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Auroral electron precipitation and flux tube erosion in Titan's upper atmosphere

D. Snowden [a,*], R.V. Yelle [a], M. Galand [b], A.J. Coates [c,d], A. Wellbrock [c,d], G.H. Jones [c,d], P. Lavvas [e]

[a] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA
[b] Department of Physics, Imperial College, London SW7 2AK, UK
[c] Mullard Space Science Laboratory, University College London, Dorking RH5 6NT, UK
[d] Centre for Planetary Sciences at UCL/Birkbeck, Gower Street, London WC1E 6BT, UK
[e] Group de spectrométrie moléculaire et atmosphérique, CNRS UMR 7331, Université de Reims, Campus Moulin de la Housse – BP 1039, 51687 Reims, France

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ABSTRACT

Cassini dasta shows that Titan's atmosphere strongly depletes the electron content in Saturn's flux tubes, producing features known as electron bite-outs, which indicate that the flux of auroral electrons decreases over time. To understand this process we have developed a time-dependent two-stream model, which uses field line geometries and drift paths calculated by a three-dimensional multi-fluid model of Titan's plasma interaction. The boundary conditions of the model account for the time-dependent reduction or increase in electron flux along Saturn's magnetic field lines because of the loss or production of electrons in Titan's atmosphere. The modification of the auroral electron flux depends on the electron bounce period in Saturn's outer magnetosphere; therefore, we also calculate electron bounce periods along several Kronian field lines accounting for both the magnetic mirroring force and the field-aligned electric potential in Saturn's plasma sheet. We use the time-dependent two-stream model to calculate how the reduction in the auroral electron flux affects electron impact ionization and energy deposition rates in Titan's upper atmosphere. We find that the flux of higher energy (>50 eV) electrons entering Titan's atmosphere is strongly reduced over time, resulting in smaller ionization and energy deposition rates below ~1300 km altitude. Finally, we show that sample spectrograms produced from our calculations are consistent with CAPS-ELS data.

1. Introduction

Saturn's largest moon, Titan, has a dense atmosphere that interacts directly with the fields and plasma in Saturn's magnetosphere. The dynamic interaction between Titan's atmosphere and Saturn's magnetosphere affects the chemistry, structure, energetics, and evolution of Titan's thermosphere and ionosphere through particle precipitation, Joule/frictional heating, and ion outflow. For example, ionization from energetic particles from Saturn's magnetosphere, along with solar EUV and soft X-rays, produce Titan's ionosphere and subsequent ion-neutral reactions form the abundant complex organic molecules in Titan's atmosphere (e.g. Vuitton et al., 2007).

The structure of Titan's ionosphere as observed by Cassini has been described by Cravens et al. (2005), Kliore et al. (2008), Ågren et al. (2009), and Luhmann et al. (2012). The correlation between the electron density in Titan's ionosphere and the solar zenith angle indicates that solar EUV is the dominant source of ionization in Titan's dayside ionosphere (Ågren et al., 2009). The results of Ågren et al. (2009) show that the peak electron densities on the dayside vary between about 2500 cm^{-3} and 3300 cm^{-3} and that the electron density drops off steeply at solar zenith angles between 80° and 100°. Model-data comparisons also suggest that the electron density observed in Titan's dayside ionosphere above 1000 km altitude can be explained mostly with EUV ionization (Cravens et al., 2005; Galand et al., 2006, 2010; Robertson et al., 2009; Lavvas et al., 2011). In fact, both Westlake et al. (2012) and Vigren et al. (2013) showed that solar ionization produces electron densities that are about twice as large as those observed with the current values for ion loss rates in Titan's ionosphere. The reason for this discrepancy remains an open question although several possibilities are discussed in Vigren et al. (2013).

The results of Ågren et al. (2009) show that, though substantially lower than the dayside values, the electron density in Titan's nightside ionosphere is also significant with peak densities varying between 500 cm^{-3} and 1500 cm^{-3}. Titan's nightside ionosphere is produced from a combination of day to night ion transport and impact ionization from electrons and ions coming from Saturn's magnetosphere. Cui et al. (2010) showed that the relative density

* Corresponding author.
E-mail address: dsnowden@lpl.arizona.edu (D. Snowden).

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of ions with longer chemical lifetimes and ions with shorter chemical lifetimes suggests that day-to-night transport is significant. However, observations of short-lived ions indicate that magnetospheric precipitation may also be an important and variable source of ionization in Titan's nightside ionosphere (Cravens et al., 2009).

Particle precipitation is also a significant source of heat for electrons and ions in Titan's ionosphere. Richard et al. (2011) found that magnetospheric electron precipitation was needed to model the observed electron temperature in Titan's dayside and nightside ionosphere during Cassini's T18 and T5 flybys, respectively. However, Galand et al. (2006) did not need electron precipitation to model the observed electron temperature on the dayside of Titan's atmosphere during Cassini's TA flyby. These results indicate that heating from auroral electrons may be spatially or temporally variable. Knowledge of the electron temperature in Titan's ionosphere is important because it determines the electron recombination rate. Furthermore, thermal pressure in Titan's ionosphere balances the upstream magnetic pressure in Saturn's magnetosphere. Therefore, the electron temperature also affects the penetration depth of particles and fields (e.g. Ma et al., 2011).

Particle precipitation from Saturn's magnetosphere may also heat Titan's neutral atmosphere. The temperature of Titan's thermosphere has been shown to be extremely complex and variable (Müller-Wodarg et al., 2006, 2008; Cui et al., 2009; Westlake et al., 2011; Snowden et al., 2013). The results of Westlake et al. (2011) suggest that magnetospheric particle precipitation may be the source of the observed variability. De La Haye et al. (2008) calculated the neutral heating rate due to auroral electron precipitation and found that, while less than the energy deposited by solar EUV, the energy deposited by auroral electrons may be significant at altitudes higher than 700 km. On the other hand, Cassini ultraviolet spectrometer observations indicate that the energy deposited in Titan's thermosphere by magnetospheric particles is less than 10% of solar EUV (Ajello et al., 2007; Stevens et al., 2011). A better understanding of heating from magnetospheric particle precipitation and how it varies over the globe and with Titan's plasma environment is needed to understand how particle precipitation might affect the thermal structure of Titan's upper atmosphere.

Magnetospheric ions and electrons, cosmic rays, and meteoric dust are important sources of ionization and heating in Titan's atmosphere (e.g. Gronoff et al., 2009a). Meteoric ionization and cosmic ray ionization are only significant below 800 km altitude (Molina-Cuberos et al., 1999, 2001; Gronoff et al., 2011). Thermal ions with gyroradii on the order of Titan's diameter precipitate above 1000 km altitude (Shematovich et al., 2001; Michael and Johnson, 2005; Michael et al., 2005; Snowden and Yelle, 2013) but are at least partially prevented from entering the atmosphere due to gradients in the magnetic field near Titan (Ledvina et al., 2005; Sillanpää et al., 2007; Tseng and Ip, 2008). High energy (>10 keV) ions are not significantly affected by the magnetic field near Titan but precipitate mostly below 1000 km (Cravens et al., 2008; Smith et al., 2009; Gronoff et al., 2009a; Shah et al., 2009). Therefore, magnetospheric electron precipitation is thought to be the most significant ionization source in Titan's nightside ionosphere at altitudes where Cassini has made *in situ* observations. This is corroborated by the correlation between the density of short lived ions and the electron flux observed by Cassini's electron spectrometer (CAPS-ELS) during Cassini T5 flyby (Cravens et al., 2009).

Estimating auroral electron impact ionization and heating rates in Titan's atmosphere is difficult because the precipitation of auroral electrons is coupled to Titan's complex interaction with Saturn's magnetosphere. One complexity is the temporal variability. For example, Rymer et al. (2009) showed that the energy spectra of suprathermal electrons near Titan depends on Titan's plasma environment, which varies on timescales ranging from minutes to hours. Even if the electron flux in Saturn's magnetosphere near Titan was steady, the flux of electrons entering Titan's upper atmosphere may still be time dependent. Gan et al. (1992) found that Titan's atmosphere caused a strong depletion in the flux of auroral electrons with energies above ~50 eV. The depletion of higher energy electrons explained the electron 'bite-out' observed downstream of Titan by Voyager 1. These results show that thermalization and scattering in the atmosphere can erode the reservoir of electrons in flux tubes connected to Titan. Therefore, the auroral electron flux should decrease over timescales similar to the electron bounce time in Saturn's magnetosphere (Cravens et al., 2009).

Gan et al. (1993) is the only previous study to account for the time dependent reduction of flux along magnetic field lines connected to Titan's atmosphere. These authors calculated the electron flux along a parabolic field line as it traveled along the subram direction for 6000 s. Gan et al. (1993) assumed that the radial drift speed of the magnetic field line decelerated from 1 km/s at a radial distance of 6000 km to 0 km/s at 3300 km with a rate proportional to 1/r. Our study picks up where this study left off by using more realistic magnetic field line geometries, field line drift paths, and electron bounce periods in Saturn's magnetosphere.

Electron impact ionization and heating rates depend on the configuration of Saturn's magnetic field near Titan, which is complicated to understand in its own right (Gronoff et al., 2009b; Galand et al., 2006; Richard et al., 2011). Electrons in the suprathermal energy range (<10 keV) move parallel to Saturn's magnetic field because their small gyroradii (<50 km) means that they are not significantly perturbed by spatial gradients in the magnetic field that cause ions and higher energy electrons to drift perpendicular to magnetic field lines. Titan does not have a significant intrinsic magnetic field (Neubauer et al., 1984); therefore, Saturn's plasma and magnetic field comes into contact with Titan's atmosphere and is decelerated by the momentum loading of cold ions from Titan's ionosphere. This causes Saturn's magnetic field to wrap around Titan and drift into Titan's upper atmosphere; collisions between magnetospheric electrons and Titan's neutral atmosphere occur along these draped magnetic field lines.

The configuration of magnetic field lines in Titan's ionosphere is constantly changing because of the variability of Saturn's magnetosphere near Titan and the changing orientation of Titan's ionosphere relative to the magnetospheric flow. Most electron precipitation models assume that electrons precipitate along parabolic or radial magnetic field lines (e.g. Gan and Cravens, 1992; Cravens et al., 2005; Richard et al., 2011); however, the magnetic field line topology in Titan's ionosphere is more complicated and a three-dimensional model of Titan's interaction with Saturn's magnetosphere is needed to calculate realistic configurations of magnetic field lines in Titan's ionosphere.

We have developed the first model capable of estimating how both the depletion of electrons in Saturn's flux tubes over time and the global configuration of magnetic field lines in Titan's ionosphere affect electron precipitation in Titan's upper atmosphere. To do this we couple a two-stream model of electron precipitation along magnetic field lines to a three-dimensional model of Titan's plasma interaction. We do not assume dipolar bounce periods in Saturn's magnetosphere. Instead, we estimate electron bounce periods using realistic field line geometries and taking into account the ambi-polar electric field in Saturn's plasma sheet. We show that emptying the reservoir of electrons in flux tubes connected to Titan over time strongly decreases both the ionization rates and energy deposition rates in Titan's ionosphere below altitudes of about 1300 km. We also show that the electron impact ionization and heating rates depend on the configuration and drift path of magnetic field lines in Titan's ionosphere. Our intention is to examine the general characteristics of auroral electron precipitation in Titan's upper atmosphere; therefore, we used an idealized