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Cosmic Ray Ionization and Dust Charging at the Cloud Top of a Giant Gas Planet

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Abstract

In this presentation, we discuss cosmic ray transport through a DRIFT-PHOENIX model atmosphere of a free-floating giant gas planet ($T_{\rm eff} = 1000$ K, $\log g = 3$, solar metallicity). The cosmic ray transport is modelled by a Monte Carlo simulation for cosmic rays between energies of 10^6 eV $< E < 10^{12}$ eV. We apply the predictions of this simulation in order to determine a steady state degree of ionization within the upper atmosphere and into the cloud layer of the giant gas planet. We explore the potential of of cosmic ray ionization to contribute to initial conditions necessary for other plasma ionization processes, such as Alfvén Ionization [6]. Finally, we explore how the products of cosmic ray air showers may charge the dust grains that make up the clouds in the model atmosphere. We present our results in terms of the time-scale for a initiating an electron avalanche within the atmospheric gas [2], as well as the time-scale toward maximally charging grains. Grains are here considered to be maximally charged if either the build-up of negative charge on the grains produces an electrostatic force significant enough to prevent further electrons from becoming attached to the grain surface, or when adding a further electron would break the grain apart [7].

1. Introduction

On earth, cosmic rays produce extensive air showers that ionize the cloud top, providing a reservoir of free electrons for the global electric circuit. These air showers also possibly initiate lightning strikes [1]. Cosmic ray ionization has been modelled for planets and moons in our solar system, notably Mars, Jupiter and Titan. The effect of cosmic ray ionization on planets outside our solar system is still largely unexplored. In Section 2, we will consider the model atmosphere of a free-floating giant gas planet, and model the cosmic ray transport through this atmosphere in Section 3. Section 4 contains a brief description of our results.

2. The Model Atmosphere

We examine the effects of the cosmic ray ionization on a giant gas planet atmosphere modelled by DRIFT-PHOENIX, with a surface gravity of $\log g = 3$ and an effective temperature of $T_{\rm eff} = 1000$ K. This atmosphere is the result of the solution of the coupled equations of radiative transfer, convective energy transport (modelled by mixing length theory), chemical equilibrium (modelled by laws of mass action), hydrostatic equilibrium, and dust cloud formation [8].

3. Cosmic Ray Transport and Grain Charging

Cosmic ray transport is calculated using a Monte Carlo model following 10000 cosmic rays with binned over a range of energies from 10^6 eV $< E < 10^{12}$ eV, according to the initial flux spectrum of Lerche & Schlickeiser [3]. The model accounts for energy loss via inelastic collisions and some magnetic field effects [4]. This is accomplished by assigning each of the 10000 cosmic rays a random number, x_n (where n goes from 0 to 10000); x_n takes a value between 0 and 1. The cosmic rays then traverse a portion of the atmosphere, ΔN [cm^{-2}]. The random number for each cosmic ray, x_n, is compared to $\sigma \Delta N$, where σ [cm^2] is the cross-section for an inelastic collision between the cosmic ray and an atom or molecule within the atmospheric gas (in this case, molecular hydrogen). If $x_n S < \sigma \Delta N$, then the n'th cosmic ray experiences an inelastic collision and loses a portion of its energy. The 10000 cosmic rays are re-binned, and a new flux spectrum at the new atmospheric depth is calculated. The flux spectra are modified in order to account for Alfvén waves [5]. This process is repeated until the entire atmosphere is traversed. The relevant output of this model is the cosmic ray ionization rate, Q [cm^{-3} s^{-1}].

4. Results

The calculated cosmic ray ionization rate, Q, is used to predict the steady-state degree of ionization by the formula:

$$f_e(p_{\rm gas}) = \frac{1}{n_{\rm gas}}\sqrt{\frac{Q}{k_{r2}+n_{\rm gas}k_{r3}}}, \qquad (1)$$

where $n_{\rm gas}$[cm^{-3}] is the gas density at a pressure $p_{\rm gas}$, k_{r2} [cm^3 s^{-1}] is the two-body recombination rate, and k_{r3} [cm^6 s^{-1}] is the three-body recombination rate. The predicted steady-state degree of ionization, $f_e > 10^{-8}$, when $p_{\rm gas} < 10^{-8}$ bar, approaching the degree of ionization sufficient for a weakly ionized plasma. The figure below presents f_e as a function of $p_{\rm gas}$.

We utilize the degree of ionization in order to determine a time-scale for charging dust grains, which we estimate as:

$$1/\tau \approx f_e n_{\rm dust}\langle\sigma_{\rm dust}\rangle c_e, \qquad (2)$$

where $n_{\rm dust}$ [cm^{-3}] is the number density of the dust, $\langle\sigma_{\rm dust}\rangle$ [cm^2] is the average cross-sectional area of the dust and c_e [cm/s] is the electron thermal velocity. This time-scale is compared to the time-scale for an electron avalanche [2] and the time-scale for the coulomb explosion of the dust grain [7].

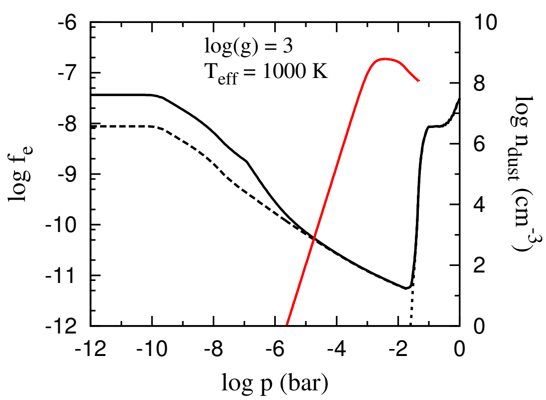

Figure 1: The steady-state degree of ionization, f_e, in the presence of cosmic rays $E > 10^6$ eV (black solid, left axis), $E > 10^9$ eV (black dashed, left axis), and in the absence of cosmic rays (black dotted, left axis), as a function of gas pressure $p_{\rm gas}$ [bar]. The number density of the dust is shown (red line, right axis), in order to indicate the location of the cloud layer.

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