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Aerosols: The key to understanding Titan's lower ionosphere

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A B S T R A C T

The Permittivity Wave and Altimetry system on board the Huygens probe observed an ionospheric hidden layer at a much lower altitude than the main ionosphere during its descent through the atmosphere of Titan, the largest satellite of Saturn. Previous studies predicted a similar ionospheric layer. However, neither previous nor post-Huygens theoretical models have been able to reproduce the measurements of the electrical conductivity and charge densities reported by the Mutual Impedance (MI) and Relaxation Probe (RP) sensors. The measurements were made from an altitude of 140 km down to the ground and show a maximum of charge densities of $\approx 2\times10^9$ m^{-3} positive ions and $\approx 450\times10^6$ m^{-3} electrons at approximately 65 km. Such a large difference between positive and negative charge densities has not yet been understood. Here, by making use of electron and ion capture processes in to aerosols, we are able to model both electron and positive ion number densities and to reconcile experimental data and model results.

1. Introduction

The atmosphere and surface of Titan, the largest moon of Saturn, was explored by the ESA Huygens Probe in 2005 (Lebreton et al., 2005). During the three hours of descent and surface operations, the probe measured for the very first time the physical properties of its deeper atmosphere and hidden surface. The Permittivity Wave and Altimetry (PWA) subsystem, part of the Huygens Atmospheric Structure Instrument (HASI), determined the atmospheric electrical conductivity by making use of two independent sensors: the Mutual Impedance (MI) and Relaxation Probe (RP) and discovered an ionized layer at approximately 65 km of altitude (Fulchignoni et al., 2005; Grard et al., 2006).

This low ionospheric layer is thought to be produced by cosmic radiation (Capone et al., 1976; Molina-Cuberos et al., 1999b), which is the most penetrating kind of radiation and the only one able to ionize the lower portion of the atmosphere. Cosmic rays ionize the neutral constituents of the atmosphere, producing positive ions and electrons. The PWA data shows that, for example, at the peak of electron density, the concentration of positive ions is approximately four times higher than that of electrons, and the ratio increases with altitude, reaching a factor of approximately 1000 at the top of the sounding range, 140 km (Hamelin et al., 2007; López-Moreno et al., 2008; Molina-Cuberos et al., 2010). In order to explain dissimilar concentrations of electrons and positive ions reported by the PWA sensors in the lower ionosphere, either electrophilic molecular species, embryos or aerosol particles able to attain negative charge must be considered (Borucki et al., 2006, Borucki and Whitten, 2008; Whitten et al., 2007; Mishra et al., 2014).

The existence of an upper ionospheric layer was known since the Voyager 1 flyby (Bird et al., 1997). This layer extends up to approximagely 2200 km in altitude (Galand et al., 2014) and it is produced by ultraviolet radiation from the Sun on the dayside (Cravens et al., 2005) and energetic particle on the nightside (Cravens et al., 2009). Electrons trapped in the Saturnian magnetosphere can also contribute to the ionization depending on the Saturnian magnetosphere and the Saturn Local time of Titan (Edberg et al., 2015). The dayside electron number densities deduced from the Radio Plasma Wave Science/Langmuir Probe (RPWS/LP) measurements peak at values of $\sim 2000-5000$ cm^{-3} in the altitude range from 1000 to 1200 km (Vigren et al., 2015), being a factor of ~ 2 lower than the values derived in the Cassini multi-instrumental study by Vigren et al. (2013).

Titan is the satellite with the densest atmosphere in the Solar System and has the only nitrogen-rich atmosphere aside from Earth's. Its atmosphere is mainly composed of nitrogen (97%) and methane (2.7 ± 1%), and lodges trace amounts of a high variety of hydrocarbons such us ethane, diacetylene, methylacetylene, acetylene, and cyanoacetylene (Niemann et al., 2005; Coustenis and Taylor, 2008). The atmosphere is

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characterized by distributed hazes of aerosol layers and the known Titan orange haze at altitudes of around 500 km (Israël et al., 2005; Coates et al., 2009; Lavvas et al., 2013). Solar radiation and energetic particles coming from the Saturnian magnetosphere dissociate N_2 and CH_4, the major atmospheric constituents, into radicals and ions, which trigger a complex organic chemistry (Cravens et al., 2006; Magee et al., 2009; Mandt et al., 2012) and subsequently leads to the formation of aerosol particles (Niemann et al., 2005; Coates et al., 2009; Lavvas et al., 2013). Those particles can then become charged positively or negatively. At higher altitudes, just below the main ionospheric peak above 950 km, negative and positive molecular ions and predominantly negative charged nm-sized grains have been detected (Coates et al., 2007; Waite et al., 2007; Shebanits et al., 2013, 2016). Several articles have shown the significant role of physical aggregation and ion-neutral chemistry in the production of aerosols (Sittler et al., 2009; Lindgren et al., 2017; Lavvas et al., 2013). It is now widely admitted that studying the ionosphere of Titan at all altitudes cannot be done without considering aerosols.

The models developed before the Huygens arrival predicted that the electron and ion abundances can be affected by attachment to aerosols, during both nighttime and daytime (Borucki et al., 1987, 2006). The post-Huygens models also included other species to decrease the concentration of electrons and to reproduce the observations. Whitten et al. (2007) developed a time-dependent model of the nightside ionosphere and found that the electrical charging of aerosol particles is negative and the formation of negative ions is of major importance at night. The presence of a very small abundance (in the range between 10^{-13} and 10^{-11} mol fraction) of electrophilic neutral species in which electrons can be attached by the three-body process and produce negative ions, can reduce appreciably the concentration of electrons below 40 km (Molina-Cuberos et al., 2000).

Borucki and Whitten (2008) modeled the size and abundance distribution of aerosols by assuming a constant mass flux with altitude and using the reported optical depth at the lower ionosphere by Tomasko et al. (2005) as a constraint. Then, the obtained profiles were used to calculate the electron and ion densities and conductivities for varios solar UV photoelectron emission thresholds, because the Huygens' descent took place during daytime conditions, with a solar zenith angle of around 40°. The comparison with PWA observations indicated that photoemission of electrons cannot be an important source of ionization (Borucki and Whitten, 2008) Therefore, the structure of the lower ionosphere does not depend on the solar local time. In order to find agreement with observation, they also find that both an additional population of aerosol embryos above 50 km and a very low mole fraction of electrophilic molecules at lower altitudes are needed. Embryos are very small particles ($\approx 7\times10^{-4}$ μm) that, at the atmospheric conditions of Titan, can be fullerenes and polycyclic aromatic hydrocarbons (Sittler et al., 2009).

Mishra et al. (2014) solved the state equations for ions and electrons in the presence of aerosols and embryos, allowing both particles to be positively and negatively charged. In order to agree with the observations obtained by the MI sensor (Hamelin et al., 2007), both the concentration of embryos and the photoemission thresholds of aerosols/embryos were adjusted at each altitude. In contrast with Borucki and Whitten (2008), the presence of aerosols increases the conductivity due to electrons and their predictions at 140 km differ approximately by four orders of magnitude with conductivity data retrieved from the RP sensor (López-Moreno et al., 2008; Molina-Cuberos et al., 2010).

In the present work, we take a step forward towards understanding the physical process related with the charge distribution in Titan's atmosphere below 140 km. Cardnell et al. (2016) recently revealed the fundamental role that aerosols play in the photochemistry of the low ionosphere of Mars. Here we follow a similar approach and find that the size and density distribution of aerosols affects the concentration of both positive and negative charge carriers. By making use of electron and ion capture processes onto aerosols and aerosol profiles from Huygens measurements (Tomasko et al., 2008; Lavvas et al., 2010), we are able to reconcile experimental data and model results. We also find that, unlike previous works, no additional population of small embryo particles nor electrophilic neutrals are needed in order to attain a reasonable agreement with the PWA observations.

2. Model

The lower ionosphere of Titan is modeled by considering the balance equations for one kind of cations, electrons and aerosols. A similar treatment was used by Cardnell et al. (2016) in the lower Martian ionosphere. Here we make use of the same processes and formulation with the only difference being neglecting electron photodetachment processes (Borucki and Whitten, 2008) due to the large distance to the Sun and the strong absorption of Titan's dense atmosphere (Lara et al., 1996). The photoemision of aerosols was taken into account by Mishra et al. (2014) and they found that, in contrast with Borucki and Whitten (2008), the production of electrons by the photoemission of aerosols is an important process, particularly above 80 km. However, the inclusion of this process increases the concentration of electrons and the obtained results disagree with the observations above 80 km.

Transport phenomena can be neglected in the lower atmosphere because the transport time is several orders of magnitude larger than the chemical lifetime (Molina-Cuberos et al., 1999a). Ions and electrons are produced by cosmic rays and lost by ion-electron recombination and by attachment to aerosols. Assuming steady-state conditions, the continuity equations for positive ions, electrons and aerosols can be written as (Banks and Kockarts, 1973):

$$q - \alpha n^+ n^e - \sum_{i=-i_{max}}^{i_{max}-1} \beta_+^i n^+ N^i = 0 \tag{1}$$

$$q - \alpha n^+ n^e - \sum_{i=-i_{max}+1}^{i_{max}} \beta_e^i n^e N^i = 0 \tag{2}$$

$$\beta_+^{i-1} n^+ N^{i-1} + \beta_e^{i+1} n^e N^{i+1} - \beta_+^i n^+ N^{i-1} - \beta_e^i n^e N^i = 0 \tag{3}$$

where n^+ and n^e are the cation and electron number densities, respectively, N^i is the number density of aerosols with i elementary charges, q is the production rate of cations and electrons due to cosmic rays, α the ion-electron recombination coefficient, β_+^i and β_e^i are the attachment coefficients of cations and electrons, respectively, to aerosols with i elementary charges, and $\pm i_{max}$ is the maximum number of elementary charges in an aerosol.

We make use of the atmospheric model reported by Coustenis and Taylor (2008) and an adapted cosmic rays spectra for Saturn's orbit and moderate solar activity (Molina-Cuberos et al., 1999b) in order to calculate the ionization rate by cosmic rays. Solar wind interacts with the cosmic particles in the interplanetary medium and its variations related to the solar activity produce changes in the spectrum of cosmic rays. However, due to the long distance to the Sun and the strong absorption of the atmosphere, the effects of the solar conditions on the ionization rate below $\approx$ 150 km are quite low (Molina-Cuberos et al., 1999b), and, therefore, the results of our model do not depend on the solar activity. The high amount of hydrocarbons and the low temperatures of the atmosphere favour the production of cluster ions (Capone et al., 1976; Borucki et al., 1987; Molina-Cuberos et al., 1999a), which are composed of the electrostatic aggregation of one or several neutral molecules into an ion and recombine with electrons more quickly than the covalently bonded cations. The ion-electron dissociative recombination rates for the most abundant ions are on the form $\alpha_{300}\times(T_e/300)^\gamma$, with α_{300} being the rate coefficient at $T_e = 300$ K and with $(T_e/300)^\gamma$ describing the electron temperature dependence of the reaction (Vigren et al., 2013). At the lower atmosphere of Titan, the electron temperature is equal to the atmospheric temperature, T. Experimental values for α_{300} and γ range from