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Photoionization Modeling of Titan's Dayside Ionosphere

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Abstract

Previous modeling studies of Titan's dayside ionosphere predict electron number densities that are roughly a factor of 2 higher than those observed by the RPWS/Langmuir probe. The issue can equivalently be described as the ratio between the calculated electron production rates and the square of the observed electron number densities resulting in roughly a factor of 4 higher effective recombination coefficient than expected from the ion composition and the electron temperature. Here we make an extended reassessment of Titan's dayside ionization balance, focusing on 34 flybys between TA and T120. Using a recalibrated data set and by taking the presence of negative ions into account, we arrive at lower effective recombination coefficients compared with earlier studies. The values are still higher than expected from the ion composition and the electron temperature, but by a factor of ~2–3 instead of a factor of ~4. We have also investigated whether the derived effective recombination coefficients display dependencies on the solar zenith angle (SZA), the integrated solar EUV intensity (<80 nm), and the corotational plasma ram direction (RAM), and found statistically significant trends, which may be explained by a declining photoionization against the background ionization by magnetospheric particles (trends in SZA and RAM) and altered photochemistry (trend in EUV). We find that a series of flybys that occurred during solar minimum (2008) and with similar flyby geometries are associated with enhanced values of the effective recombination coefficient compared with the remaining data set, which also suggests a chemistry dependence on the sunlight conditions.

Keywords

atmospheric effects; molecular processes; planets and satellites: individual (Titan); plasmas

1. Introduction

Titan, the largest moon of Saturn, has been studied in detail by the *Cassini* spacecraft. Titan hosts an organic atmosphere, extending up to ~2200 km in altitude (Niemann et al. 2005; Wahlund et al. 2005; Waite et al. 2005; Cravens et al. 2006; Waite et al. 2007; Wahlund et al. 2009b; Edberg et al. 2010), which is ionized primarily by the solar EUV (dayside; see, e.g., Ågren et al. 2009; Shebanits et al. 2013) and energetic particles (nightside; see, e.g., Ågren et al. 2007; Cravens et al. 2009; Sagnières et al. 2015). The ionization initiates a complex organic chemistry (Vuitton et al. 2014 and references therein), which contributes to the aerosol formation (Niemann et al. 2005; Coates et al. 2009; Gudipati et al. 2013; Lavvas et al. 2013). While the understanding of the intricate ion (and radical) chemistry of Titan's upper atmosphere has improved significantly, there are still unresolved questions regarding the basic ionization balance. Using a *Cassini* data set from four Titan dayside flybys (T40, T41, T42, and T48), Vigren et al. (2013) presented model–observation comparisons of electron number densities. They found that while the electron number density *altitude profile* agreed well with Radio and Plasma Wave Science Langmuir probe (LP) observations at altitudes between 1050 and 1200 km, the model overestimated the density by a factor of ~2. Whether the cause of the discrepancy is overestimated plasma production, underestimated plasma loss, or a combination of the two, remains an open question. A model by Richard et al. (2015) suggested the loss rate to be the cause. However, Vigren et al. (2015) found a reasonable agreement with the observations when applying a nightside model similar to the one in Vigren et al. (2013), with the electron production rates based on the suprathermal electrons spectra from the Electron Spectrometer (*Cassini* Plasma Spectrometer package, CAPS/ELS); the authors utilized a similar approach to losses as Galand et al. (2010) and Vigren et al. (2013) and showed that if the dayside model overestimation is due to underestimated loss processes, tuning the recombination coefficients introduces a model *underestimation* on the nightside. This is one indication that the issue on the dayside could be an overestimated plasma production. Another indication is reported by Sagnières et al. (2015), who showed that the solar energy deposition model yielded a factor of ~2 higher N_2^+ production rates than those inferred from an empirical chemical model based on the ambient number densities of CH_4 and CH_3^+ measured by the Ion Neutral Mass Spectrometer (INMS). Third, Vigren et al. (2016; again focusing on T40, T41, T42, and T48) showed that the suprathermal electron intensities calculated from the solar energy deposition model were typically a factor of 3 ± 1 higher than observed by CAPS/ELS for electron energies <60 eV, covering the bulk of the photoelectron energy distribution.

The present work, which in essence is an extended reassessment of Vigren et al. (2013), has several motivations. First of all, it is relevant to investigate whether the reported model–observation discrepancy prevails throughout the solar cycle. Second, since the work of Vigren et al. (2013) was published, a significant degree of electron depletion (negative ion formation) was shown at altitudes of ~1100 km (Shebanits et al. 2013, 2016; Wellbrock et al. 2013), and here we take that into account. Finally, the INMS has recently been recalibrated (Teolis et al. 2015) and the neutral number density profiles in the present work have been updated accordingly.

The outline of the article is as follows. Section 2 describes the ionospheric model, the utilized *Cassini* data set and measurement principles. In Section 3, we present and discuss results with a focus on the effective recombination coefficient α_{eff} , needed to make the observed plasma densities consistent with the calculated plasma production rate. Section 3.1 compares the results with earlier works and with expected effective recombination coefficients based on measured ion compositions (e.g., Mandt et al. 2012) and electron temperatures. We investigate (Section 3.2) whether the derived α_{eff} is dependent on parameters such as the solar zenith angle (SZA), the integrated solar EUV intensity and the corotational plasma ram direction (RAM). Section 3.2 summarizes the provides our conclusions.

2. Method

2.1. Ionospheric Model

Assuming a photochemical equilibrium in a quasi-neutral plasma consisting of free electrons, singly charged positive ions, and negative ions with a charge Zq_e (charge densities n_e, n_+ and Zn_- , respectively), the positive ion–electron pair production rate P_e , derived from the continuity equation (e.g., Larsen et al. 1972; Vigren et al. 2014), relates to the plasma densities via

$$\frac{P_e}{n_e n_+} = \alpha_{\text{eff}} + \frac{n_-}{n_e} k_{\text{eff}}, \quad (1)$$

where α_{eff} and k_{eff} are the effective rate coefficients (see, e.g., Galand et al. 2010) for ion–electron dissociative recombination and ion–ion mutual neutralization, respectively. Because $\alpha_{\text{eff}} \gg k_{\text{eff}}$ (Vigren et al. 2014), the left-hand side of Equation (1) is expected to be a good proxy for α_{eff} at least as long as $Zn_-/n_e < 1$.

While the RPWS/LP provides n_e , n_+ and Zn_- (see Section 2.2), the parameter P_e is derived from the photoionization $P_{e,\text{ph}}$ and the secondary electron-impact ionization $P_{e,\text{imp}}$:

$$P_e = P_{e,\text{ph}} + P_{e,\text{imp}}. \quad (2)$$

Since ~97% of Titan’s atmosphere consists of N_2 (Niemann et al. 2005; Waite et al. 2005; Coustenis et al. 2007), the photoionization rate may be calculated as

$$P_{e,\text{ph}}(z) = \sum_{\lambda} n_{\text{N}_2}(z) \sigma_{\text{ion},\text{N}_2}(\lambda) I(z, \lambda) \quad (3)$$

Where $n_{\text{N}_2}(z)$ is the N_2 density at altitude z (from the INMS measurements), extrapolated as an exponential to the limit of Titan’s atmosphere z_0 (defined as $n_{\text{N}_2}(z_0 = 100 \text{ cm}^{-3})$), $\sigma_{\text{ion},\text{N}_2}(\lambda)$ is the ionization cross section at wavelength λ (Samson et al. 1987; Stolte et al. 1998; Galand et al. 2010) and

$$I(z, \lambda) = I_{\infty}(\lambda) e^{-N_{\text{col}}(z) \sigma_{\text{abs}, N_2}(\lambda)}, \quad (4)$$

is the solar irradiance at wavelength λ and altitude z (Beer–Lambert law) with $N_{\text{col}}(z)$ representing the N_2 column density, $\sigma_{\text{abs}, N_2}(\lambda)$ denoting the absorption cross section and $I_{\infty}(\lambda)$ being the solar irradiance immediately outside Titan’s atmosphere, translated by distance and time from TIMED/SEE solar EUV measurements near Earth (1 au from the Sun). Note that we assume a homogeneous atmosphere for each flyby, while the N_2 profiles given by the INMS are along the *Cassini* trajectory. Furthermore, the N_2 altitude profiles vary with the solar EUV flux (see Figure 1(a)). To account for this, the N_2 density is used instead of the altitude for plotting throughout this paper.

To account for further ionization by photoelectrons and their secondaries, we use an empirical relation linking the primary efficiency (η) to N_{col} along the ray path,

$$\eta = 0.18 + 2 \times 10^{-18} N_{\text{col}} = \frac{P_{e, \text{imp}}}{P_{e, \text{ph}}}, \quad (5)$$

derived by fitting the solar energy deposition model of Vigren et al. (2013) applied to a pure N_2 atmosphere (Figures 1(b), (c)). The relation is applicable for the EUV flux and column densities relevant here. The underlying model utilizes the local approximation (negligible transport and local electron energy degradation), expected to be valid in the presented region of Titan’s ionosphere (see, e.g., Lavvas et al. 2011). We have also verified that the addition of a few percent of methane has a very limited influence on the results: P_e below 1200 km altitude changes within 2% (~5% near 1250 km) when introducing CH_4 with T40-like relative abundances. The data points with $P_e < 3 \text{ cm}^{-3} \text{ s}^{-1}$ are excluded to remove the plasma transport region and the regions where nonsolar ionization sources may be comparable to or stronger than the solar ionization.

2.2. Measurements

The *Cassini* RPWS/LP instrument and measurement details can be found in, e.g., Gurnett et al. (2004), Wahlund et al. (2009a), Edberg et al. (2010), Morooka et al. (2011), Ågren et al. (2012), and Shebanits et al. (2013, 2016). The LP measures collected plasma current as a function of bias voltage, producing a current-voltage characteristic (CVC). The plasma number densities (n_e , n_+ and Zn_-) and electron temperatures (T_e) are derived from the negative and the positive voltage parts of the CVC, respectively. The electron number densities are normally derived from the positive voltage CVC. However, in Titan’s ionosphere, they may be contaminated by the negative ions (especially in the dusty plasma region where the electrons are depleted), see examples in Figures 1(d) and (e). All of the plasma densities used in this study are therefore derived from the negative voltage CVC. The electron temperature strongly influences the efficiency of dissociative recombination (for details, see Section 3).

The *Cassini* INMS and its measurements are described in detail in, e.g., Waite et al. (2004), Cui et al. (2009), Magee et al. (2009), Mandt et al. (2012), and Teolis et al. (2015). The INMS is a quadrupole mass analyzer, measuring neutrals and ions in the 1–99 amu range. For this study, we are only using N₂ densities, which contribute ~97% of Titan's atmosphere (Niemann et al. 2005).

TIMED/SEE measurements are described in detail on the LISIRD homepage (http://lasp.colorado.edu/lisird/data/timed_see_ssi_l3/). The final data product is the solar irradiance in the 0.5–115.5 nm range. For the purpose of this study, we only use the 80 nm < spectra (henceforth referred to as “EUV flux”) since the ionization threshold for N₂ is 79.6 nm (Schunk & Nagy 2009). The translation of the measured irradiance to Saturn (by distance and time) has been validated by a comparison of the photoelectron current measured by the RPWS/LP (at Saturn) to the one calculated based on the translated EUV flux (Shebanits et al. 2017).

The data set covers the dayside/terminator flybys between TA and T117, 34 in total (T16, T18–20, T23, T32, T34, T36, T38–T43, T48, T49, T51, T58, T61, T71, T83, T84, T86, T87, T91, T92, T95, T98, T100, T104, T107, T108, T113, and T117). The data is sorted into inbound and outbound trajectories due to possible chamber contamination effects in the INMS measurements (for the outbound densities).

3. Results and Discussion

3.1. Effective Rate Coefficients and Comparison with Previous Works

The estimated effective loss rate coefficients α_{eff} are plotted versus the ambient N₂ number density (empty triangles in Figure 2), based on the left-hand side of Equation (1) with the calculated P_e and measured n_e and n_+ . Fit of α_{eff} to $n(\text{N}_2)$ from Vigren et al. (2013) is included (based on the flybys T40, T41, T42, and T48, color-coded solid triangles mark the original data set). Updated data points from the same flybys have matching colors. The pink shaded area in Figure 2 represents the expected range of rate coefficients for an ion population with $a_{\text{eff},300}$ between 6×10^{-7} and $12 \times 10^{-7} \text{ cm}^3 \text{ s}^{-1}$ and an average electron temperature profile (Vigren et al. 2013, 2015). Gray circles mark the points for which $Zn_-/n_e > 1$; for these points, the second term on the right-hand side of Equation (1) may not be negligible (which would mean that the plotted α_{eff} is overestimated).

Comparing our data points with the fit from Vigren et al. (2013), we notice a clear reduction in α_{eff} , with a growing difference toward higher N₂ densities (lower altitudes). This is directly related to electron depletion and the fact that Vigren et al. (2013) calculated α_{eff} as $P_e n_e^{-2}$ (appropriate for $Zn_- \ll n_e$) rather than $P_e (n_e n_+)^{-1}$. A point by point comparison with data from Vigren et al. (2013) indicates that the underlying cause is typically a modest change in P_e caused by the changes in $n(\text{N}_2)$ due to the INMS calibration update (which also shifts locations of the points in the y-direction) as well as the negative ion contamination of n_e .

Our α_{eff} values are a factor of ~2 higher than the values expected from the ion composition and the electron temperatures (Figure 2, pink shaded area), an improvement compared to the

factor of ~ 4 discrepancy in Vigren et al. (2013). The data points seem to be grouped, with one group associated with higher values (including the four flybys studied by Vigren et al. 2013). The previously reported issue of models overestimating electron number densities in Titan's dayside ionosphere by a factor of ~ 2 is reduced here to a milder problem with models overestimating plasma densities roughly by a factor of ~ 1.2 – 1.4 for one group of flybys and a factor of ~ 1.5 – 1.7 for another group of flybys. We shall see in the following section that the variability of α_{eff} with $n(\text{N}_2)$ largely (and to no surprise) reflects electron temperatures decreasing with increasing neutral densities.

3.2. Dependencies of the Effective Rate Coefficient on Various Parameters

The extended data set in the present study allows us to investigate the effects of various parameters on the effective recombination coefficients (Figure 3). The same data points as the empty triangles in Figure 2 are color-coded with the SZA (Figure 3(a)), the angle to the corotational plasma ram direction (RAM in Figure 3(b), 0° is the ram side ionosphere, 180° is the wake side) and the EUV flux (Figure 3(c)). Trends are present in all three cases: the rate coefficients increase with decreasing SZA, increasing RAM, and decreasing EUV.

Estimates of the 300 K effective recombination coefficient $\alpha_{\text{eff},300}$ are plotted in Figures 3(d)–(f), derived as $\alpha_{\text{eff},300} = \alpha_{\text{eff}} (T_e/300)^{0.7}$. In Figure 3(d), we include a fit of $\alpha_{\text{eff},300}$ based on Vigren et al. (2013) to again illustrate an improvement. Based on the ion composition, $\alpha_{\text{eff},300}$ values largely exceeding $10^{-6} \text{ cm}^3 \text{ s}^{-1}$ are unlikely, though, for the complex composition of the deep ionosphere, such a statement is uncertain due to the still rather limited amount of experimental studies into dissociative recombination reactions involving complex ions with masses >100 amu. The trends persist: $\alpha_{\text{eff},300}$ also tends to increase with decreasing SZA (Figure 3(d)), increasing RAM (Figure 3(e)) and decreasing EUV flux (Figure 3(f)). An empirical nonlinear least squares fit (Table 1) of the $\alpha_{\text{eff},300}$ values to the SZA, RAM, and EUV flux (and $n(\text{N}_2)$) verifies the respective variations as statistically significant.

The SZA dependency (Figures 3(a) and (d)) is most likely due to the fading solar EUV illumination, which decreases the modeled photoionization P_e toward the terminator, while the measured densities only decrease to the levels of the energetic particle ionization (Ågren et al. 2007; Cravens et al. 2009; Galand et al. 2014). The latter is expected to correlate with the corotational plasma ram direction. An increase toward larger RAM angles is indeed seen in Figures 3(b) and (e), consistent with the expected particle precipitation due to Saturn's magnetic field draping around Titan. The interaction between Saturn's magnetosphere and Titan's ionosphere has been shown to heat the latter (Westlake et al. 2011). It should be noted that including the ionization by energetic particles into the model would further increase the derived recombination coefficients and therefore not alleviate the overestimation. The EUV flux has been suggested to affect the photochemistry (Westlake et al. 2014; Shebanits et al. 2017), which in turn affects the precipitation of the heavier particles and may explain the EUV-dependency (Figures 3(c) and (f)). An additional implication of the chemistry being involved is the similarity between the variations in the α_{eff} and the volume mixing ratios of *HCN* (Figure 4, see also Cui et al. 2016)—a molecule that has been identified as the dominant cooling agent of Titan's thermosphere (Yelle 1991).

The group of higher values of α_{eff} correspond to flybys with higher *HCN* volume mixing ratios, and vice versa. The grouping of the α_{eff} into two sets in Figures 3(a)–(c) is therefore most likely due to a change in the photochemistry driven by the varying EUV flux and should then reflect different ion compositions with different effective recombination coefficients.

Enhanced EUV can also increase electron temperatures, leading to a reduced α_{eff} due to the negative temperature dependence of dissociative recombination reactions (e.g., Vuitton et al. 2007 and references therein). As words of caution, we note that a series of flybys associated with enhanced $\alpha_{\text{eff},300}$ have similar geometry and occurred over a limited time period near the minimum solar activity (this includes the flybys in Vigren et al. 2013), which may have introduced some bias into the fit in Table 1.

A variability of $\alpha_{\text{eff},300}$ with $n(\text{N}_2)$ may seem weak in Figures 3(d)–(f), especially in contrast to what was reported by Vigren et al. (2013; see their Figure 12 or their fitted function in our Figure 3(a)). However, the coefficient of variability with respect to $n(\text{N}_2)$ is as high as the coefficient for the SZA (Table 1) and has a higher significance level; it should also (and again) be noted that the fit from Vigren et al. (2013) is based on $\alpha_{\text{eff},300} \propto P_e n_e^{-2}$, whereas our data points represent $\alpha_{\text{eff},300} \propto P_e (n_e n_+)^{-1}$.

4. Conclusions

We have derived effective recombination coefficients in Titan's sunlit ionosphere based on data from 34 dayside/terminator flybys through Titan's upper atmosphere by the Cassini spacecraft. The values are obtained using the updated data sets and are lower than those reported by Vigren et al. (2013), who also focused on only four flybys. The recombination coefficients are still, however, about a factor of 2–3 higher than what is anticipated from the ion composition and the electron temperature. We see trends of increasing rate coefficients (and, interestingly, also *HCN* volume mixing ratios) with decreasing SZA, toward the corotational plasma wake of Titan and decreased solar EUV flux. Empirical statistical analysis shows that all trends are statistically significant. The SZA trend may be explained by the declining photoionization against the background ionization by energetic particles. The corotational plasma direction dependency is directly correlated to the particle ionization. The EUV flux trend is likely due the photochemistry changes with the varying EUV flux (see also Westlake et al. 2014; Shebanits et al. 2017). It is noted, however, that a series of flybys contributing to the trends occurred at similar flyby geometry and over a limited period (2008), coinciding with a solar minimum. This includes the flybys used by Vigren et al. (2013). With the current data set, we cannot conclusively determine whether the main cause of the overestimation by the photoionization models is the loss coefficient or the production rate. We want to point out, however, that the nightside particle ionization modeling with a similar loss coefficient produced densities consistent with the measurements (Vigren et al. 2015). An extended study of Titan's nightside ionosphere would be of interest and should ideally include not only electron-impact ionization but also ionization associated with the energy degradation of energetic magnetospheric ions (see, e.g., Snowden & Yelle 2014).

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References

- Ågren K, Edberg NJT, & Wahlund JE 2012, *GeoRL*, 39, L10201
- Ågren K, Wahlund JE, Garnier P, et al. 2009, *P&SS*, 57, 1821
- Ågren K, Wahlund J-E, Modolo R, et al. 2007, *AnGeo*, 25, 2359
- Coates AJ, Wellbrock A, Lewis GR, et al. 2009, *P&SS*, 57, 1866
- Coustenis A, Achterberg RK, Conrath BJ, et al. 2007, *Icar*, 189, 35
- Cravens TE, Robertson IP, Waite JH, et al. 2006, *GeoRL*, 33, L07105
- Cravens TE, Robertson IP, Waite JH, et al. 2009, *Icar*, 199, 174
- Cui J, Cao Y-T, Lavvas PP, & Koskinen TT 2016, *ApJL*, 826, L5
- Cui J, Yelle RV, Vuitton V, et al. 2009, *Icar*, 200, 581
- Edberg NJT, Wahlund JE, Ågren K, et al. 2010, *GeoRL*, 37, L20105
- Galand M, Coates AJ, Cravens TE, & Wahlund J-E 2014, in *Titan's ionosphere*, in *Titan*, ed. Muller-Wodarg I et al. (Cambridge: Cambridge Univ. Press), 376
- Galand M, Yelle R, Cui J, et al. 2010, *JGRA*, 115, A07312
- Gudipati MS, Jacovi R, Couturier-Tamburelli I, Lignell A, & Allen M 2013, *NatCo*, 4, 1648
- Gurnett DA, Kurth WS, Kirchner DL, et al. 2004, *SSRv*, 114, 395
- Larsen T, Jespersen M, Murdin J, et al. 1972, *JATP*, 34, 787
- Lavvas P, Galand M, Yelle RV, et al. 2011, *Icar*, 213, 233
- Lavvas P, Yelle RV, Koskinen T, et al. 2013, *PNAS*, 110, 2729 [PubMed: 23382231]
- Magee BA, Waite JH, Mandt KE, et al. 2009, *P&SS*, 57, 1895
- Mandt KE, Gell DA, Perry M, et al. 2012, *JGRE*, 117, E10006
- Morooka MW, Wahlund JE, Eriksson AI, et al. 2011, *JGRA*, 116, A12221
- Niemann HB, Atreya SK, Bauer SJ, et al. 2005, *Natur*, 438, 779
- Richard MS, Cravens TE, Wylie C, et al. 2015, *JGRA*, 120, 1264
- Sagnières LBM, Galand M, Cui J, et al. 2015, *JGRA*, 120, 5899
- Samson JAR, Masuoka T, Pareek PN, & Angel GC 1987, *JChPh*, 86, 6128
- Schunk R, & Nagy A 2009, *Ionospheres* (2nd ed.; Cambridge: Cambridge University Press)
- Shebanits O, Vigren E, Wahlund J-E, et al. 2017, *JGRA*, 122, 7491
- Shebanits O, Wahlund JE, Mandt K, et al. 2013, *P&SS*, 84, 153
- Shebanits O, Wahlund J-E, Edberg NJT, et al. 2016, *JGRA*, 121, 10075
- Snowden D, & Yelle RV 2014, *Icar*, 228, 64
- Stolte W, He Z, Cutler J, Lu Y, & Samson JA 1998, *ADNDT*, 69, 171
- Teolis BD, Niemann HB, Waite JH, et al. 2015, *SSRv*, 190, 47
- Vigren E, Galand M, Shebanits O, et al. 2014, *ApJ*, 786, 69
- Vigren E, Galand M, Yelle RV, et al. 2013, *Icar*, 223, 234
- Vigren E, Galand M, Yelle RV, et al. 2015, *Icar*, 248, 539

- Vigren E, Galand M, Wellbrock A, et al. 2016, ApJ, 826, 131
- Vuitton V, Dutuit O, Smith MA, & Balucani N 2014, in Chemistry of Titan's atmosphere, in Titan, ed. Muller-Wodarg I et al. (Cambridge: Cambridge Univ. Press), 224
- Vuitton V, Yelle RV, & McEwan MJ 2007, Icar, 191, 722
- Wahlund J-E, André M, Eriksson AIE, et al. 2009a, P&SS, 57, 1795
- Wahlund J-E, Boström R, Gustafsson G, et al. 2005, Sci, 308, 986
- Wahlund J-E, Galand M, Müller-Wodarg I, et al. 2009b, P&SS, 57,1857
- Waite JH, Lewis WS, Kasprzak WT, et al. 2004, SSRv, 114, 113
- Waite JH, Niemann H, Yelle RV, et al. 2005, Sci, 308, 982
- Waite JH, Young DT, Cravens TE, et al. 2007, Sci, 316, 870
- Wellbrock A, Coates AJ, Jones GH, Lewis GR, & Waite JH 2013, GeoRL, 40, 4481
- Westlake JH, Bell JM, Waite JH, et al. 2011, JGRA, 116, A03318
- Westlake JH, Waite JH, Bell JM, & Perryman R 2014, JGRA, 119, 8586
- Yelle RV 1991, ApJ, 383, 380

Figure 1.

Model inputs: (a) Variation of the N_2 density altitude profiles with the solar EUV flux (color-coded). At higher altitudes, the N_2 densities are enhanced by the thermosphere expanding with increasing EUV flux, but at lower altitudes the densities are diminished (see also Westlake et al. 2014). (b) Primary efficiency η_{SEDM} calculated from a solar energy deposition model (Vigren et al. 2013), using solar spectra associated with the EUV values of 30 (blue) and 40 (green) μWm^{-2} , and the fit function given by Equation (5) (dashed line). (c) Ratio of η_{SEDM} to the fit function η_{fit} (dashed line). (d) T16 and (e) T95 examples of the negative ion contamination of the electron density derived from the electron current. The electron density plotted in blue is derived from the electron current and in red from the ion current. Charge densities of the negative ions are plotted in green and the positive ions are plotted in yellow. Altitude is shown in gray for reference.

Figure 2.

Effective loss rate coefficients calculated as $a_{\text{eff}} \approx P_e(n_e n^+)^{-1}$, plotted vs. N_2 densities (empty triangles, orange downward for inbound and green upward for outbound). Filled triangles (color-coded by flyby) show $a_{\text{eff}} (\approx P_e n_e^{-2})$ and the best fit $\pm 1\sigma$ (solid and dashed black lines) from Vigren et al. (2013). Points from the same flybys in our data set are colored accordingly. The pink shaded area represents the a_{eff} estimated by Vigren et al. (2013) from the measured ion composition and electron temperatures. Gray circles at higher N_2 densities mark the points with $Zn_-/n_e > 1$.

Figure 3.

Estimated loss rate coefficients calculated as $\alpha_{\text{eff}} \approx P_e(n_e n^+)^{-1}$, plotted vs. N_2 densities with color-coded SZA (a), RAM (b) and the solar EUV flux (c). $\text{SZA} < 70^\circ$ corresponds to the dayside, and $70^\circ < \text{SZA} < 110^\circ$ corresponds to the terminator. The RAM angle is 0° on the upstream side of Titan (ram side) and 180° is on the downstream side (wake side). (d)–(f): same as (a)–(c) but with $\alpha_{\text{eff},300} = \alpha_{\text{eff}} (T_e/300)^{0.7}$. The black line in (d) is a fit of $\alpha_{\text{eff},300}$ based on Vigren et al.(2013; dashed lines correspond to the $\pm 1\sigma$ confidence interval).

Figure 4. Effective rate coefficient α_{eff} (a) and HCN volume mixing ratio (b) color-coded and plotted vs. EUV flux and N_2 number density for comparison. Both variables decrease with increasing EUV flux.

Table 1

Nonlinear Least Squares Fit to $\alpha_{\text{eff}, 300} \times 10^6 a_1 sc(N_2) + a_2 sc(F_{\text{EUV}}) + a_3 \cos \text{SZA} + a_4 \cos \text{RAM} + a_5$

Coefficients	Estimate	Standard Deviation	T-statistic	p-value
$N_2 \rightarrow a_1$	0.255	0.080	3.17	1.71×10^{-3}
$F_{\text{EUV}} \rightarrow a_2$	-0.160	0.061	-2.61	9.59×10^{-3}
$\text{SZA} \rightarrow a_3$	0.268	0.135	1.98	4.88×10^{-2}
$\text{RAM} \rightarrow a_4$	-0.336	0.074	-4.52	9.77×10^{-6}
a_5	1.83	0.104	17.7	3.13×10^{-45}
Fit statistics	R2	Adjusted R2	F-statistic versus const. model	p-value
	0.209	0.196	15.8	1.76×10^{-11}

Note. $sc(x)$ denotes a normalization of x to interval $(-1, 1)$, introduced to avoid parameter bias.