Icarus 305 (2018) 186–197

Contents lists available at ScienceDirect

Icarus

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

Energy deposition and ion production from thermal oxygen ion precipitation during Cassini's T57 flyby

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ARTICLE INFO

Article history:
Received 24 January 2017
Revised 7 June 2017
Accepted 10 January 2018
Available online 11 January 2018

Keywords:
Titan
Atmosphere
Aeronomy

ABSTRACT

Cassini's Radio Science Investigation (RSS) and Langmuir Probe observed abnormally high electron densities in Titan's ionosphere during Cassini's T57 flyby. We have developed a three-dimensional model to investigate how the precipitation of thermal magnetospheric O^+ may have contributed to enhanced ion production in Titan's ionosphere. The three-dimensional model builds on previous work because it calculates both the flux of oxygen through Titan's exobase and the energy deposition and ion production rates in Titan's atmosphere. We find that energy deposition rates and ion production rates due to thermal O^+ precipitation have a similar magnitude to the rates from magnetospheric electron precipitation and that the simulated ionization rates are sufficient to explain the abnormally high electron densities observed by RSS and Cassini's Langmuir Probe. Globally, thermal O^+ deposits less energy in Titan's atmosphere than solar EUV, suggesting it has a smaller impact on the thermal structure of Titan's neutral atmosphere. However, our results indicate that thermal O^+ precipitation can have a significant impact on Titan's ionosphere.

1. Introduction

Cassini has discovered that most of the O^+ and other water group ions (e.g. H_2O^+, OH^+) in Saturn's magnetosphere originate from the plumes of Enceladus. Once ionized, these particles are confined to a region near Saturn's magnetic equator known as the plasma sheet. Eventually, the water group ions are transported to Saturn's outer magnetosphere where Titan orbits. Near Titan, Saturn's plasma sheet is only a few Saturn radii thick and the tilt of Saturn's magnetic axis causes the plasma sheet to be morphed into a bowl shape by the pressure of the solar wind. Therefore, depending on the season, the average position of the plasma sheet is above or below Titan's orbital plane. However, the plasma sheet does not stay in its average position, rather it is highly dynamic and is observed oscillate with a period similar to Saturn's rotational period (around 10.7 h). The motion of the plasma sheet causes it to periodically move past Titan, exposing Titan's atmosphere to the water group ions that are confined there (Arridge et al., 2008). Hörst et al. (2008) showed that the oxygen containing ions that originated from Enceladus's interior have a significant and lasting impact on the chemistry and composition of Titan's atmosphere. Despite this, there are relatively few studies that quantify how thermal O^+ precipitation affects Titan's thermosphere and ionosphere.

We have developed a three-dimensional ion precipitation model to quantify the flux of magnetospheric thermal (1 eV to 10 keV) O^+ into Titan's atmosphere. We use this model to investigate how precipitating oxygen affects Titan's thermosphere and ionosphere by calculating global ionization and energy deposition rates. In particular, we examine the O^+ precipitation during Cassini's T57 flyby. Titan was observed to be in Saturn's plasma sheet both before and after T57 (Rymer et al., 2009; Nemeth et al., 2011); therefore, Titan's atmosphere should have been exposed to thermal O^+ precipitation while Cassini was making in situ measurements. Also, during T57, Cassini's Radio Science Investigation (RSS) and Langmuir Probe observed abnormally high electron densities in Titan's ionosphere near 1200 km altitude suggesting enhanced ionization from thermal ions or electrons from Saturn's magnetosphere (Kliore et al., 2011; Richard et al., 2015).

The flux of oxygen through Titan's exobase calculated here is in agreement with other recent simulations of O^+ precipitation at Titan (e.g. Sillanpaa and Johnson, 2015); however, our model is unique in that we also calculate how this flux affects Titan's atmosphere. We find that, in limited regions, ionization rates from magnetospheric O^+ in the thermal energy range are high enough to explain ionospheric density enhancements on the order of

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https://doi.org/10.1016/j.icarus.2018.01.014
0019-1035/

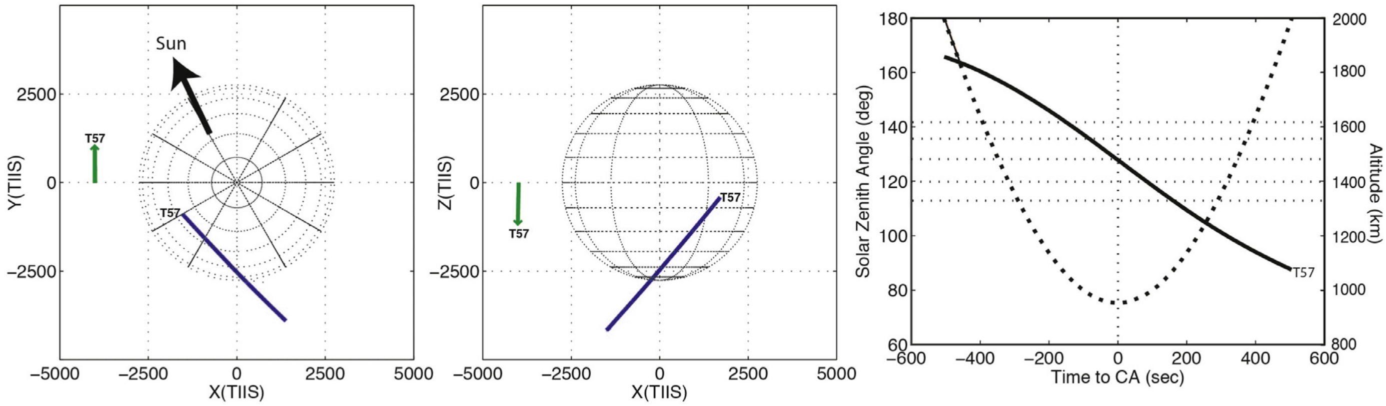

Fig. 1. The trajectory during Cassini's T57 flyby as seen from above the equatorial plane and looking toward Saturn. Cassini's altitude (dashed) and solar zenith angle (solid) versus altitude. Results are displayed in the TIIS coordinate system with the *x*-axis pointing in the nominal magnetospheric flow direction, the *y*-axis pointing toward Saturn, and the *z*-axis completing the right handed system. The arrow labeled T57 shows the average upstream magnetic field direction.

1000 cm^{-3}. The precipitation of O^+ into Titan's atmosphere occurs over a limited region of Titan's ionosphere. For a magnetic field configuration similar to the T57 flyby, we find that the region of enhanced ionization is close to but does not overlap with the area where RSS observed enhanced densities in Titan's ionosphere. However, high ionization rates do overlap with the area that Cassini's Langmuir Probe measured enhanced densities. Our results suggest that both thermal O^+ precipitation and thermal magnetospheric electron precipitation can be important ionization sources in Titan's atmosphere above 1000 km. We find that the energy deposited by thermal O^+ is similar to the energy deposited by other magnetospheric particles, but less than the energy deposited by solar EUV.

2. Cassini's T57 flyby

Cassini's T57 flyby took place at 18:32 UT on 2009 June 22. Fig. 1 shows the trajectory of the flyby and the solar zenith angles traversed in Titan's atmosphere. Cassini entered Titan's atmosphere on the anti-Saturn/night side, downstream of the corotational magnetospheric ram direction. Cassini then traveled toward the ram direction and exited on the day side of Titan's ionosphere. During T57, Titan was on the night side of Saturn's magnetosphere at 22 h Saturn local time.

The average ambient magnetic field was [2.27, 4.77, −1.05] nT and the B_y component of the magnetic field indicates that Titan was below Saturn's magnetic equator (Simon et al., 2010). Moments derived from Cassini Plasma Spectrometer (CAPS) data show that the upstream density, temperature, and velocity was variable for several hours before T57 (see Fig. 2). Rymer et al. (2009) and Nemeth et al. (2011) have classified this flyby as a mix of bi-modal and plasma sheet types. A bi-modal classification means that the oxygen ions have a higher density and are colder than what is typically observed in the plasma sheet and is most likely correlated with Titan passing through Saturn's current sheet. Finally, as previously discussed, occultation data has been used to calculate the electron density during this flyby and Kliore et al. (2011) showed that it was abnormally high compared to previously observed densities on the solar limb. The peak electron density measured by the Langmuir Probe was also high for Titan's nightside ionosphere at 1380 cm^{-3} (Snowden and Yelle, 2014b; Richard et al., 2015; Agren et al., 2009). Both observation suggest significant ionization from magnetospheric particles.

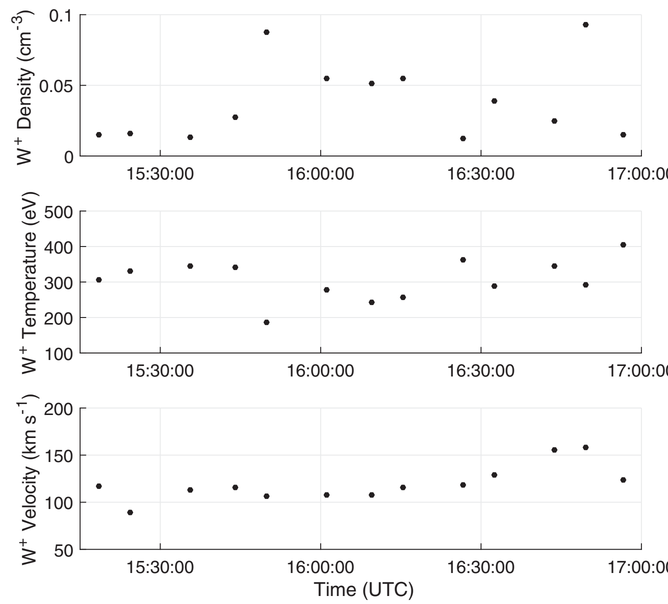

Fig. 2. Ion moments derived from CAPS/IMS (ion mass spectrometer) data taken before closest approach during the T57 flyby (Young et al., 2004). The top panel shows W^+ ion density, which is an ion group that includes the density of H_2O^+, OH^+, and O^+. The center panel shows W^+ group temperature and the bottom panel shows W^+ bulk velocity.

3. Model

3.1. 3D model of Titan's plasma interaction

Titan does not have an intrinsic magnetic field and the plasma and electromagnetic fields that make up Saturn's magnetosphere interact directly with Titan's atmosphere. In Saturn's outer magnetosphere, where Titan orbits, the plasma densities vary between about 0.01 and 0.1 cm^{-3} depending on the relative location of Saturn's plasma sheet. The bulk magnetospheric plasma velocity is about 100 km/s and the direction can vary significantly from corotation (Thomsen et al., 2010). The magnetic field near Titan has a strength of about 5 nT and the convective electric field, which nominally points away from Saturn, has a strength of about 0.3 mV/m (Arridge et al., 2011a; Arridge et al., 2011b). The slowing of the magnetospheric plasma causes a pile-up and enhancement of the magnetic field upstream of Titan. The perturbation of the magnetic and electric field near Titan's atmosphere affects the cy-