Titan’s nitrogen-rich atmosphere is directly bombarded by energetic ions, due to its lack of a significant intrinsic magnetic field. Singly charged energetic ions from Saturn’s magnetosphere undergo charge-exchange collisions with neutral atoms in Titan’s upper atmosphere, or exosphere, being transformed into energetic neutral atoms (ENAs). The ion and neutral camera, one of the three sensors that comprise the magnetosphere imaging instrument (MIMI) on the Cassini/Huygens mission to Saturn and Titan, images these ENAs like photons, and measures their fluxes and energies. These remote-sensing measurements, combined with the in situ measurements performed in the upper thermosphere and in the exosphere by the ion and neutral mass spectrometer instrument, provide a powerful diagnostic of Titan’s exosphere and its interaction with the Kronian magnetosphere. These observations are analysed and some of the exospheric features they reveal are modelled.

Keywords: Titan; exosphere; Saturn; magnetosphere

1. Introduction

The exosphere (or corona) is the uppermost part of an atmosphere, where collisions between particles are negligible (Chamberlain 1963). Particle trajectories are governed mainly by the gravitational field, and they can be ballistic, outgoing hyperbolic (escaping), incoming hyperbolic, satellite orbits or particles transiting through the exosphere (figure 1). The exosphere is thus the region from where atmospheric particles can eventually escape into space.
Titan is the second largest planetary satellite in the Solar System (radius of 2575 km), and is the only satellite that has an atmosphere as substantial as that of the Earth. Its orbit places it, most of the time, within Saturn’s magnetosphere. The absence of an intrinsic magnetic field gives the Kronian magnetospheric plasma direct access to the upper Titan atmosphere, where a variety of complex phenomena take place (Neubauer et al. 1984, 2006; Brecht et al. 2000; Nagy et al. 2001; Blanc et al. 2002; Kallio et al. 2004; Sittler et al. 2005; Modolo & Chanteur 2008). Energetic ions in the magnetosphere occasionally will undergo a charge-exchange collision with cold neutral atoms from the upper Titan atmosphere, giving rise to the production of energetic neutral atoms (ENAs). The energy of the incident ions is almost entirely transferred to the charge exchange produced ENAs that then propagate along nearly rectilinear ballistic trajectories. The straight-line paths of the energetic neutral atoms allow construction of an image of the ENA emitting exosphere (Williams et al. 1992). The coexistence of energetic ions and cold tenuous gas in the Saturn/Titan system thus makes this system particularly suitable for magnetospheric imaging via ENA detection (Amsif et al. 1997).

The Cassini mission, since the Saturn Orbit Insertion in July 2004, provides a wealth of information on the environment of Saturn and its satellites. Titan is one of the main objectives, with more than forty flybys of it scheduled during the nominal mission.

2. ENA production parameters

ENAs are atoms with energies of approximately 10 keV to a few MeV, that are produced when singly charged energetic ions undergo charge-exchange collisions with the cold atoms that constitute the exosphere (Roelof 1987). During such a collision an energetic ion $X^+$ is neutralized by acquiring an electron from an exospheric neutral atom $Y$, producing thus an ENA. The charge-exchange reaction is

$$X^+ + Y \rightarrow X_{\text{ENA}} + Y^+.$$  (2.1)
Because only a few eV are lost in this resonant charge-exchange interaction, the energetic neutral atom (X_{ENA}) has almost the same energy and direction as the incident ion X^+. ENA production is a function of the ion energy, flux and species and of the neutral exospheric density and composition. The ENA unidirectional differential flux $F_i(E)$, measured by an ENA imager at energy $E$ and corresponding to the ion species $i$, is given by the line of sight integral

$$F_i(E) \left( \text{cm}^2 \, \text{s} \, \text{sr} \, \text{keV} \right)^{-1} = \sum_{i,k} \sigma_{ik}(E) \int_{\ell_1}^{\ell_2} j_i(E, \ell) \cdot n_k(\ell) d\ell,$$

where $j_i(E, \ell) \left( \text{cm}^2 \, \text{s} \, \text{sr} \, \text{keV} \right)^{-1}$ is the magnetospheric ion flux for species $i$ at energy $E$ and along the direction of the line of sight to the ENA imager from point $\ell$, $n_k(\ell)$ is the density of the neutral exospheric gas for species $k$ and at $\ell$, and $\sigma_{ik}(E)$ is the energy dependent charge-exchange cross section between the magnetospheric ion species $i$ and the exospheric neutral species $k$. The line of sight integral runs from the ENA imager position to infinity, along the look direction opposite to that of the arriving ENA. In practice, however, the integration is limited between points $\ell_1$ and $\ell_2$, which bound the interaction region visible by the imager. Note that equation (2.2) is valid for the ‘optically thin’ case, where any loss of ENAs between the emission point and the camera position can be neglected.

The ENA images thus contain quantitative information on the magnetosphere–exosphere interaction processes, on a global scale. The ENA flux, measured in each pixel of an image, is the line of sight integral (along the line of sight direction of the pixel) given by equation (2.2) and contains an admixture of information on energetic ions and on cold neutral distributions.

3. Instrumentation

The magnetospheric imaging instrument (MIMI) experiment onboard Cassini (Krimigis et al. 2004) comprises three sensors: the charge energy mass spectrometer (CHEMS), the low energy magnetospheric measurement system (LEMMS) and the ion and neutral camera (INCA). CHEMS provides the energetic ion (3–220 keV q$^{-1}$) composition, LEMMS measures the fluxes of the energetic ions (more than 30 keV) and electrons (more than 15 keV) and INCA measures the fluxes of ENAs or ions (more than 7 keV), providing images with a 90°×120° field-of-view and with a good (approx. 5° for energetic hydrogen) angular resolution.

The ion and neutral mass spectrometer (INMS) experiment onboard Cassini (Waite et al. 2004) analyses the composition of the in situ neutral and low-energy ion populations, providing their densities and temperatures.

4. Ta Titan flyby and thermal exosphere modelling

On the 26 October 2004, the Cassini Saturn orbiter, on its inbound leg of its orbit, performed the first targeted flyby of Titan at the closest approach altitude of 1200 km. Titan was inside Saturn’s magnetosphere, in the pre-noon sector. Figure 2 shows a hydrogen ENA image of Titan’s exosphere, acquired by MIMI/INCA before the closest approach, at an altitude of approximately 8000 km (Mitchell et al. 2005). Several features appear in this image.
— A right–left asymmetry, with an ENA emissions shadow on the left part of the image (north is upwards). This asymmetry is a confirmation of a theoretical expectation, based on a three-dimensional kinetic modelling of the trajectories of the ENA parent ions, which when they charge exchange with the exospheric populations produce the imaged ENAs (Dandouras & Amsif 1999). These ions have gyroradii comparable with the Titan radius, and as a result Titan and its lower atmosphere produce screening effects on a portion of the trajectories of these parent ions (figure 3).

— A limb brightening effect is visible, forming a crescent and resulting from a maximum integrated optical depth for lines of sight skimming through the dense layers close to the exobase.

— A ‘hole’ in the ENA emission, below the crescent and centred on Titan, which results from the absorption of energetic ions by Titan’s dense lower atmosphere (see §6).

These observations, combined with the INMS measurements in the lower exosphere, were used to develop a first Cassini era model of Titan’s exosphere (Garnier et al. 2007). This model is based on the Chamberlain formalism (Chamberlain 1963), and assumes a Maxwellian distribution function at the exobase for each of the major exospheric species. The exospheric species included in this model are CH$_4$, N$_2$, N, H$_2$ and H, and the exobase altitude and temperature are $Z_c = 1425$ km and $T_c = 149$ K, respectively, as deduced from the analysis of the INMS measurements (Waite et al. 2005). The exobase densities used for each of these five species come from the latest version of the Toublanc
photochemical model (adapted from Toublanc et al. 1995). The resulting altitude profiles for these species are shown in figure 4. These altitude density profiles have then been used to simulate the expected ENA fluxes, using as input for the parent ion fluxes those measured by MIMI/LEMMS in Saturn’s magnetosphere, in the vicinity of Titan, and the simulation results have subsequently been checked for consistency with the ENA data acquired by MIMI/INCA.

Figure 3. Equatorial view of the energetic proton gyration in the Titan vicinity. The dashed circle represents the Titan exobase, and the shadowed area shows where the production of ENAs, having trajectories directed towards the imager, is not possible. See Dandouras & Amsif (1999) for details.

Figure 4. Chamberlain-type Titan exosphere model for the five main species (CH₄, N₂, N, H₂ and H), based on the analysis of the Ta flyby. From Garnier et al. (2007). Blue, N(4S); green, H; red, H₂; turquoise, N₂; violet, CH₄.
5. Non-thermal modelling of Titan’s exosphere

Titan’s upper atmosphere, however, is not expected to be in thermal equilibrium. Dissociative mechanisms, sputtering, chemical and photochemical sources and energy deposition from ions contribute to the presence of supra-thermal populations (Lammer & Bauer 1991, 1993; Cravens et al. 1997; Shematovich et al. 2003; Michael & Johnson 2005; De La Haye et al. 2007a; Vuitton et al. 2007; Cui et al. 2008). An analysis of the INMS data, for the Ta/Tb/T5 flybys and for altitudes below 2000 km, shows the presence of a non-thermal corona; this analysis shows also that for N\textsubscript{2} and CH\textsubscript{4} the distribution functions are best fitted by kappa distributions (De La Haye et al. 2007b). These, first introduced by Vasyliunas (1968) to describe the distribution functions of the electrons in the Earth’s magnetosphere, are a combination of a Maxwellian, at the lower energy part, and of a power law for the higher energies. Note that a kappa distribution function becomes similar to a Maxwellian when the kappa parameter value goes to infinity.

This led to the development of a non-thermal model for Titan’s exosphere altitude profiles, using kappa distribution functions at the exobase and averaged over the first five flybys (Garnier 2007). The resulting kappa parameter values, for CH\textsubscript{4}, N\textsubscript{2} and N, are of the order of 12–13. These values are high enough to imply only a small deviation from a Maxwellian distribution; they are, however, adequate to produce a strong effect at high altitudes (above approx. 4000 km), because the altitude acts as a velocity filter, so that only the high-energy tails of the distributions are selected.

This modelling allows then the calculation of the escape rates from the exosphere.

6. ENA absorption mechanisms

Titan exosphere ENA images, as the one shown in figure 2, show a lower altitude limit of ENA emissions, below the bright crescent. This limit can be caused by mechanisms preventing the parent ions from entering certain atmospheric regions, as, for example, finite parent ion gyroradii effects. But loss mechanisms also play a role, through collisions that result in a thermalization or in a change of the charge state for the particles: an ENA can be ionized and then it is no longer detectable by the ENA imager (unless again neutralized).

Several mechanisms can remove an ENA, such as charge-exchange collisions with ionospheric or magnetospheric ions, electron impact ionization, photoionization or charge-exchange collisions with exospheric neutrals. An analysis, however, shows that charge-exchange collisions with exospheric neutrals is the dominant loss mechanism for ENAs in Titan’s lower exosphere/upper thermosphere, and that all the other mechanisms are comparatively negligible (Garnier 2007; Garnier et al. 2008). The calculated limit between the optically thin (statistically less than one collision) and the optically thick regime is situated, for an approximately 30 keV ENA on a tangential path, at an altitude of approximately 1500 km, i.e. close to the exobase. Below this altitude, an ENA can undergo several successive charge-exchange collisions with exospheric neutrals, alternating from neutral to ion, and only a few (approx. 30) eV are ‘lost’ in each such
collision. Figure 5, adapted from Garnier et al. (2008), shows the final energy of an initially 30 keV ENA originating from Titan’s exosphere, when it reaches the imager which is situated well above the exobase. Between approximately 1000 and 1500 km altitude the ENA can suffer multiple collisions, but it can still emerge with adequate energy (several keV) to be detected by an imager situated at higher altitudes. Below approximately 1000 km, however, the collision frequency increases drastically and the accumulative loss of energy is such that the ENA can be considered as absorbed. It is at these altitudes also, i.e. below approximately 1000 km, that energetic protons and oxygen ions from Saturn’s magnetosphere that precipitate into Titan’s atmosphere deposit their energy, ionize and drive ionospheric chemistry (Cravens et al. 2008).

7. Titan’s extended exosphere

The ENA emissions due to the Titan’s exosphere can be used to infer exospheric distributions up to 40 000 km altitude. The Titan exosphere is indeed very extended: the Hill sphere radius for Titan, which gives the limit of its gravitational influence and thus an estimate for the possible external limit of its exosphere, is approximately 50 000 km.

Figure 6 shows a hydrogen ENA image of Titan’s extended exosphere obtained by MIMI/INCA during the Tb flyby (13 December 2004). This image not only clearly illustrates the extent of the exosphere, but also it allows one to fit its density profile: as shown by Brandt et al. (2005), the observed ENA emissions are best reproduced when a homogeneous energetic H\(^+\) flux around Titan and a 1/r\(^2\) law for a molecular hydrogen exosphere (the main exospheric constituent at
these high altitudes) are assumed. Such a $1/r^2$ law characterizes either an escaping population or a satellite population, whereas a ballistic population would follow a $1/r^{5/2}$ law.

We note that in a purely collisionless exosphere a satellite population would not exist, since this population results from particles with trajectories initially connected to the exobase (mostly particles on ballistic trajectories), that due to various collision mechanisms have their trajectories modified and thus become a satellite population. An important question is then to know whether or not the balance between sources and loss mechanisms can establish a significant satellite population. As Garnier (2007) has shown, such satellite particles would indeed dominate the ballistic (and escaping) populations above approximately 8000 km altitude, where the partition function of the satellite population takes over that of the other two populations.

The analysis of the INCA energetic neutral atom images of the Titan extended exosphere by Brandt et al. (2005) showed also that this asymptotic satellite distribution is observed in the absence of relatively intense magnetospheric ion fluxes. For more active magnetospheric conditions, however, these exospheric particle populations can be depleted in the presence of intense energetic ion fluxes, through charge exchange reactions.

8. Conclusions

The Cassini mission is acquiring a wealth of information on Titan, its upper atmosphere and its interaction with Saturn’s magnetosphere. The INCA sensor of the MIMI experiment, which images and measures the fluxes of the energetic neutral atoms produced by this interaction, combined with the in situ
measurements performed in the upper thermosphere and in the exosphere by the INMS instrument, provide a powerful diagnostic of Titan’s exosphere. Analysis of these data allows one to calculate the altitude profiles of the major exospheric species and reveals the non-thermal character of their distributions. The energetic neutral atoms produced by the interaction of Titan’s exosphere with Saturn’s magnetosphere get almost completely absorbed below approximately 1000 km, where also the energetic ions from Saturn’s magnetosphere deposit their energy, ionize and drive ionospheric chemistry. On the other side, the MIMI/INCA data show an extended exosphere, which can be detected up to a 40 000 km altitude above Titan.

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