Ionization processes in the atmosphere of Titan
(Research Note)

III. Ionization by high-Z nuclei cosmic rays

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ABSTRACT

Context. The Cassini-Huygens mission has revealed the importance of particle precipitation in the atmosphere of Titan thanks to in-situ measurements. These ionizing particles (electrons, protons, and cosmic rays) have a strong impact on the chemistry, hence must be modeled.

Aims. We revisit our computation of ionization in the atmosphere of Titan by cosmic rays. The high-energy high-mass ions are taken into account to improve the precision of the calculation of the ion production profile.

Methods. The Badhwar and O’Neill model for cosmic ray spectrum was adapted for the Titan model. We used the TransTitan model coupled with the Planetocosmics model to compute the ion production by cosmic rays. We compared the results with the NAIRAS/HZETRN ionization model used for the first time for a body that differs from the Earth.

Results. The cosmic ray ionization is computed for five groups of cosmic rays, depending on their charge and mass: protons, alpha, Z = 8 (oxygen), Z = 14 (silicon), and Z = 26 (iron) nucleus. In contrast to our previous calculations (Paper I: Gronoff et al. 2009a,b), but underestimates the intensity below an altitude of 400 km, especially between 200 and 400 km altitude where alpha and heavier particles (in the cosmic ray spectrum) are responsible for 40% of the ionization. The comparison of several models of ionization and cosmic ray spectra shows that the stability of the altitude of the ionization peak (65 km altitude) with respect to the solar activity.

Conclusions. These new computations show for the first time the importance of high Z cosmic rays on the ionization of the Titan atmosphere. The updated full ionization profile shape does not differ significantly from that found in our previous calculations (Paper I: Gronoff et al. 2009a), but demonstrates that the altitude of the peak was smaller than 50%. This confirms our main conclusions in the previous paper, but high-quality cosmic ray spectrum is required to accurately model the ionization processes in the Titan atmosphere.

Key words. atmospheric effects – methods: numerical – planets and satellites: atmospheres – planets and satellites: individual: Titan

1. Introduction

The chemistry in the troposphere of Titan is very complicated, and needs to be addressed in order to understand the aerosols and the cycle of methane. One of the important input for the chemical models is the ionization by Galactic cosmic rays (GCR) (Lavvas et al. 2008). The first computation of cosmic ray ionization in the atmosphere of Titan was addressed by Capone et al. (1976, 1980, 1983) (with an improvement following the discovery of N2 in the Titan’s atmosphere). The study of GCR in the atmosphere of Titan was also performed by Borucki et al. (1987); Molina-Cuberos et al. (1999a); Molina-Cuberos et al. (1999b); Wilson & Atreya (2005); Borucki et al. (2006); Borucki & Whitten (2008), and Krasnopolsky (2009, 2010), all of these ionization computations being based on the same model from O’Brien (1969). However, these models assumed that the cosmic rays consist of protons and alpha particles. In these papers, the altitude of the peak was varied between 60 and 100 km. The most recent of them focused on the relation between the cosmic ray energy deposition and the haze layer.

In our previous paper (Gronoff et al. 2009a, Paper I), we computed the ionization due to pure proton cosmic rays with the Planetocosmic model. The computed peak, at 65 km altitude, was consistent with the observations. However, it is worth to check our assumption, we had to compute the influence of heavy cosmic ray particles is known to be non-negligible (Usoskin et al. 1994; Webber & Highie 2003; Usoskin et al. 2008), hence needs to be addressed for Titan. A first approximation, where the ionization of a high-Z nucleus of mass A and energy E is assumed to be equal to the ionization of a proton of energy E/A, demonstrated that the difference at the peak was smaller than 50%. This is consistent with the full simulation for the Earth in Velinov & Mateev (2008); Velinov (2008), but not sufficient since the latter results shows a high-Z contribution of more than 50% for the ionization in the upper and middle atmosphere. In the present paper, the result of more detailed computation is presented, confirming our main conclusions in the previous paper, but highlighting important differences when studied in detail.
2. The Galactic cosmic rays in Titan’s atmosphere

To compute the ionization by Galactic cosmic rays with a mass dependence, we needed to assume a precipitation spectrum and composition. We divided the composition of the cosmic rays into standard mass groups: protons, alpha particles, L, M, H, and VH.

2.1. The cosmic ray source

The GCR flux spectrum is computed with the Badhwar & O’Neill (1996) and O’Neill (2006) model, which solves the steady state Fokker-Plank transport equation for the diffusion and convection of GCR entering the heliosphere. The diffusion to convection ratio, \( k(r) \), depends on the modulation parameter \( \phi \), which contains all of the time dependence, the reduced speed \( \beta = \frac{V}{c} \) and the rigidity \( R \) of the particle, the solar wind speed \( V_{SW} \) (nominally 400 km s\(^{-1}\)), the distance to the Sun \( r \), and two empirically determined parameters \( k_0 \) and \( r_0 \)

\[
k(r) = \left( \frac{k_0}{V_{SW}} \right) \frac{\beta R}{\phi} \left[ 1 + \left( \frac{r}{r_0} \right)^2 \right].
\]

As a result, we can use the modulation potential \( \phi \) measured at the Earth as a parameter. To avoid confusion with the \( \phi \) parameter corrected for the position of the object studied, in the following, we use \( \Phi_{Earth} \) and vary its intensity between 450 and 1300 MV, which are characteristic values for solar minimum and maximum. The upper limit to our incident GCR flux is set at 100 GeV. Above this energy limit, the cosmic ray cascade reaches mainly the ground and has very little influence on the atmosphere. The cosmic ray composition is usually divided into six groups of protons, alpha, L, M, H, and VH (Velinov & Mateev 2008). The L group of the cosmic ray composition, consisting mainly of lithium nuclei, has a negligible influence and was not taken into account. The M group, with mean values of \( Z = 7 \) and \( A = 14 \), consists of carbon and oxygen nuclei, the H group, \( Z = 12, A = 24 \), mainly of silicon nuclei, and the VH group, \( Z = 26, A = 56 \), consists mainly of iron nuclei.

2.2. The energy cutoff

We assumed a rigidity cutoff of 0.2 GV (see Paper I), which means an energy cutoff of 20 MeV for cosmic ray protons and alpha particles. (The relativistic formula between the kinetic energy \( E_k \) and the rigidity \( R \) is, considering the mass \( m \) of the particle each one in units of GeV: \( E_k = \sqrt{m^2 + Z R^2} - m \).) For the M group, the energy cutoff is 75 MeV, for the H group, 130 MeV, and for the VH group, 250 MeV. These different energy cutoffs associated with the GCR model enable one to compute the spectrum of cosmic ray precipitation at Titan, for high and low solar activity, shown in Fig. 1.

3. Ion production by high-Z nuclei

The Planetocosmic model was used to compute the influence of each of the cosmic ray Z-groups. To retrieve the ionization from the energy deposition, we used an ion-electron pair production energy of 35 eV. Figure 2 indicates the ionization rate for each of these groups. The main species, protons and alpha, but also the M group, ionize mainly at an altitude of 65 km. We inferred a production rate of between 29 cm\(^{-3}\)s\(^{-1}\) (1200 MV) and 32 cm\(^{-3}\)s\(^{-1}\) (350 MV) for the protons, 5. to 5.5 cm\(^{-3}\)s\(^{-1}\) for the alpha, and 0.61–0.62 cm\(^{-3}\)s\(^{-1}\) for the M group. For the H group, the peak is at an altitude of 74 km with a production rate of 0.10–0.11 cm\(^{-3}\)s\(^{-1}\). For the VH group, the peak is at 200 km altitude with a production rate of 4. \( \times 10^{-2} \)–4.6 \( \times 10^{-2} \) cm\(^{-3}\)s\(^{-1}\).

A computation of the ionization with the NAIRAS/HZETRN model (Mertens et al. 2007, 2010, and references herein), adapted for Titan, gives the result shown in Fig. 3. The Planetocosmics and NAIRAS models give similar peaks for proton, alpha, and total productions. The high-Z ionization differ in terms of the peak position and shape of the ionization curve for the two models. These differences lie in the physics of the models: the Planetocosmic simulation takes into account the creation and transport of muons, which ionize at low altitude, while the coupling of the deterministic MESTRN (meson-muon transport) code with NAIRAS/HZETRN is currently underway (Blattning et al. 2004). Another source of uncertainty is found in the Planetocosmics model. It concerns the ion-ion interaction model i.e. the spallation model where two nuclei interact with each other (Battistoni et al. 1996; Wilson et al. 1991). The currently used model is inaccurate above a few GeV/n for the H and VH groups (and above \( \approx 10 \) GeV/n for the other groups, but does
5. Revised evaluation of the total ionization profile

Our revised computation allows us to update the profile of the energy precipitation in the atmosphere of Titan. Figure 5, revised since Paper I, summarizes the different types of precipitation in the atmosphere of Titan i.e., caused by the solar photons, electrons, and protons from the magnetosphere of Saturn, and the GCR for low solar activity conditions ($\Phi_{\text{Earth}} = 450$ MV). We can also refine the plot of the full ionization in the atmosphere of Titan in Fig. 6. The main difference from Paper I lies in the depth of the gap at 400 km altitude between the Saturn’s magnetosphere proton ionization layer and the cosmic ray ionization layer, slightly lower in the present paper. The remaining presence of that gap ensures that there are still two separate layers of ionization caused by cosmic rays and Saturn’s protons, which is consistent with our previous conclusions. The cosmic ray ionization peak, at 65 km altitude, agrees with the Huygens data, which indicates that an ion layer peaks at this altitude (Paper I; López-Moreno et al. 2008; Hamelin et al. 2007, and references therein). The second difference is the altitude and the intensity of the peak due to electron precipitation at an altitude of 900 km, to account for the influence of magnetic field lines, explained in Paper II (Gronoff et al. 2009b), we assumed a dip angle of 20° for the electron precipitation.

When examining the influence of high-Z cosmic rays (Figs. 2 and 6), we see that the ionization above the altitude of 200 km due to M, H, and VH groups corresponds to a fifth of the total (17% of the production at 300 km altitude) production, being comparable to the alpha particle production (20%). At the 65 km altitude peak, 14% of the production is due to alpha particles and 2% to M, H, and VH groups; while at the altitude of 100 km, 18% of the production is due to the alpha and 3% to the high-Z.

The new cosmic ray ionization rate is between 2 and 10 ($>200$ km altitude) times higher than the one presented in Paper I over the whole altitude range. This is mainly due to the more precise cosmic ray precipitation spectrum used but also to the alpha and high-Z contribution. The doubling of the 65 km altitude peak intensity, which is very important for quantitative studies, highlights the importance of our improved calculations.

In Fig. 6, the haze layers are represented by the shaded areas, which illustrates the relationship with ion production. The main haze layer, in the troposphere, is probably associated with the cosmic ray production, the detached haze layer around 500 km altitude is related to the magnetospheric proton production, and...
Fig. 6. Updated full ionization profile for the nightside, high precipitation conditions, and low solar activity ($\Phi_{\text{Earth}} = 450 \text{ MV}$, Fig. 18 in Paper I). The parts highlighted in gray are the haze layers, including the thermosphere.

the thermosphere, considered a supplementary haze layer because of the detection of aerosols by Cassini, is associated with photon and electron ionization.

6. Conclusion

For the first time, we have calculated the ionization by each Z-group of cosmic rays in the atmosphere of Titan, confirming that the cosmic ray ionization layer peaks at 65 km altitude independent of the solar activity. Moreover, our calculations have demonstrated an improved ionization profile for the 200–400 km altitude range. These conclusions are also consistent with ionization models.

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References

Krasnopolsky, V. A. 2009, Icarus, 201, 226
Krasnopolsky, V. A. 2010, Planet. Space Sci., 58, 1507