are neglected, essentially due to the low electron to ion mass ratio [Gan et al., 1992, 1993; Roboz and Nagy, 1994]. Ions are cooled (or heated if there is drift motion) through elastic collisions with the neutral species.

Equation (2) is time-dependent, but steady state solutions were obtained. The equations are calculated along a single magnetic field line and a constant solar zenith angle with parameters (solar zenith angle, shape, altitude of the apex point, etc.) determined by a combined analysis of magnetometer data and the spacecraft trajectory (see Figure 1). Results are usually displayed versus altitude (above Titan's surface) as opposed to the distance along the magnetic field line from the apex of the parabola. For electrons, the dynamical terms (i.e., those terms depending on the bulk flow velocity, \( \mathbf{u}_s \)) are not important and are neglected, essentially due to the low electron to ion mass ratio [Gan et al., 1992, 1993; Roboz and Nagy, 1994]. Ions are cooled (or heated if there is drift motion) through elastic collisions with the neutral species.

The energy equation, second moment of the Boltzmann equation, for a species \( s = e \) or \( i \) [Schunk and Nagy, 2009] is as follows:

\[
\frac{3}{2} k_B n_s \frac{\partial T_s}{\partial t} + \frac{3}{2} k_B n_e u_s \cdot \nabla T_s + \frac{3}{2} k_B T_s n_s \nabla \cdot \mathbf{u}_s + \frac{3}{2} k_B (T_s - T_n) S_s \\
+ \nabla \cdot (-K_s \nabla T_s) = \sum \frac{n_t m_t \nu_{st}}{m_s + m_t} [3k_B (T_s - T_t) \\
+ m_t (u_t - \bar{u}_t)^2] + Q_s - L_s \tag{2}
\]

where \( k_s \) is Boltzmann's constant, \( n_s \) is the number density (\( n_e = n_i \) here), \( T_s \) is the temperature, \( \mathbf{u}_s \) is bulk velocity of species \( s \), \( m_s \) is the mass, and \( t \) is time. Mass loading is implemented with the term \( S_s \), which represents a source of species \( s \), and \( T_n \) is the neutral temperature. \( K_s \) is the modified Spitzer thermal conductivity [Gan et al., 1992, 1993] of species \( s \), and \( \nu_{st} \) is the momentum transfer collision frequency between species \( s \) and \( t \) from Schunk and Nagy [2009].

The heating rate of species \( s \) is \( Q_s \). Electrons are heated by Coulomb collisions with suprathermal electrons, and ions are heated through Coulomb collisions with the thermal electron population. The cooling rate of a species is denoted by \( L_s \). For electrons the cooling rate includes contributions from vibrational, rotational, and electronic excitation cooling from electron-neutral collisions as well as heat lost by the thermal electrons to the thermal ion species [Gan et al., 1992, 1993]. Methane provides a large contribution to the cooling rate of the thermal electrons (see Figure 6) despite its relatively low abundance compared to molecular nitrogen [Gan et al., 1992, 1993]. Ions are cooled (or heated if there is drift motion) through elastic collisions with the neutral species.

Only one “average” ion species is considered in this model with an average mass of 29 amu (i.e., \( \text{C}_2 \text{H}_2 \) [Robertson et al., 2009]), which is found to be a major species in the ion chemistry [Cravens et al., 2008]. This mass value also serves
as a pseudo-average between the average mass in the lower ionosphere, which contains more massive species, and the upper ionosphere, which contains less massive ion species from data reviewed by Cravens et al. [2009b]. The ion density was taken to be equal to the electron density as the plasma was assumed to be quasi-neutral.

[26] Dynamical terms depending on individual species flow velocities, \( \mathbf{u}_s \), could play an important role in establishing the ion temperature; however, the effect that such terms have on the electron temperature is negligible. In this study dynamical terms in equation (2) with the exception of Joule heating have been excluded. In section 5.2, Joule heating is shown to be able to provide a non-negligible heat source to the thermal ion population with relative ion-neutral velocities on the order of the estimates made by Cravens et al. [2010]. The impact of Joule heating is discussed further in section 5.2. Three-dimensional MHD models are needed to provide accurate information regarding flow velocities above 1100 km [Backes, 2004; Ma et al., 2009].

4. Model Inputs

4.1. Dayside Conditions (T18)

[27] The T18 flyby of Titan took place on 23 September 2006 when Titan was located at 2.27 SLT and reached an altitude of 960 km at closest approach near the dayside terminator as the Cassini spacecraft left the ionosphere on the dayside. Solar zenith angles (SZA) for the outbound, dayside portion of the T18 flyby. This is especially evident when viewing the flyby in the X-Z plane in the Titan Interaction System (TIIS) coordinates in Figure 1 as you can see distinct magnetic field vectors almost parallel to the surface of Titan. In this coordinate system, x is the nominal corotational flow direction, y points toward Saturn and z completes the right-handed coordinate system [Backes et al., 2005].

[30] MHD models of the Titan encounter [Backes, 2004; Ma et al., 2009] also show the draping of magnetic field lines and hence that the field lines are horizontal at most altitudes. In order to simulate this configuration in the model and ensure that the local magnetic field lines are horizontal, a “nested” case was implemented using multiple parabolic field lines (described by Gan et al. [1991, 1993], Cravens et al. [2004], and Robertson et al. [2009] and in section 3) as illustrated in Figure 2. An example of the thermal electron temperature obtained by solving equation (2) along a single field line anchored at 960 km (closest approach for the T18 encounter) with a solar zenith angle of 90.93° is shown in Figure 3, along with the corresponding altitude. Figure 7 shows the heating and cooling rates of thermal electrons along this field line. The apex point of each parabola used to construct the nested case was set to an altitude coinciding with an altitude where the Cassini spacecraft made measurements. The thermal electron and ion temperatures at each apex point, i.e., the s = 0 point in Figure 3, were taken and compiled from a large number of model runs and combined into a single case that will be referred to as the “nested case.” For the dayside case, three field line configurations were tested and compared, including a radial field line, a single parabola anchored at the surface, and the nested case mentioned above.

[31] The following dayside cases are considered in the model:

[32] Case D1—Radial: The adopted magnetic field line is anchored to the surface of Titan and extends outward in the radial direction. The solar zenith angle was set at a constant value of 90.93° to simulate T18 conditions near CA at the terminator.

[33] Case D2—Parabolic Surface-Anchored Field Line: A single parabolic magnetic field line anchored at the surface of
thermal electron flux at very high altitudes for the boundary condition. Rymer et al. [2009] classified both the T8 and T18 flybys as “lobe-like,” meaning the upstream magnetospheric electron conditions for Titan were similar to the lobe regions of the Earth’s ionosphere characterized by an electron density flux between $5.3 \times 10^5 – 2.4 \times 10^7$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at the peak energy (150–820 eV). Thus, the T8 suprathermal electron flux is used as a representative suprathermal electron flux for the model’s boundary conditions of the T18 encounter.

[38] Case D7—Nested Magnetic Field Lines with “Plasma Sheet-Like” Magnetospheric Electron Inputs: This case is identical to D5 except that it includes the T5 “plasma sheet-like” magnetospheric electron flux as an input at the upper boundary. It will be demonstrated in section 5.1 that the T8 magnetospheric electron flux was not sufficient to bring the modeled electron temperatures into agreement with RPWS measurements and so the more robust T5 magnetospheric electron flux is used to examine its effect on the model.

### 4.2. Nightside Conditions (T5)

[39] The deep nightside T5 flyby of Titan occurred on 16 April 2005 when Titan was located near 5.27 SLT, and the spacecraft reached a closest approach altitude of 1027 km with a corresponding SZA of approximately 137°. Electron densities were adopted from RPWS-LP for this encounter [Agren et al., 2007]. The magnetometer data collected during the T5 outbound encounter with Titan showed that field lines were at an angle of approximately 45 degrees with respect to the surface and had a large radial component near closest approach (Figure 1) not predicted by this model using only precipitation of magnetospheric suprathermal electrons [Agren et al., 2007; Cravens et al., 2005; Ma et al., 2009]. To simulate the magnetic field lines our model uses a parabolic field line anchored at the surface of Titan, for which the field lines have approximately the correct orientation at ionospheric altitudes.

[40] The T5 electron density profile can be reproduced with this model using only production from precipitation of magnetospheric suprathermal electrons [Agren et al., 2007; Cravens et al., 2009b]. A comparison of the observed CAPS-ELS suprathermal electron flux and the electron spectrum from our two-stream model is shown in Figure 8. The fluxes measured by CAPS-ELS well outside the ionosphere were used for our “magnetospheric” input (i.e., boundary conditions for the two-stream code).

[41] Five cases are considered in our nightside model and are described below.

[42] Case N1—Reduced Magnetospheric Electron Flux with E > 10 eV Only: This case will serve as the baseline case for the nightside model. The magnetic field line topology was a parabola anchored at the surface of Titan reflecting the 45° angle with respect to the radial direction observed by the magnetometer (Figure 1). Electron fluxes in the magnetosphere near Titan on magnetic flux tubes linked to Titan appear to be reduced, or depleted, probably due to losses associated with interaction with Titan’s ionosphere. This reduction of the magnetospheric electron flux, which we use as our upper boundary condition, lowers ion production rates and associated thermal electron heating rates resulting from

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**Figure 7.** Heating and cooling rates for the thermal electron population along a single parabolic field line of the D4 case anchored at 960 km with SZA = 90.93°. Magnetometer data [cf. Bertucci et al., 2009] shows that the magnetic field has a large horizontal component at this point on the Cassini trajectory. The purple line shows the total cooling rate with the effect of (black) electron-ion collisional cooling and (red) electron-neutral collisional cooling. The dark blue indicates heating due to photoelectrons. Lines indicate the (light blue) positive and (orange) negative effects of conduction.
magnetospheric electron precipitation. In order to bring chemically modeled ion densities into agreement with INMS ion density measurements, Cravens et al. [2009b] applied a reduction factor of 2.5 to the magnetospheric electron flux. This same reduction was applied in the current paper for this case. Only the contribution to the ionospheric energetics of the magnetospheric suprathermal population with energies above 10 eV is considered for this particular case, in order to exclude any possible spacecraft photoelectron contribution to the CAPS data; however, this also excludes the heating effects of very low energy magnetospheric electrons. Other cases will remove this restriction.

\[ 43 \]
Case N2—Triple Neutral Density: This case is identical to the N1 case except that the neutral densities have been tripled.

\[ 44 \]
Case N3—Reduced Magnetospheric Electron Flux over Full Energy Range: Suprathermal electrons with energies less than 10 eV were not used in the N1 case, but for the N3 case the full energy range (up to 5 keV) of the CAPS-ELS suprathermal electron flux from Cravens et al. [2008] was included in the calculations.

\[ 45 \]
Case N4—Full Magnetospheric Electron Flux with E > 10 eV Only: Cases N1, N2, and N3 reduced the magnetospheric electron fluxes and hence the heating rates obtained with the input of CAPS-ELS magnetospheric electron fluxes for T5 by a factor of 2.5. This was needed for the modeled ion densities of Cravens et al. [2009b] to be brought into agreement with measured values in a model ionosphere. For case N4 the full magnetospheric electron flux rate from the external magnetospheric electron fluxes is adopted; however, only magnetospheric electrons with energies greater than 10 eV are included.

\[ 46 \]
Case N5—Full Magnetospheric Electron Flux over Full Energy Range: This case utilizes the full CAPS-ELS measured suprathermal electron flux over the full energy range up to 5 keV.

5. Model Results

5.1. Dayside Results

\[ 47 \]
Results from the model for the dayside are described in this section. The different dayside cases considered in section 4.1 are shown in Figures 9 and 10. The resulting electron and ion temperatures determined for the various model cases show the importance of the local magnetic field line topology for the electron thermal balance. The calculated electron temperatures for the cases (D1 and D2) in which the field has a significant radial component at ionospheric altitudes are much lower than the measured temperatures as shown in Figure 9. Both heat and suprathermal electrons can be transported downward to lower altitudes in this case, and higher neutral density allows collisional losses and cooling to operate more efficiently.

\[ 48 \]
On the other hand, for the cases in which the field lines were horizontal at each altitude where Cassini measurements were made and where model comparisons were carried out (D4 and D5), much higher calculated electron temperatures (see Figure 10) result, and, at least below an altitude of about 1350–1400 km, better agreement is reached.
obtained with the measured temperatures. For these cases, the heat is bottled up at higher altitudes where cooling is less effective as the horizontal field lines limit the conduction between altitudes. This is consistent with the models of Gan et al. [1992, 1993], Roboz and Nagy [1994], and Galand et al. [2006]. The electron and ion temperatures obtained for case D5 were very similar to those obtained for case D4, indicating that the local magnetic field topology (and hence whether the field lines are locally horizontal or have strong radial components) has a greater effect on temperatures than the exact solar zenith angle does (as long as it is on the dayside at least).

The measured temperatures above 1350 km exceed the model temperatures, suggesting that the model is missing some high altitude heat source. Recall that no magnetospheric inputs were included in model cases D1–D5 (Figures 9 and 10), which might be unrealistic even on the dayside. In order to fix this problem and to increase the electron temperature for the D4 case between 1500 and 1800 km, T8 superthermal fluxes [Rymer et al., 2009] were adopted as the upper boundary condition for the electron flux in the D6 case. The T8 flyby, like T18, was classified by Rymer et al. [2009] as a “lobe-like” plasma environment so the two flybys should have similar magnetospheric electron fluxes. The model electron temperatures with this addition (shown in Figure 10) increased the electron temperature by 200 K at 1700 km. RPWS thermal electron temperatures [Ågren et al., 2009] still exceed the model temperature by 800 K at this altitude. Using the T5 magnetospheric flux brought the model electron temperatures into agreement with measured values from Ågren et al. [2009] between 1500 and 1700 km; however, with this change the modeled temperatures exceed the measured temperatures at 1300 km by nearly 700 K. Unfortunately, T5 magnetospheric electrons are not appropriate for T18 conditions and were used in this study as an upper bound for the magnetospheric electron flux. The actual heat source for the T18 upper ionosphere is still under investigation.

Note that there is a dip in the modeled electron temperatures near 1500 km (Figure 10). As altitude increases the neutral density decreases, as do the electron density and heating rate of the thermal electrons due to photo electron and magnetospheric electron heating. The cooling rate of the thermal electrons due to collisions with neutral and ion species also decreases with altitude due to the decreased densities of the ions and neutral species. The balance of these terms, together with conduction along the field line, determines the thermal electron temperature, but for the nested field line case, heat conduction is less important. Photoelectron heating is mainly balanced by electron-neutral cooling, but near 1500 km electron-ion cooling is relatively more important than at other altitudes.

Model cases (D6, D7) were run with external suprathermal electron fluxes, as described earlier. In particular we adopted, as inputs at the top of the atmosphere, magnetospheric electron fluxes as seen by Cassini outside Titan’s ionosphere during the T8 and T5 encounters. Magnetospheric fluxes will increase the ion production rates at higher altitudes as magnetospheric electrons ionize the upper atmosphere while the rate of ion production near the peak (1.03 × 10^-3 cm^-3 s^-1 near 1208 km) is relatively unchanged. At an altitude of 1350 km the relative importance of magnetospheric electrons’ contribution to the ion production rate becomes significant when the T8 “lobe-like” (D6) and T5 (D7) magnetospheric electron fluxes are used, giving ion production rates at this altitude of 1.58 × 10^-2 and 2.49 × 10^-3 cm^-3 s^-1, respectively. Neglecting the fluxes at 1350 km when the SZA is 78.38° (D5) as it was during the time when Cassini made measurements yielded an ion production rate of 7.64 × 10^-3 cm^-3 s^-1. Above 1350 km and SZA > 78° the impacts of magnetospheric electron precipitation on the ion production rates need to be considered.

Now consider the modeled electron temperature in the lower ionosphere. The calculated temperatures for all cases and for altitudes below 1000 km converge on the neutral temperature of about 150 K, but the measured electron temperatures remain at values of about 400 K [Ågren et al., 2007]. The electron-neutral thermal coupling is quite large at lower altitudes where the neutral density is high, so the 400 K measured temperatures are difficult to explain.

Figure 11 shows the ion temperature altitude profiles for all of the cases mentioned above. The calculated temperatures for cases D4, D5, D6, and D7 agree the best with the measured ion temperatures from Crary et al. [2009] below an altitude of 1600 km. The measured temperatures exceed the model temperatures for altitudes above 1600 km, but no dynamical terms were included in the ion energy.
The triangles on the graph represent ion temperatures versus altitude for various \cite{Cravens2009}. The lines represent electron temperatures for the nested case (case D4) with a magnetospheric suprathermal electron flux from the T5 flyby \cite{Cravens2008}.

5.2. Frictional/Joule Heating Term

\cite{54} The main focus of this paper is not on the effects of dynamics on the ion energetics, which requires the dynamical information from MHD type models, but we do examine one process: ion-neutral collisional heating (or Joule heating), as shown in Figure 12. Joule heating occurs from the collisions between two species when ions and neutrals move at different velocities. This extra heating can significantly increase the ion temperature. In equation (2) this term is \( \frac{n_i m_{m} v_{si}}{m_i + m_n} \left[ m_i (\bar{u}_i - \bar{u}_n) \right]^2 \). To consider the effects of this term we introduced into the model a range of ion-neutral relative velocities but kept the relative velocity constant with altitude (which will not be the case in reality). A more realistic variation of this relative velocity with altitude was presented by \cite{Cravens2010}, who estimated velocities using pressure gradients and ion-neutral collision frequencies based on Cassini data. \cite{Cravens2010} adapted vertical and horizontal length scales (100 and 500 km respectively) when computing these estimates. The relative ion-neutral velocity near 1000 km was estimated to be only a few m/s or less, but increased up to a km/s or so by 1400–1500 km. Above 1500 km the estimated flow speeds approached or exceeded the magnetosonic speed, and the assumptions used to estimate the velocities broke down. For the case of a relative ion-neutral velocity of 100 m s\(^{-1}\) the ion temperature increase is not significant (\(\Delta T_i \approx 7\) K at an altitude of 2000 km); however, for a relative velocity of 250 m s\(^{-1}\) \(\Delta T_i \approx 45\) K near 1500 km, which brings the model’s ion temperature into reasonable agreement with the measured temperature at that altitude. Joule heating is an important source of ion heating in the upper ionosphere. \cite{55} \cite{Cravens2010} pointed out that below an altitude of 1300 km the high-ion-neutral collision frequency strongly couples the ion and neutral velocities such that the ion velocity tends to be brought near the neutral velocity which reduces Joule heating. In order to more accurately determine ionospheric flow velocities, and all of the dynamical terms in the ion energy equation (see equation (2)), global MHD or hybrid models are needed (see discussion by \cite{Cravens2009} and \cite{Ma2007, Ma2009}).

5.3. Nightside Results

\cite{56} On the nightside of Titan, photoionization or heating due to solar radiation does not occur, but suprathermal electrons coming into the ionosphere from outside can provide energy to the ionospheric thermal electron population if these electrons can gain access to the ionosphere along the induced magnetic field lines. The magnetic field line topology is thus especially important for the nightside. The choice of field line topology determines how much of the atmosphere a suprathermal electron interacts with before reaching the altitude of interest. Our model was run for Cassini T5 (outbound) conditions in which the field lines had a large radial component.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure11.png}
\caption{Ion temperatures versus altitude for various field line cases. Again, the nested field line approach shows the best agreement with measured ion temperatures from \cite{Cravens2009}. The lines represent electron temperatures for the nested case (case D4) with a magnetospheric suprathermal electron flux from the T5 flyby \cite{Cravens2008}.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure12.png}
\caption{The effect of relative ion and neutral velocities (in m s\(^{-1}\)) on calculated ion temperatures. That is, Joule heating is shown to be an effective heat source for ions for sufficiently high relative ion-neutral drift speeds. The value of \(u_i - u_n\) is kept constant for each line, but large values are expected only at higher altitudes.}
\end{figure}
Figures 13 and 14 show the model electron temperatures for the nightside cases. Figure 13 shows that for the N1 case (magnetospheric electrons with energies less than 10 eV were excluded and the overall flux was reduced by a factor of 2.5) the calculated thermal electron temperatures are ∼400 K lower than the temperatures reported by RPWS [Ågren et al., 2007] at 1200 km. Tripling the neutral densities (N2) resulted in a shift of the temperature curve up in altitude by 60–80 km, approximately one neutral scale height, but the shape of the curve is similar to the previous case. Including suprathermal electrons with energies less than 10 eV raised the thermal electron temperature at the higher altitudes (above 1300 km) by 250 K to a temperature of 900 K. Although reducing the magnetospheric electron flux (and the associated thermal electron heating rates) as was done in the N1, N2, and N3 cases provided the necessary correction to the ionospheric model densities of Cravens et al. [2009b] and Ågren et al. [2007], the heat input is apparently not adequate, as the modeled electron temperatures are approximately 400 K lower than the temperatures reported by RPWS [Ågren et al., 2007] at 1200 km. Tripling the INMS neutral densities merely shifts the temperature curve up by about 60 km (i.e., a neutral scale height).

Cases N4 and N5 (Figure 14) show that with the full magnetospheric electron flux, and hence the full heating rate, the modeled electron temperatures agree with the RPWS measurements at 1200 km. The N4 case also shows that using the full magnetospheric electron flux (but with energies less than 10 eV excluded) produces electron temperatures that agree with RPWS measured temperatures of about 1100 K in the vicinity of 1300 km. At 1400 km the model temperatures are still somewhat lower than RPWS temperatures by 400 K. The N5 case also included magnetospheric electrons with energies less than 10 eV (and no flux reduction was included). The calculated electron temperature is now close to 1500 K at an altitude of 1360 km. N5 shows the best agreement between the modeled temperatures and the RPWS [Ågren et al., 2007] T5 measurements, differences of only ≈25 K near 1100 km and ≈100 K near 1400 km (i.e., within 15%). If the neutral densities were increased...
tripled the N5 curve on Figure 14 would be shifted upward by about 70 km and bring the modeled temperatures further into even better agreement with the RPWS values. This illustrates the importance to the thermal electron energy balance of the upper ionosphere of the input of magnetospheric electrons of all energies, including lower energies below 10 eV.

[59] The calculated ion temperatures for the above cases are presented in Figure 15. Note that dynamical terms were not included in the ion energy equation for these cases. As mentioned for the dayside results, the ion temperature is strongly coupled to the neutral temperature below approximately 1400 km. The model ion temperatures for the nightside case above 1400 km indicate that dynamical terms in the ion energy equation no doubt play a role in the upper ionosphere on the nightside as they do on the dayside. As the thermal electron temperature increases and the electrons become more energetic, their collisional cross-section with the thermal ions decreases [cf. Gan et al., 1992, 1993], therefore lowering the ion temperature as shown.

6. Discussion and Conclusions

[60] Thermal electron and ion temperature profiles from the ionospheric electron and ion temperature model were compared in this paper to ion and electron temperatures measured by Cassini instruments for a dayside (T18) and a nightside (T5) case. Previously modeled temperatures were only available for electrons for the Ta encounter [Galand et al., 2006]. The study by Galand et al. reported the electron temperature at two positions of the Cassini spacecraft (near 1200 and 1350 km) and did not include any information about the temperatures below 1200 km. The electron temperatures from our model were compared to RPWS-LP data [Ågren et al., 2007, 2009; Cravens et al., 2009a; Robertson et al., 2009], and ion temperatures were compared to the measured temperatures presented by Cravy et al. [2009]. We show that the magnetic field line topology is important for the electron energetics due to its effect on heat conduction and transport of suprathermal electrons throughout the ionosphere. This conclusion appears in agreement with pre-Cassini models [Gan et al., 1992, 1993; Roboz and Nagy, 1994] and with Cassini Ta models of Galand et al. [2006]. It is also shown that one can create a reasonable model of the electron temperature below 1400 km with only “local” knowledge of the magnetic field line topology. For the day and nightside, our model also shows that the thermal electron temperature is strongly coupled to the neutral temperature below an altitude of 1000 km and that the ion temperature is strongly coupled to the neutral temperature below an altitude of 1400 km.

[61] Analysis of the dayside (T18) case showed that suprathermal electrons (i.e., photoelectrons) produced by absorption of solar radiation are sufficient to heat the thermal electrons for altitudes below 1400 km if the field lines are kept largely horizontal. Our model did this using a “nested” field line approach to limit thermal conductivity between altitudes and simulate local magnetic topology. The nested approach is consistent with the study by Galand et al. [2006] of Titan’s ionospheric electron temperature, which utilized various magnetic field lines. Above 1400 km magnetospheric electron inputs are needed to provide sufficient heat to the thermal electron population. The T8 magnetospheric suprathermal electron flux, while classified as “lobe-like” magnetospheric conditions similar to T18 [Rymer et al., 2009], did not provide sufficient heat for thermal electrons above 1400 km. Using the more robust T5 “plasma sheet” magnetospheric suprathermal electron flux brought the modeled electron temperatures between 1500 and 1600 km into agreement with measured temperatures but overshot measured temperatures between 1150 and 1350 km. However, it seems unlikely that the “lobe-like” magnetospheric suprathermal electron flux will provide sufficient heating to thermal electrons and that alternative heat sources need to be considered in the upper ionosphere.

[62] For the ion temperature on the dayside, dynamical terms associated with the bulk ion plasma flow are potentially important in the upper ionosphere. In particular, Joule heating (i.e., relative ion-neutral drift) was able to provide a sufficient temperature boost to the ions to bring the model temperature into agreement with measured values reported by Cravy et al. [2009] for relative ion-neutral speed values in agreement with the empirical estimates made by Cravens et al. [2010]. A 3-D global MHD model similar to the type used by Ma et al. [2006, 2007, 2009] is able to constrain the values of the bulk flow velocity more accurately at the spacecraft position and in future studies this could improve the analysis of dynamical effects.

[63] Our energetics model applied to the nightside ionosphere showed that magnetospheric electron fluxes measured by CAPS-ELS in the nearby magnetosphere of Saturn during T5, as discussed by Cravens et al. [2008], can provide sufficient heating to bring the modeled thermal electron temperatures into agreement with the RPWS-LP data presented by Ågren et al. [2007]. Lower energy (E < 10 eV) magnetospheric electrons are important for the thermal energy balance as well. An unresolved issue is how much magnetospheric electron fluxes are reduced as induced magnetic field lines get caught up in Titan’s ionosphere and atmosphere (see discussion by Gan et al. [1992] and Cravens et al. [2008]). The role of the magnetic field topology is also important, and although reasonable topologies were adopted for T5 and T18 in the current paper, the variation of thermal quantities for different flybys (and field line configurations) should be investigated.

[64] The model ion temperatures on the nightside fall within the values presented by Cravy et al. [2009] below 1400 km; however, they are about 25 K lower at an altitude of ~1650 km, indicating that dynamical terms are important for ion temperatures at higher altitudes on the nightside as well as on the dayside.

[65] In conclusion, the key findings of this study are:

[66] (1) Below approximately 1400 km on the dayside, solar inputs sufficiently explain ionospheric electron temperatures when appropriate magnetic field lines are adopted.

[67] (2) On the nightside and the dayside above 1400 km, magnetospheric inputs are needed to heat the electrons.

[68] (3) Dynamical terms, most notably Joule heating, play an important role at higher altitudes in the energy balance for the ions at Titan.
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