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On the thermal electron balance in Titan's sunlit upper atmosphere

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ABSTRACT

The Cassini mission has investigated Titan's upper atmosphere in detail and found that, under solar irradiation, it has a well-developed ionosphere, which peaks between 1000 and 1200 km. In this paper we focus on the T40, T41, T42 and T48 Titan flybys by the Cassini spacecraft and use *in situ* measurements of N_2 and CH_4 densities by the Ion Neutral Mass Spectrometer (INMS) as input into a solar energy deposition model to determine electron production rates. We combine these electron production rates with estimates of the effective recombination coefficient based on available laboratory data for Titan ions' dissociative recombination rates and electron temperatures derived from the Langmuir probe (LP) to predict electron number densities in Titan's upper atmosphere, assuming photochemical equilibrium and loss of electrons exclusively through dissociative recombination with molecular ions. We then compare these predicted electron number densities with those observed in Titan's upper atmosphere by the LP. The assumption of photochemical equilibrium is supported by a reasonable agreement between the altitudes where the electron densities are observed to peak and where the electron production rates are calculated to peak (roughly corresponding to the unit optical depth for HeII photons at 30.38 nm). We find, however, that the predicted electron number densities are nearly a factor of two higher than those observed throughout the altitude range between 1050 and 1200 km (where we have made estimates of the effective recombination coefficient). There are different possible reasons for this discrepancy; one possibility is that there may be important loss processes of free electrons other than dissociative recombination in Titan's upper atmosphere.

1. Introduction

Titan is the largest satellite of Saturn and the only satellite in the Solar System to hold a dense and permanent atmosphere. The Cassini mission has considerably improved and challenged our understanding of Titan's upper atmosphere. Solar EUV photons and soft X-rays and energetic charged particles from Saturn's magnetosphere ionize, excite, and dissociate N_2 and CH_4, the main constituents of Titan's upper atmosphere. This initiates a network of chemical reactions, forming the most chemically complex ionosphere in the Solar System, including long-chain hydrocarbons, aromatic molecules and nitrogen containing (in particular nitrile-) molecules (e.g., Vuitton et al., 2007). Ion chemistry acting in Titan's upper atmosphere is a significant source of Titan's aerosols, which ultimately precipitate to the surface of the Moon (Waite et al., 2007; Vuitton et al., 2008; Wahlund et al., 2009). In this paper we challenge our understanding of Titan's dayside ionosphere. More specifically the goal is to test the ability to accurately predict electron number densities in the dayside ionosphere of Titan following assumptions of photochemical equilibrium and loss of free, thermal electrons exclusively by dissociative recombination with molecular ions. We focus in particular on four Titan flybys by the Cassini spacecraft (T40, T41, T42 and T48) and for each flyby we use a multi-instrumental Cassini dataset, accurate information on the impinging solar EUV/XUV spectra as observed from Earth and extrapolated to Saturn, laboratory data of photo- and electron-impact processes and of dissociative recombination reactions, and a solar energy deposition model (based on Galand et al.,

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2010) that combined gives the opportunity to predict electron number densities within a well-constrained parameter space.

Solar photons are the main source of ionization on the dayside, and even somewhat beyond the terminator due to the extended nature of Titan's atmosphere (see e.g., Ågren et al., 2009; Galand et al., 2006, 2010; Robertson et al., 2009; Kliore et al., 2011; Luhmann et al., 2012). This and the fact that Titan's ionosphere is dominated by molecular ions that have large electron recombination rate coefficients (Cravens et al., 2005; Vuitton et al., 2006, 2007) yielding short chemical lifetimes, implies that the ionosphere should be Chapman-like, by which we mean that the electron density profile is determined by a local balance between solar photoionization and recombination. This behavior is indeed supported by the variations of the magnitude and the altitude of the peak electron density with solar zenith angle in Titan's ionosphere (Ågren et al., 2009).

The continuity equation applied to the electron number density, n_e, is given by

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{u_e}) = P_e - n_e L_e \qquad (1)$$

where P_e (cm^{-3} s^{-1}) and L_e (s^{-1}) are the electron production and loss rates, respectively, and the second term on the left-hand side is the flux divergence with $\mathbf{u_e}$ being the electron drift velocity. When charge balance applies and electrons are lost exclusively through recombination with molecular ions, L_e in Eq. (1) can be expressed as $n_e\alpha_{eff}$ where α_{eff} is the effective recombination coefficient (for definition see Eq. (4)). The peak electron density in Titan's dayside ionosphere is roughly 2500 cm^{-3}. Adopting 5×10^{-7} cm^3 s^{-1} as a typical recombination rate coefficient implies a recombination time constant of about 800 s, which is about three orders of magnitude shorter than a Titan day and consequently diurnal variations should not affect the dayside electron densities significantly, i.e. the time dependent term of Eq. (1) may be neglected. Another requirement for a local balance between photo-ionization and recombination is that chemistry dominates over transport, i.e. that the flux divergence term in Eq. (1) may be neglected. Ma et al. (2006) investigated this question and found that chemistry should dominate over transport below about 1300 km (see also Robertson et al., 2009; Cravens et al., 2010). As we primarily focus our studies to altitudes below 1200 km Eq. (1) then takes the simple form of local balance between electron production and loss rates:

$$P_e(z) = n_e(z)L_e(z) \qquad (2)$$

Ågren et al. (2009) showed that nightside n_e values are about 20% of the dayside values. The nightside ions are likely due to a combination of ionization from magnetospheric auoral electrons (and their secondaries) (e.g., Cravens et al., 2005, 2009) and survival of some long-lived dayside ions through the Titan night (Cui et al., 2009, 2010). The contribution of magnetospheric electrons to the dayside electron production rate is, however, expected to be small (about 5%) as further discussed in Section 3.3. These arguments apply to the mean ionosphere between about 1050 and 1200 km. Negative ions have been observed to exist in high abundances near 1000 km and below (Coates et al., 2007; Ågren et al., 2012) while transport becomes important at higher altitudes.

Following these lines we anticipate Titan's ionosphere to be Chapman-like, in accordance with other ionospheres in the Solar System, such as the E region of the terrestrial ionosphere, and regions of the ionospheres of Mars and Venus (e.g. Rasmussen et al., 1988; Mendillo et al., 2011; Fox, 2007). Local balance between solar-driven ionization and recombination implies, as mentioned, specific relationships for the variation of the peak value of n_e and the altitude of the n_e peak with solar zenith angle. This behavior has been demonstrated in several studies of the martian ionosphere (see e.g., Fox and Yeager, 2006; Martinis et al., 2003; Mendillo et al., 2011) and for Venus at least in terms of how the peak values of n_e vary with SZA. A non-Chapman behavior has been observed in terms of how the peak altitudes of n_e vary with SZA in the venusian ionosphere, being at a nearly constant level of 140 km as the SZA increases from about 25° to 70° and then decreasing slightly to 135 km as the SZA increases from 70° to 85° (Cravens et al., 1981). This behavior may be ascribed to the variations of the near-terminator thermosphere, in which the values of the neutral densities decrease with increasing SZA (Fox, 2007; Cravens et al., 1981). It is noted that photochemical equilibrium models of the dayside martian and venusian lower ionospheres have been found to reproduce measured electron densities typically better than to within 25% and clearly within the error bars of the model predictions and observations (for Mars e.g., Mendillo et al., 2011; Fox and Yeager, 2006, for Venus e.g., Cravens et al., 1981; Fox, 2007). This high accuracy is possible because the dominance of local chemistry lessens or removes uncertainties due to diffusion rates, advection velocities, and magnetic topology. Counterexamples are seen in the ionospheres of the giant planets where H^+, a major ion, has a long lifetime. These ionospheres are severely more complicated to model due to the presence of strong winds and also due to the limited knowledge of the abundance of vibrationally excited H_2 molecules ($v \geqslant 4$) and the inflow of water molecules, both of which effectively can convert H^+ to shorter-lived molecular ions and thereby strongly affect the predicted electron number densities (see e.g., Yelle and Miller, 2004; Moore et al., 2010 and references therein, Moses and Bass, 2000; Waite et al., 1997 and references therein).

To simplify Chapman-like ionospheres even further an effective recombination coefficient may be adopted to avoid dealing with numerous ion-neutral reactions. This leads to the following expression for the electron number density (e.g., Galand et al., 2010):

$$n_e(z) = \sqrt{P_e(z)/\alpha_{eff}(z)} \qquad (3)$$

where P_e is the electron production rate and where the effective recombination coefficient, α_{eff}, here is defined as the weighted average

$$\alpha_{eff}(z) = \frac{\sum_j \alpha_j(T_e) n_j(z)}{\sum_j n_j(z)} \qquad (4)$$

where the sums are over all positive ions j, n_j is the number density and $\alpha_j(z)$ is the dissociative recombination rate coefficient of ion species j, which primarily depends on the ambient electron temperature, T_e.

The concept of an effective recombination coefficient is not really needed on Mars and Venus where O_2^+ strongly dominates the ionospheric composition in the regions where photochemical equilibrium may be assumed, but it has proven useful for the terrestrial ionosphere. In the E-region of Earth's ionosphere the dominant ions are NO^+ and O_2^+. As the rate coefficient for dissociative recombination of NO^+ is about twice that of O_2^+, knowing the relative abundances of NO^+ and O_2^+, which vary with solar activity and season (e.g., Titheridge, 1997), is necessary for estimating electron number densities accurately. In addition below 80 km in the D-region of Earth's ionosphere, the increased relative abundances of hydrated cluster ions, with significantly higher dissociative recombination rate coefficients than O_2^+ and NO^+, must be taken into consideration to enable more accurate n_e predictions (e.g., Osepian et al., 2009). For Titan's ionosphere an effective recombination coefficient is indeed a very useful approximation because it eliminates the need to accurately model the complex chemistry if only the electron density is of interest. For example, an effective recombination rate approximation has been used in models of Titan's magnetospheric interaction where the added computation burden