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Note

Revisited modeling of Titan's middle atmosphere electrical conductivity

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ABSTRACT

The atmospheric electrical conductivity measured by the Permittivity, Wave and Altimetry (PWA) subsystem on board the Huygens probe, during the landing mission on Titan, has been modeled in the present work. Previous modeling studies showed a Galactic Cosmic Ray (GCR) peak of conductivity at a higher altitude and a quantitative overestimation in the altitude range 0–100 km compared to that observed by the PWA instrument. Recently the PWA data was revisited and provided new constraints on the conductivity at altitudes 100–180 km. Because the aerosols in the atmosphere are known to alter the electron concentration, using a detailed distribution of the aerosols at all altitudes, the electron conductivity has been calculated in the altitude range 0–180 km. By using a variable range of photoemission threshold for the aerosols, the present model is able to reasonably predict the altitude at which the GCR peak of conductivity occurs and to meet the new constraints for the conductivity profile.

1. Introduction

The electron conductivity results from the presence of free electrons in planetary atmospheres. At night time, the attachment of electrons to the aerosol substantially reduces the electron abundance and thus the conductivity. However during daytime solar ultraviolet radiation impinging on the aerosol particles causes emission of electrons, leaving the particles with positive charge and greatly increasing the electron conductivity. Through photoemission from embryos and negative ions as well as ionization of molecules by Galactic Cosmic Rays (GCR), there is further addition to the free electron concentration in the atmosphere along with the formation of positive ions (Borucki et al., 2006). An interaction between all of these charge carrying species, as well as neutral aerosols, occurs in the atmosphere. These interactions involve loss of electrons by recombination with positive ions, attachment with neutral as well as charged aerosols, formation of negative ions by attachment of electron to neutral embryos and attachment with positively charged embryos. Further interactions amongst positive ions, negative ions and aerosols are also an integral part of the aerosol charging process occurring in the atmosphere. These interactions are important to the prediction of electron densities as well as inhibition of coagulation of aerosols. Inhibition in coagulation of aerosols is important as these favors the presence of larger concentrations of smaller particles, and thus affect the vertical deposition of solar flux. This in turn affects the rate of photoemission of electrons in the atmosphere.

Fulchignoni et al. (2005) and Hamelin et al. (2007) reported the electrical measurements made using the PWA subsystem, which is a component of the Huygens Atmospheric Structure Instrument (HASI) during the Huygens probe landing at Titan. PWA detected an ionized layer in the altitude region of 50–80 km, attributed mainly to GCRs, with a maximum conductivity at around 60–65 km, although the previous models (Molina-Cuberos et al., 1999; Borucki et al., 1987, 2006) predicted instead a peak at higher altitude, at around 90–100 km. The altitude profile of conductivity and electron concentration were also observed from 100 km down to the surface by the PWA instrumentation (Hamelin et al., 2007), but the measurements were not in agreement with the existing models. These disagreements could be caused by a wrong estimate of the electron attachment to different kinds of aerosol layers. Borucki and Whitten (2008) estimated the conductivity in the altitude range 0–150 km keeping constraints of abundance and size of the aerosols deduced from the Huygens probe measurements. Tomasko et al. (2005) reported that the size and the concentration of aerosols may be independent of altitude, which is an unexpected explanation. Borucki and Whitten (2008) obtained the size and abundance distribution by assuming constant mass flux with altitude and measured optical depth as a constraint. However, the conductivity profile calculated by Borucki and Whitten (2008) was not in agreement with PWA data, except for altitudes 50–55 km.

In this paper a model has been developed based on previous works by Michael et al. (2007, 2008, 2009). The conductivity in our current model has been computed for the altitude range of 0–180 km and has been compared to the values observed below 100 km and also fitted to the constraints applied to higher altitudes regions determined by Béghin et al. (2012) and Béghin (2014). Although previous models have not been able to simulate these profiles, we have been able to make significant progress in this direction by adjusting certain parameters, especially the photoemission threshold (Borucki and Whitten, 2008) with some assumptions.

2. General description of the model

In this model, the atmospheric electron conductivity and the electrical charges of the aerosols in the altitude range from 0 to 180 km are estimated from steady-state calculations, based on first, the ionization due to the absorption of high-energy particles by atmospheric gases, and second, the solar UV radiation on the aerosols, followed by the recombination of ions and electrons. The required inputs to the model are the vertical profile of temperature, pressure, ion pair production rate and aerosol size distribution, as well as number density concentration. Temperature and pressure profiles were obtained from the HASI data file, whereas the aerosol size distribution was provided by Lavvas through personal communication (the details about the model is provided in Lavvas et al. (2008)). The ion pair production rates have been treated in detail by Gronoff et al. (2009). Solar fluxes used for the calculation of the photoionization of aerosols were scaled for Titan using the data provided by Huebner et al. (1992).

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2.1. Photoionization of aerosols

Apart from the electron produced from absorption of GCR by the gaseous species of the atmosphere, there is a significant contribution during day time by photoemission from the aerosols due to solar UV radiation of wavelength greater than 150 nm.

Aerosols in the atmosphere of Titan exist as aggregates of smaller particles. A detailed explanation of such aggregates is provided in Tomasko et al. (2008). In the present study we have used the Discrete Dipole Approximation (DDScat ver 7.3) to compute the extinction and scattering efficiencies. The refractive indices were taken from Tran et al. (2003). The attenuated intensity is then calculated using the 2 stream Radiative-Transfer model as follows:

$$\frac{d\varphi^{+}(z,\lambda)}{dz} + (\sigma_{ext})N(z)\varphi^{+}(z,\lambda) = N(z)\sigma_{scat}\varphi^{-}(z,\lambda) \quad (1)$$

$$\frac{d\varphi^{-}(z,\lambda)}{dz} - (\sigma_{ext})N(z)\varphi^{-}(z,\lambda) = -N(z)\sigma_{scat}\varphi^{+}(z,\lambda) \quad (2)$$

where $\varphi^{+}(z, \lambda)$ and $\varphi^{-}(z, \lambda)$ are the downward and upward solar fluxes, $N(z)$ is the number concentration of aerosols and σ_{ext} and σ_{scat} are respectively the extinction and scattering cross-sections of the aerosols. The relationships between the cross-sections and the efficiencies are described by Moosmüller et al. (2009). To account for the poly disperse nature (i.e. a distribution of aerosols is used at each altitude instead of an equivalent size at each altitude) of aerosols, following relations were used in the calculation of extinction and scattering cross sections of an ensemble of particles:

$$(\sigma_{ext})N(z) = \int_{D_{p,min}}^{D_{p,max}} \frac{\pi D_p^2}{4} Q_{ext} n(D_p) dD_p \quad (3)$$

$$(\sigma_{scat})N(z) = \int_{D_{p,min}}^{D_{p,max}} \frac{\pi D_p^2}{4} Q_{scat} n(D_p) dD_p \quad (4)$$

Here $D_{p,max}$ is the maximum size of the particle and $D_{p,min}$ the minimum; Q_{ext}, and Q_{scat} are the extinction and scattering efficiencies; $n(D_p)$ denotes the concentration of aerosols of particle size D_p. The photoelectric ejection rate from aerosols is then calculated as:

$$q_e = \int_{\lambda}^{th} W(z)\sigma_x(\lambda) d\lambda \quad (5)$$

Here $W(z)$ is the attenuated solar intensity at altitude z, σ_x is the ionization cross-section of aerosol. The integration was performed within required limits of wavelengths. The lower limit wavelength was fixed at 150 nm whereas the threshold wavelength varied, as required for calculation, from 170 nm to 207 nm.

2.2. Photoionization of embryos and negative ions

Embryos were introduced in our model for altitudes above 80 km. Embryos are very small particles ($\sim 7 \times 10^{-4}$ μm) but possess a higher mobility with respect to the atmosphere. These small particles can be fullerenes or Polycyclic Aromatic Hydrocarbons (PAH). Sittler et al. (2009) reported that the existence of fullerenes and PAH is possible in the atmospheric conditions of Titan. The concentration of embryos is 97.9 cm^{-3} at 80 km. It increases with altitude and peaks in the altitude range 100–120 km with a concentration of 1.38×10^3 cm^{-3}. Then the concentration decreases with altitude and becomes 789.6 cm^{-3} at 150 km. Since they have the same composition as the aerosols, they too contribute to the photoemission of electrons. However owing to small size, higher mobility as well as an electrophilic nature, electrons when attach to embryos they can behave as negative ions in the atmosphere. Photoionization of embryos as well as negative ions were included in the model. However taking into account the very small size of embryos, Mie Theory was no longer applicable. Thus we resorted to the Rayleigh scattering regime for calculation of scattering and extinction coefficients. Since embryos are equivalent to aerosols in all properties except size, threshold of photoionization remains unchanged. But the presence of negative charge on embryos is likely to decrease its threshold of photoionization, thus an upper limit of 600 nm (2.07 eV; see Table 3, Borucki et al., 2006) was used in Eq. (5) for the calculation of the photo electron ejection rate.

2.3. Steady state ion and electron concentration

The steady state concentrations of ions and electrons are calculated using the following charge balance equations:

$$\frac{dn_e}{dt} = q_e + q + q_{emb} + q_{neg} - \alpha_e n_e n_+ - \beta_{emb} n_{emb} n_e - \beta_{emb}^{+} n_{emb}^{+} n_e - n_e \sum_i \sum_k \beta_{ek}^{i} N_k^{i} \quad (6)$$

$$\frac{dn_-}{dt} = \beta_{emb} n_{emb} n_e - q_{neg} - \alpha n_+ n_- - n_- \sum_i \sum_k \beta_{2k}^{i} N_k^{i} \quad (7)$$

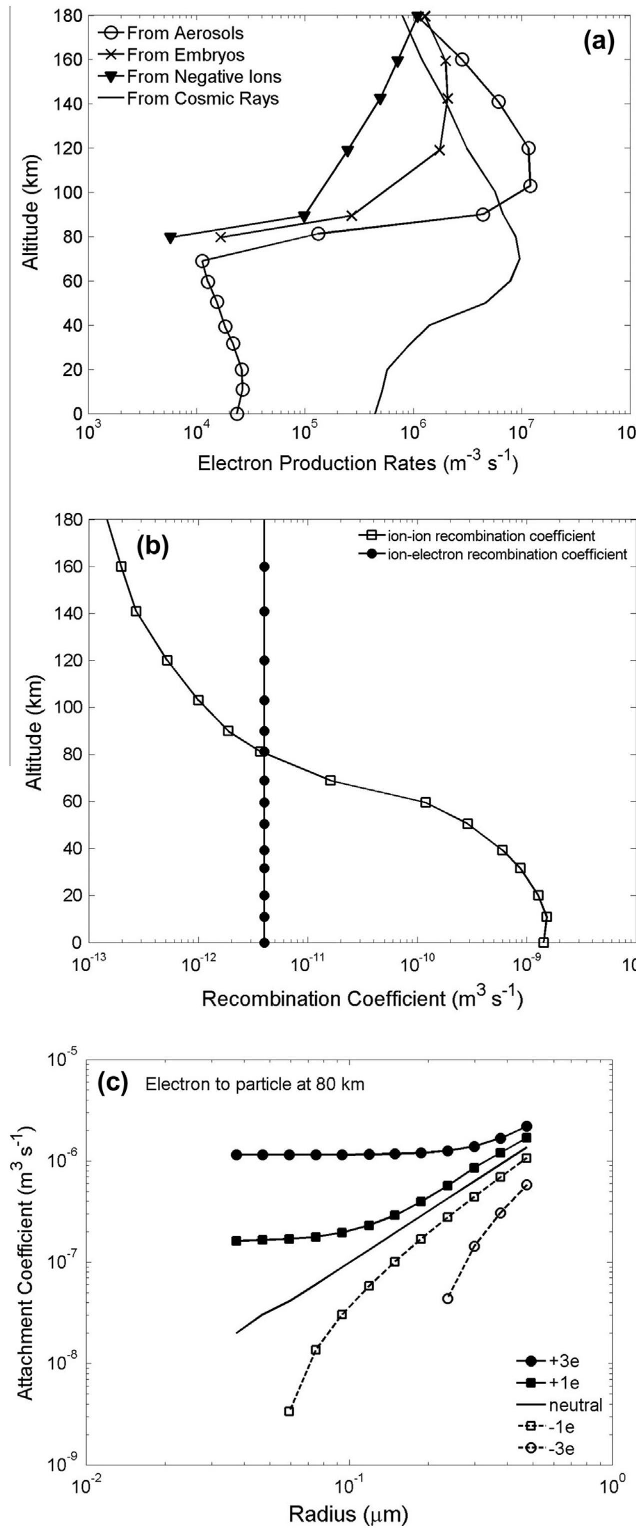

Fig. 1. (a) Electron production rates from different sources, (b) ion–ion and ion–electron recombination coefficient, and (c) electron–aerosol attachment coefficient at 80 km.

$$\frac{dn_+}{dt} = q - \alpha n_+ n_- - \alpha_e n_+ n_e - n_+ \sum_i \sum_k \beta_{1k}^{i} N_k^{i} \quad (8)$$

$$\frac{dn_{emb}^{+}}{dt} = q_{emb} - \beta_{emb}^{+} n_{emb}^{+} n_e \quad (9)$$

where n_e, n_- and n_+ are the concentrations of electron, negative ions and positive ions respectively, n_{emb} the concentration of embryos and n_{emb}^{+} is the concentration