Icarus 248 (2015) 539–546

Contents lists available at ScienceDirect

Icarus

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

Ionization balance in Titan's nightside ionosphere

E. Vigren[a,f,*], M. Galand[a], R.V. Yelle[b], A. Wellbrock[c], A.J. Coates[c], D. Snowden[b], J. Cui[d], P. Lavvas[e], N.J.T. Edberg[f], O. Shebanits[f], J.-E. Wahlund[f], V. Vuitton[g], K. Mandt[h]

[a] Department of Physics, Imperial College London, London SW7 2AZ, UK
[b] Lunar and Planetary Laboratory, University of Arizona, Tucson 85721-0092, USA
[c] Mullard Space Science Laboratory, University College London, Dorking, Surrey RH5 6NT, UK
[d] Key Laboratory of Lunar and Deep Space Exploration, Chinese Academy of Sciences, Beijing 100012, China
[e] Groupe de Spectrométrie Moléculaire et Atmosphérique, Université Reims Champagne-Ardenne, UMR 7331, 51687 Reims, France
[f] Swedish Institute of Space Physics, Uppsala, Sweden
[g] Univ. Grenoble Alpes, CNRS, IPAG, F-38000 Grenoble, France
[h] Space Science and Engineering Division, Southwest Research Institute, San Antonio, TX 78228, USA

ARTICLE INFO

Article history:
Received 26 March 2014
Revised 27 August 2014
Accepted 7 November 2014
Available online 22 November 2014

Keywords:
Titan
Ionospheres
Titan, atmosphere

ABSTRACT

Based on a multi-instrumental Cassini dataset we make model versus observation comparisons of plasma number densities, $n_P = (n_e n_I)^{1/2}$ (n_e and n_I being the electron number density and total positive ion number density, respectively) and short-lived ion number densities (N^+, CH_2^+, CH_3^+, CH_4^+) in the southern hemisphere of Titan's nightside ionosphere over altitudes ranging from 1100 and 1200 km and from 1100 to 1350 km, respectively. The n_P model assumes photochemical equilibrium, ion–electron pair production driven by magnetospheric electron precipitation and dissociative recombination as the principal plasma neutralization process. The model to derive short-lived-ion number densities assumes photochemical equilibrium for the short-lived ions, primary ion production by electron-impact ionization of N_2 and CH_4 and removal of the short-lived ions through reactions with CH_4. It is shown that the models reasonably reproduce the observations, both with regards to n_P and the number densities of the short-lived ions. This is contrasted by the difficulties in accurately reproducing ion and electron number densities in Titan's sunlit ionosphere.

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1. Introduction

Titan, the largest satellite of Saturn, has a dense and extended atmosphere dominated by N_2 and CH_4. The Cassini mission has revealed a chemically complex ionosphere around Titan. N_2 and CH_4 are ionized and/or dissociated by solar photons or particle irradiation marking the onset of a chain of chemical reactions, which produce hydrocarbon and nitrile ions, heavy positive and negative ions, and eventually aerosols (e.g., Vuitton et al., 2007; Coates et al., 2007, 2009; Waite et al., 2007; Wahlund et al., 2009; Crary et al., 2009; Ågren et al., 2012; Shebanits et al., 2013; Lavvas et al., 2013; Wellbrock et al., 2013). However, Titan dayside ionospheric models have shown difficulties in reproducing observed electron number densities (e.g., Vigren et al., 2013), as well as the observed number densities of $HCNH^+$, the dominant ion in the main ionosphere (e.g., Vuitton et al., 2009; Westlake et al., 2012). The sunlit side electron number densities derived in the Cassini multi-instrumental study by Vigren et al. (2013) are systematically a factor of ~2 higher than the values deduced from the Radio Plasma Wave Science/Langmuir Probe (RPWS/LP) measurements. From the latter, the dayside electron number densities are found to peak typically at values ~2000–5000 cm^{-3} in the altitude range 1000–1200 km. The model predicts the observed shape of the electron number density in altitude and both the observations and the model show that a decreased solar zenith angle decreases the altitude and increases the magnitude of the electron number density peak. Whether the cause of the discrepancy in magnitude is overestimated plasma production, underestimated plasma loss or a combination of the two is an open question. There are different levels of agreement in existing model-observation comparisons of short-lived ions in Titan's dayside ionosphere (short-lived ions include e.g., N^+, N_2^+ and $CH_x{}^+$ with $x < 5$; ions that are reactive with CH_4 and typically lost in ~5–200 s upon formation in the altitude range 1000–1350 km). On the one hand, Robertson et al. (2009), Westlake et al. (2012) and Richard (2013) obtain a good agreement with the Ion Neutral Mass

* Corresponding author at: Swedish Institute of Space Physics, Box 537, SE-75121 Uppsala, Sweden.
E-mail address: erik.vigren@irfu.se (E. Vigren).

http://dx.doi.org/10.1016/j.icarus.2014.11.012
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Spectrometer/Open Source Ion mode (INMS/OSI) observations for their model derived number densities of {N^+,CH_2^+}, CH_3^+ and CH_4^+ (note that N^+ and CH_2^+ cannot be separated by the INMS/OSI due to their similar mass-to-charge ratios). On the other hand Vuitton et al. (2009) overestimate the observed number densities of {N^+,CH_2^+} and CH_3^+ and Mandt et al. (2012) derive significantly higher number densities than observed for these species as well as for CH_4^+. Nevertheless, when Mandt et al. (2012) utilize a high resolution cross-section set for the N_2 photodissociation beyond the N_2 ionization threshold, an action that affect the ionization rate profile of CH_4 (see Lavvas et al., 2011), the model-data comparison improves notably for CH_3^+ and CH_4^+.

In the present work we focus on Titan's nightside ionosphere with the purpose of comparing modeled ionospheric number densities with observations. Firstly (in Section 2) we compare modeled *plasma number densities* with RPWS/LP observations in the altitude range 1100–1200 km (the selection of upper and lower limits of the altitude range are motivated in Section 2.1). The plasma number density is here defined as $n_P = (n_e n_I)^{1/2}$ with n_e and n_I being the electron number density and the total positive ion number density, respectively. Secondly (in Section 3) we compare over a more extended altitude range (1100–1350 km) modeled and observed number densities of the short-lived ions N^+, CH_2^+, CH_3^+ and CH_4^+.

Titan's nightside ionospheric particle balance has previously been modeled by Ågren et al. (2007) (focusing on the T5 flyby) and Cravens et al. (2009) (focusing on the T5 and T21 flybys). In brief they considered upstream electron fluxes measured by the Cassini Plasma Spectrometer/Electron Spectrometer (CAPS/ELS) and modeled by different means the electron precipitation through the upper atmosphere. The number densities of the dominant N_2 and CH_4 molecules were constrained by measurements by the Ion Neutral Mass Spectrometer (INMS) operating in its Closed Source Neutral (CSN) mode. Ionization rates versus altitude were calculated and electron- and ion number densities derived from ion-chemistry models. In the deep ionosphere, below 1200 km, the modeled electron number densities significantly exceeded the RPWS/LP observations. In Ågren et al. (2007) the modeled n_e exceeded the observations by more than a factor of 6 (see their Fig. 8), though sub-sequent to their work a re-calibration of the CAPS/ELS instrument was made (see Cravens et al., 2009 and in particular Lewis et al., 2010), which taken into account reduces the discrepancy to a factor of ~3. Cravens et al. (2009) remarked that a satisfactory model-observation comparison in the deep ionosphere would be achieved following a reduction by a factor of 5–10 in the incident electron fluxes used in their model.

Our approach to investigate Titan's nightside ionosphere differ in several aspects from the works by Ågren et al. (2007) and Cravens et al. (2009). Most importantly we do not attempt to model the magnetospheric electron precipitation but use instead in each considered location the *ambient* suprathermal electron fluxes measured by the CAPS/ELS to derive electron-impact ionization rates. As highlighted in e.g., Ågren et al. (2007), Cravens et al. (2009), Gronoff et al. (2009) and Snowden et al. (2013) the electron precipitation is highly sensitive to the magnetic field line topology, which in the case of Titan can be very complicated. In fact, Snowden et al. (2013) discuss the results of Ågren et al. (2007) and Cravens et al. (2009) and show that the significant electron flux depletion required to reach consistency with observations in the deep nightside ionosphere is fully plausible. A further difference in our model to derive plasma number densities is that we utilize the concept of an effective ion–electron recombination coefficient, which removes the computational burden of modeling in detail the complex chemistry associated with Titan's ionosphere. We use in the present study the most recently analyzed data from the INMS/CSN (Cui et al., 2012), INMS/OSI (Mandt et al., 2012), CAPS/ELS (see e.g., Lewis et al., 2010; Wellbrock et al., 2012) and RPWS/LP (Edberg et al., 2013; Shebanits et al., 2013).

2. Plasma number density

2.1. Flyby information and description of model

We focus the n_P study to the altitude regime 1100–1200 km using Cassini data from the five consecutive T55–T59 Titan flybys, which share similar geometrical features (see Table 1).

The upper and lower limits of the altitude range are set respectively to probe a photochemically controlled region and a region where magnetospheric electron precipitation is the dominant ionization source on the nightside (see e.g., Robertson et al., 2009; Galand et al., 2014). Overall the study is restricted to nine points sampled from the flybys, mainly because the RPWS/LP made sweep mode measurements only once every 24 s and as we consider only parts of the flybys at sufficiently high solar zenith angles (>110°) such that we can safely neglect any contribution to the ion–electron pair production by solar EUV photons.

Let n_e, n_I and n_N be the number densities of electrons, positive ions and negative ions, respectively. Under the assumptions of photochemical equilibrium, and overall charge neutrality with singly charged positive and negative ions ($n_I = n_e + n_N$) the following ionospheric relation can be derived (see Larsen et al., 1972):

$$P_e = \alpha_{eff} n_e n_I + \alpha_{MN} n_N n_I \tag{1}$$

where α_{eff} and α_{MN} are the effective ion–electron dissociative recombination and ion–ion mutual neutralization rate coefficients, respectively. Introducing $\lambda = n_N/n_e$ and the plasma number density $n_P = (n_e n_I)^{0.5}$ Eq. (1) can be rewritten as

$$P_e = (\alpha_{eff} + \lambda\alpha_{MN}) n_P^2 \tag{2}$$

In the considered altitude regime $n_e > n_N$ (Shebanits et al., 2013) and in addition it is anticipated that $\alpha_{eff} \gg \alpha_{MN}$ (see Vigren et al., 2014). This implies that ion–electron recombination is the dominant plasma neutralization process in the considered altitude range. Assuming further that the effective recombination coefficient is proportional to $(T_e/300)^{-0.7}$ where T_e is the electron temperature (see further Section 2.6.3) Eq. (2) can be reduced to:

$$n_{P,Model} \approx \sqrt{\frac{P_e}{\alpha_{eff,300}(T_e/300)^{-0.7}}} \tag{3}$$

Table 1
Titan nightside flybys considered in the present study with information on date and Saturn Local Time (SLT). Also shown are the values of the Local Time (LT) on Titan, Solar Zenith Angle (SZA), the latitude and the longitude for altitudes of 1200 km along the Cassini inbound trajectory. The values within brackets are those at 1200 km for the outbound part of the flybys.

Flyby (date)	SLT (h)	LT (h)	SZA (°)	Latitude (°)	Longitude (°)
T55 (2009-05-21)	21.95	22.6 [21.0]	159 [122]	4S [39S]	167 [192]
T56 (2009-06-06)	21.91	22.6 [20.7]	154 [115]	14S [49S]	167 [195]
T57 (2009-06-22)	21.87	22.6 [20.3]	149 [107]	23S [59S]	166 [200]
T58 (2009-07-08)	21.83	22.6 [19.7]	141 [99]	33S [68S]	165 [208]
T59 (2009-07-24)	21.78	22.7 [18.2]	134 [91]	43S [75S]	163 [230]

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