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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 Badhwahr 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. Protons and alpha particles ionize mainly at 65 km altitude, while the higher mass nucleons ionize at higher altitudes. Nevertheless, the ionization at higher altitude is insufficient to obscure the impact of Saturn's magnetosphere protons at a 500 km altitude. The ionization rate at the peak (altitude: 65 km, for all the different conditions) lies between 30 and 40 $cm^{-3}s^{-1}$.
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. 2009, 506, 955) but undergoes a strong increase in 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 (in intensity and composition) reassures us about the stability of the altitude of the ionization peak (65 km altitude) with respect to the solar activity.

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 N_2 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 to carefully check our assumption, we had to compute the influence of a higher quality cosmic ray spectrum. The contribution of heavy cosmic ray particles is known to be non-negligible (Velinov et al. 1974; Webber & Higbie 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 protons 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 ϕ, 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 $V_{\rm SW}$ (nominally 400 km s^{-1}), the distance to the Sun r, and two empirically determined parameters k_0 and r_0

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

As a result, we can use the modulation potential ϕ measured at the Earth as a parameter. To avoid confusion with the ϕ parameter corrected for the position of the object studied, in the following, we use $\Phi_{\rm Earth}$ 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: $E_{\rm k} = \sqrt{m^2 + ZR^2} - m$.) 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.

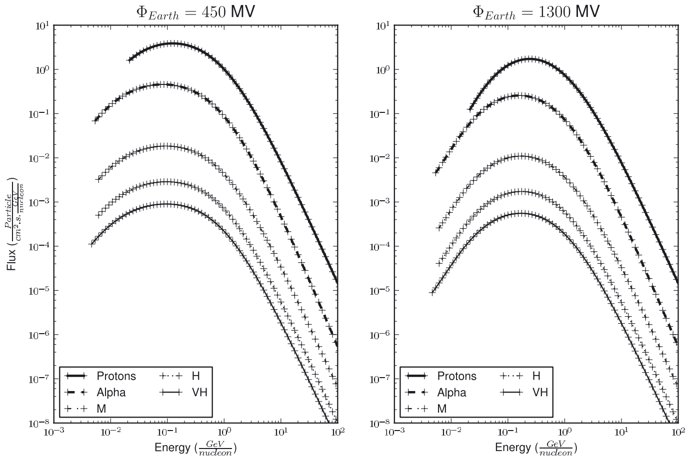

Fig. 1. GCR precipitation spectrum in the atmosphere of Titan, with a 0.2 GV cutoff, for low $\Phi_{\rm Earth}$ = 450 MV (*left*) and high $\Phi_{\rm Earth}$ = 1300 MV (*right*) solar activities.

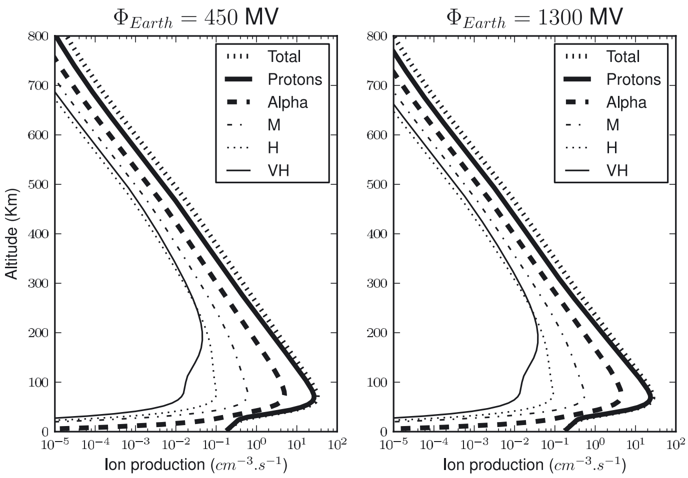

Fig. 2. GCR ionization in the atmosphere of Titan, with respect to the species, for low $\Phi_{\rm Earth}$ = 450 MV (*left*) and high $\Phi_{\rm Earth}$ = 1300 MV (*right*) solar activities.

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 $4. \times 10^{-2}$–4.6×10^{-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 (Blattnig 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 ≈10 GeV/n for the other groups, but does

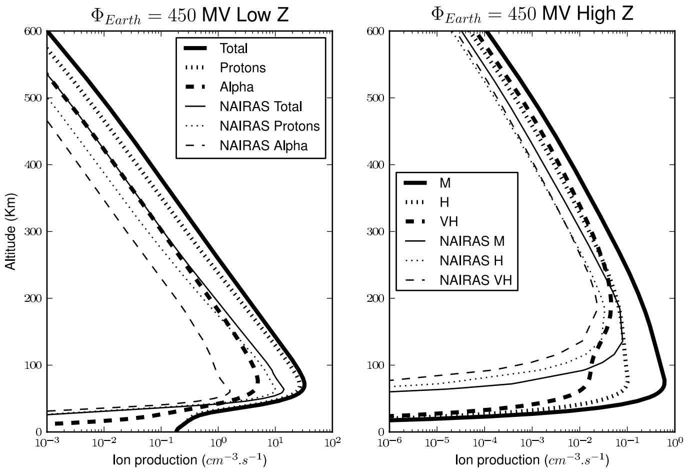

Fig. 3. GCR ionization in the atmosphere of Titan, with respect to the species, for low $\Phi_{\rm Earth}$ = 450 MV solar activities. Computed with the Planetocosmics and NAIRAS models.

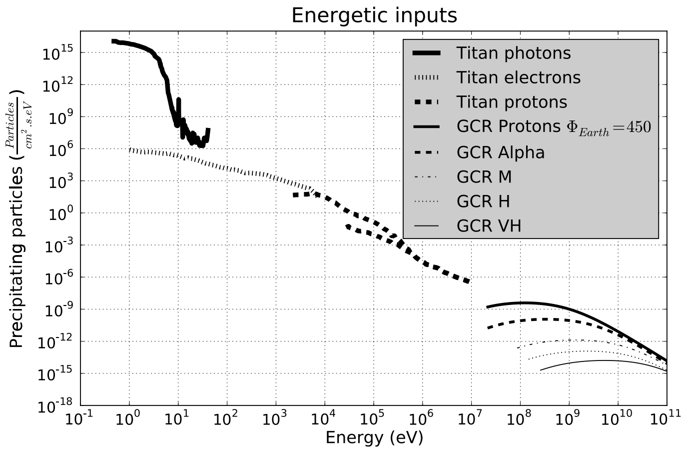

Fig. 5. Energy spectrum of ionizing radiation in the atmosphere of Titan (Fig. 1 in Paper I). The cosmic ray precipitation spectrum is computed for the $\Phi_{\rm Earth}$ = 450 MV conditions.

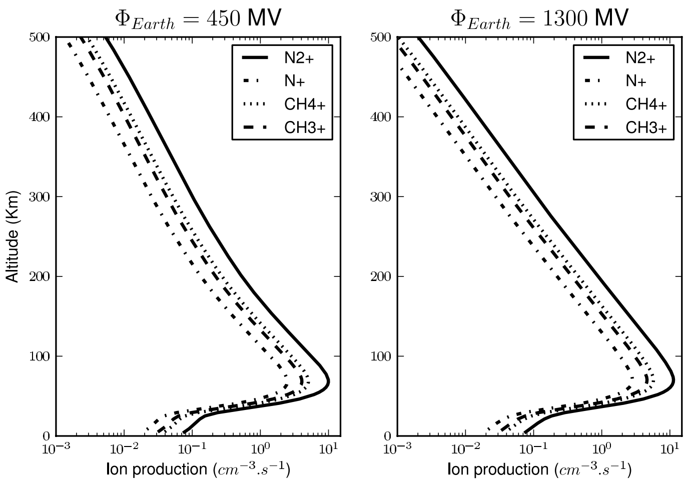

Fig. 4. GCR ionization in the atmosphere of Titan, with species production, for low $\Phi_{\rm Earth}$ = 350 MV (*left*) and high $\Phi_{\rm Earth}$ = 1200 MV (*right*) solar activities.

not affect the results). The planned inclusion of the DPMJET model[1] in Planetocosmics-titan will improve these results.

The overall ion production by these different models and spectra do not differ significantly within their respective uncertainties. We can assume that the ionization in Fig. 2 accurately describes the processes in the lower atmosphere of Titan.

4. The cosmic-ray total ion production

The ion production composition was computed using branching ratios, determined from the data of Straub et al. (1996) for N_2 and CH_4. The branching ratio for electron impact was assumed to be applicable for cosmic rays. The result of this total ionization, presented in Fig. 4, shows that the GCR ionize mainly at an altitude of 65 km, which is consistent with Huygens observations (López-Moreno et al. 2008; Hamelin et al. 2007) as shown in Paper I. The main ion produced is N_2^+, followed by CH_4^+, CH_3^+, and N^+.

[1] http://reat.space.qinetiq.com/marsrem/

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 ($\Phi_{\rm Earth}$ = 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 herein). 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 isvery 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

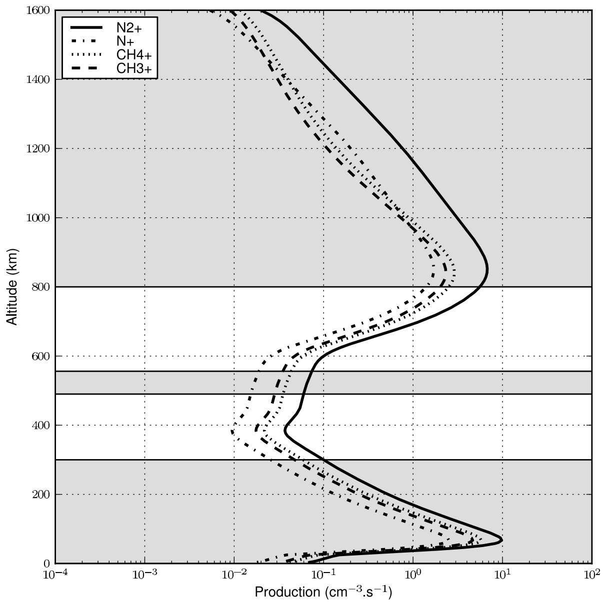

Fig. 6. Updated full ionization profile for the nightside, high precipitation conditions, and low solar activity (Φ_{Earth} = 450 MV, Fig. 18 in Paper I). The parts highlighted in gray are the haze layers, including the thermosphere.

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 independently 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

Badhwar, G. D., & O'Neill, P. M. 1996, Adv. Space Res., 17, 7
Battistoni, G., Bloise, C., Forti, C., et al. 1996, Astropart. Phys., 4, 351
Blattnig, S. R., Norbury, J., Norman, R. B., et al. 2004, NASA Technical Manual, 212995
Borucki, W. J., & Whitten, R. C. 2008, Planet. Space Sci., 56, 19
Borucki, W. J., Levin, Z., Whitten, R. C., et al. 1987, Icarus, 72, 604
Borucki, W. J., Whitten, R. C., Bakes, E. L. O., Barth, E., & Tripathi, S. 2006, Icarus, 181, 527
Capone, L. A., Whitten, R. C., Dubach, J., Prasad, S. S., & Huntress, Jr., . W. T. 1976, Icarus, 28, 367
Capone, L. A., Dubach, J., Whitten, R. C., Prasad, S. S., & Santhanam, K. 1980, Icarus, 44, 72
Capone, L. A., Dubach, J., Prasad, S. S., & Whitten, R. C. 1983, Icarus, 55, 73
Gronoff, G., Lilensten, J., Desorgher, L., & Flückiger, E. 2009a, A&A, 506, 955 (Paper I)
Gronoff, G., Lilensten, J., & Modolo, R. 2009b, A&A, 506, 965 (Paper II)
Hamelin, M., Bghin, C., Grard, R., et al. 2007, Planet. Space Sci., 55, 1964
Krasnopolsky, V. A. 2009, Icarus, 201, 226
Krasnopolsky, V. A. 2010, Planet. Space Sci., 58, 1507
Lavvas, P. P., Coustenis, A., & Vardavas, I. M. 2008, Planet. Space Sci., 56, 67
López-Moreno, J. J., Molina-Cuberos, G. J., Hamelin, M., et al. 2008, Geophys. Res. Lett., 35, 22104
Mertens, C. J., Wilson, J. W., Walker, S. A., & Tweed, J. 2007, Adv. Sp. Res., 40, 1357
Mertens, C. J., Kress, B. T., Wiltberger, M., et al. 2010, Space Weather, 8, 3006
Molina-Cuberos, G. J., López-Moreno, J. J., Rodrigo, R., & Lara, L. M. 1999a, J. Geophys. Res., 104, 21997
Molina-Cuberos, G. J., López-Moreno, J. J., Rodrigo, R., Lara, L. M., & O'Brien, K. 1999b, Planet. Space Sci., 47, 1347
O'Brien, K. 1969, Nucl. Instrum. Meth., 72, 93
O'Neill, P. M. 2006, Adv. Space Res., 37, 1727
Straub, H. C., Renault, P., Lindsay, B. G., Smith, K. A., & Stebbings, R. F. 1996, Phys. Rev. A, 54, 2146
Usoskin, I. G., Desorgher, L., Velinov, P., et al. 2008, Acta Geophys., 57, 88
Velinov, P. 2008, J. Atmo. Solar-Terr. Phys., 70, 574
Velinov, P., Nestorov, G., & Dorman, L. 1974, Sofia Izdatel Bolgarskoi Akademii Nauk
Velinov, P. I. Y., & Mateev, L. 2008, Adv. Space Res., 42, 1586
Webber, W. R., & Higbie, P. R. 2003, J. Geophys. Res., 108, 11
Wilson, E. H., & Atreya, S. K. 2005, J. Geophys. Res., 109, 06002
Wilson, J. W., Townsend, L. W., Schimmerling, W. S., et al. 1991, NASA STI/Recon Technical Report N, 92, 15956