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The distribution of Titan's high-altitude (out to ~50,000 km) exosphere from energetic neutral atom (ENA) measurements by Cassini/INCA

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ABSTRACT

We report observations of Titan's high-altitude exosphere detected out to about 50,000 km altitude. The observations were made by the Ion Neutral Camera (INCA) on board the Cassini spacecraft. INCA detects energetic neutral atoms (ENA) that are formed when the ambient magnetospheric ions charge exchange with Titan's neutral atmosphere and exosphere. We find that Titan's exospheric H_2 distribution follows closely a full Chamberlain distribution including ballistic, escaping and satellite distributions. As expected, neutral densities are dominated by a satellite distribution above about 10,000 km. The maximum detectable extent of the exosphere (~50,000 km) coincides with the radius of the Hill sphere of gravitational influence from Saturn. While we find no direct indications of a neutral Titan torus with densities greater than about 1000 cm^{-3}, we observe interesting asymmetries in the distribution that warrants further investigation. Based on these findings we compute the average precipitating ENA flux to be about 5×10^6 keV/(cm^2 s), or 8×10^{-3} erg/(cm^2 s), which is directly comparable to that of precipitating energetic ions (Sittler, et al., 2009) and slightly higher than that of solar EUV (Tobiska, 2004). Thus, the energy deposited by precipitating ENAs must also be taken into consideration when studying the energy balance of Titan's thermosphere.

1. Introduction

Titan has a remarkably large atmosphere, only comparable to that of Venus that may be attributed to its location at the edge of Saturn's outer magnetosphere, where the energetic particle and plasma densities causing atmospheric escape are lower than in the case of, for example Io (Johnson, 2004). Understanding the sources and losses of Titan's atmosphere is therefore important for understanding not only the evolution and fate of Titan's own atmosphere, but also for other weakly magnetized bodies of the solar system. For example, the loss of Titan's exospheric H_2 distribution can be used to put constraints on the CH_4 destruction rate in the atmosphere (Yelle et al., 2006). The loss of exospheric H_2 has been attributed to non-thermal processes such as charge-exchange, sputtering or ion pick-up. The first mechanism relies on hot topside ionosphere below the exobase where relatively energetic ions charge exchange with the atmosphere, creating an energetic neutral that can escape. In the case of sputtering, magnetospheric particles precipitate and collide with the atoms and molecules below the exobase, providing the neutrals with escape energies. However, ion pick-up loss relies on the ionized exospheric molecules being picked up by Saturn's magnetic field.

In this paper we present new observations that show that Titan's H_2 exosphere extends out to, at least the altitude of the gravitational Hill sphere (~50,000 km). We use ENA images obtained by the Cassini/INCA camera to retrieve the profile and extent of Titan's H_2 exosphere. ENA imaging is currently the only tool to explore neutral gas densities as such altitudes. For example, the Ion Neutral Mass Spectrometer (INMS) on board Cassini can derive the density for most species below about 2000 km and for H_2, up to 7000 km (Cui et al., 2008).

Amsif et al. (1997) predicted that Titan's H_2 exosphere should be visible out to about five Titan radii (R_T) and that the distribution would follow approximately a $1/r^2$ distribution, which they used as a computationally convenient approximation to a Chamberlain satellite distribution. Cui et al. (2008) demonstrated that INMS measurements followed a Chamberlain distribution with ballistic and escaping components out to about 6000 km altitude. Here, we demonstrate that Titan's H_2 exosphere follows closely a Chamberlain profile including ballistic, escaping and

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satellite components, at least out to the gravitational Hill sphere (~50,000 km altitude).

2. Observations

The Ion Neutral Camera (INCA), belonging to the MIMI experiment on board Cassini obtains ENA images in the ~7–220 keV energy range for hydrogen and ~50–300 keV for oxygen. ENAs are produced when singly charged magnetospheric ions charge exchange with neutral gas atoms or molecules, such as the H_2 exosphere of Titan (see Eq. (1)). The less dense neutral water products spread throughout Saturn's magnetosphere enable images of the global ion distributions (the "ring current") of the entire magnetosphere (Brandt, et al., 2008; Krimigis, et al., 2005; Mitchell, et al., 2009). However, ENA images are very sensitive to relatively low neutral gas densities that cannot be measured in-situ. For example, the ENA images of the Saturnian magnetosphere can indirectly see the effects of the neutral H extending out beyond $20R_S$, and as in this study, it turns out that ENA images are also sensitive to the neutral exosphere distribution profile of Titan, at least out to its outer extent at the gravitational Hill sphere and possibly much further.

The INCA camera is a relatively large geometry factor (~0.6 cm^2 sr) time-of-flight (TOF) detector with a wide Field of View (FOV) of 90° × 120° and an angular resolution of ~3° for hydrogen. Detailed descriptions of all MIMI instruments can be found at Krimigis et al., (2004).

During the time period from the SOI (1 July 2004, DOY 183/2004) to 2007, when the Cassini spacecraft surveyed the magnetosphere of Saturn, it frequently encountered Titan, thus giving the opportunity to the INCA imager on Cassini to obtain images of the Moon's atmosphere from a relatively close distance. In the present study we analyze 36-min accumulation time hydrogen images at the energy range 24–55 keV, in cases where the spacecraft was moving outbound and the INCA imager was directly looking at Titan, thus detecting ENA fluxes of purely atmospheric origin.

In general, the INCA images are dominated by ENA emissions from magnetospheric ions interacting with the neutral water products ultimately originating from Enceladus (Hansen et al., 2006; Porco et al., 2006). Thus, the outbound passes, which were analyzed in this study, were chosen primarily in order to avoid having Saturn's magnetosphere in the background within INCA's FOV, along with Titan's atmosphere (Fig. 1 right panel). Since this study is concerned with the spatial distribution of the exosphere it is important that we use cases where the ambient magnetospheric ion distribution can be assumed spatially homogeneous. This was ensured by selecting ENA images that displayed no clear temporal variations and no obvious spatial gradients in the magnetospheric flow direction. Such gradients are present when a localized ion distribution drifts across Titan.

The ion intensities around Titan (located at $\sim 20.3R_S$ from Saturn) are relatively low (Dialynas et al., 2009; Garnier et al., 2007) (compared to the ion intensities in the inner magnetospheric regions) and this is reflected in the ENA intensities that are created in this region, i.e. peak ENA intensities are usually $< 100/(\mathrm{cm}^2\ \mathrm{sr\ s})$. For that reason we have extended the integration time up to 36-min accumulation time for the H images that will be analyzed, in order to achieve sufficient statistics for the INCA imager. Furthermore, we have not applied a background correction to the obtained images since the low ENA intensities do not point towards a specific background source.

The integration time of 36 min has been determined by maximizing statistics while minimizing the smear due to the motion of the spacecraft relative to Titan. The smear is minimized to less than 2° for all cases examined in this study, i.e. less than a pixel width. In addition, cases when the spacecraft was rotating, or in general when INCA's FOV changed orientation quickly, were removed from the analysis.

Fig. 1 (left panel) illustrates a selected 36-minute accumulation time hydrogen image during DOY 120/2006, at an orbit that fulfills the aforementioned requirements. Titan is approximately at the center of the image and the Cassini spacecraft is located at $X\sim -19.3R_S$, $Y\sim -4.7R_S$, $Z\sim 0.1R_S$ ($\sim 22.6R_T$ from Titan, $1R_T = 2575$ km), during the observation, at the SZS frame, in which the X axis points roughly towards the Sun, the Z axis is parallel to Saturn rotational axis and Y axis completes the right hand system ($1R_S = 60{,}268$ km). As apparent from this image, the ENA emissions around Titan extend out to several Titan radii. Several observations and studies have already shown that the exospheric neutral number density of Titan is dominated by H_2 above about 3000 km (Yelle et al., 2006). Therefore, the hydrogen ENA emissions are produced by charge exchange between ambient magnetospheric protons and only the H_2 molecules above about 3000 km.

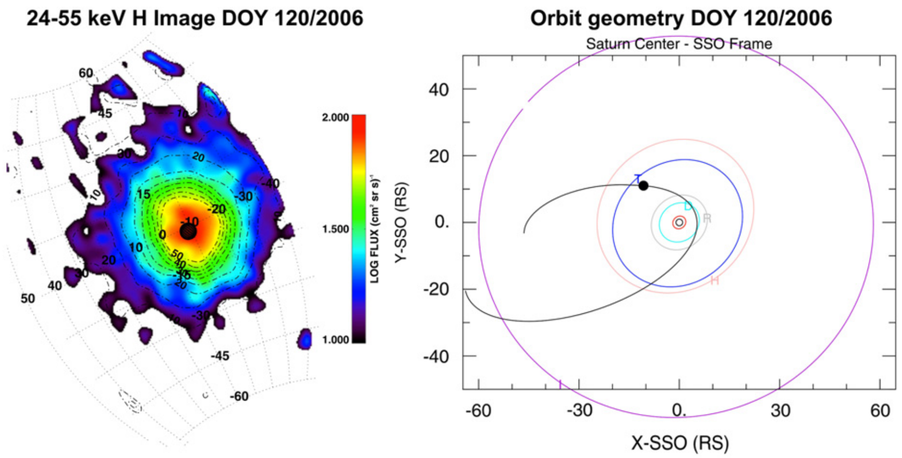

Fig. 1. Left panel shows color coded 24–55 keV Hydrogen integrated intensities obtained by the INCA imager on board Cassini during a close encounter at DOY 120/2006. Labeled contours denote ENA intensities. Charge exchange process between Titan's neutral species and fast magnetospheric ions lead to the apparent intense ENA emissions around the Moon. Right panel describes the orbit geometry during the Titan flyby on DOY 120/2006, where the image on the left panel was obtained. Cassini is located at the post-dusk region at the equatorial plane, at an outbound orbit (black solid line) towards the magnetotail. Titan is located at $\sim 20.3R_S$ at an orbit around Saturn (blue solid line) and the image data where obtained at a distance of $22.6R_T$ from Titan ($1R_T = 2575$ km). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)