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An atmospheric model designed for integration into coupled models of magma ocean planets

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Abstract

A 1D radiative-convective model of a thick (up to several hundreds of bars) H_2O-CO_2 atmosphere has been developped and coupled with a simple magma ocean interior model[1]. In this paper, we will focus on describing the atmospheric model. Preliminary results regarding observable parameters and the cooling rates of the magma ocean will also be discussed and compared with similar studies[2].

1 Introduction

Existing models of telluric planets in their magma ocean stage usually include a very simplistic atmospheric parameterization, although the volatile enveloppes surrouding these planets are expected to interact strongly with the interior in terms of volatile exchange, heat fluxes and impact energy deposition. The fast and simple 1D atmosphere model shown here intends to fill this gap, is already coupled with a simplified interior model and will soon be coupled with an impact and escape model in order to examine the early history of telluric planets before any water condensation may take place.

2 Model

2.1 Description

The atmospheric is assumed to follow the thermal profile described in [3]: dry or wet convective in the lower part (troposphere) and isothermal in approximate radiative equilibrium (mesosphere) in the upper part. Only H_2O and CO_2 are taken into account, with H_2O following a non-ideal equation of state since its critical point can be reached in such atmospheres.

Thermal fluxes are then computed from 40 up to 10000 cm^{-1}, taking into account the IR opacities of CO_2 and H_2O using a random band model in 33 spectral intervals or k-correlated opacities computed using KSPECTRUM from V. Eymet. H_2O–H_2O and CO_2–CO_2 continuum opacities are also taken into account. There is no need yet for computing solar fluxes since the thermal structure is prescribed rather than computed from convective and radiative fluxes. An effective temperature T_{eff} can then be computed and compared to the equilibrium temperature T_{eq} assuming a weakened early Sun and a high albedo due to the expected cloud cover. The discrepancy between T_{eff} and T_{eq} leads to the cooling of the whole planet over timescales much longer than the radiative time scale of the atmosphere, thus validating our approach.

2.2 Coupling

Up to now, coupling has only been achieved with a simplified magma ocean model, which provides to the atmospheric model the net outgoing heat flux (from latent heat release during the solidification of magma at the lower solid core–magma ocean boundary) and the partial pressures of CO_2 ans H_2O. Since the atmospheric model rather needs T_{surf} as an input, an iterative scheme is applied so that the prescribed T_{surf} and atmospheric content yield, through the atmospheric model, the expected outgoing radiative flux.

3 Preliminary Results

Since out radiative model deals with 33 bands in the thermal IR range, very coarse resolution spectra of the nightside thermal emission are computed by this model (see Fig. 1). Quite surprinsingly, the blanketting effect of the atmosphere is very efficient provided T_{surf} does not exceed a threshold value of about 2000 K with the standard volatile inventory (300 bar H_2O, 100 bar CO_2). In such a case, the thickness of the atmosphere combined with the adiabatic cooling yields a rather cool mesosphere ($T_0 < 300\,\mathrm{K}$) so that T_{eff} remains quite moderate. The situation is quite reminiscent of the situation of Venus, where the very high $T_{\mathrm{surf}} = 735\,\mathrm{K}$ is maintained despite a quite low $T_{\mathrm{eff}} = 233\,\mathrm{K}$ thanks to the thickness of its CO_2 atmosphere. Here, it is even exaggerated due to the increased thickness of the atmosphere (several hundred of kilometers, see Fig. 2) and IR opacity of H_2O with respect to almost pure CO_2 as in the Venusian case. This very low outgoing flux enables a longer lifetime for the magma ocean than initally foreseen (see [1]), and casts doubt on the detectability of this class of exoplanets using their thermal infrared emission.

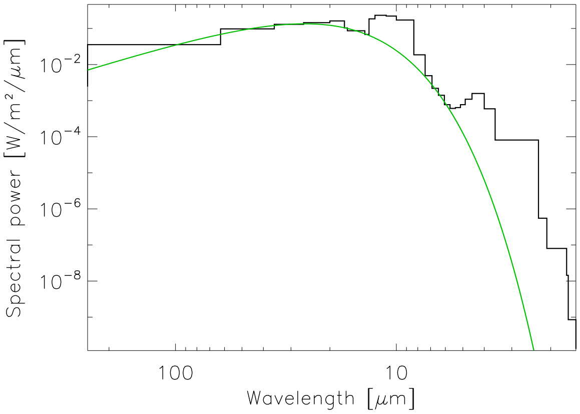

Figure 1: Thermal spectrum in the standard case ($T_{\mathrm{surf}} = 1400\,\mathrm{K}$, $P_{CO_2} = 100\,\mathrm{bar}$, $P_{H_2O} = 300\,\mathrm{bar}$). The green line stands for the blackbody emission at the mesospheric temperature. CO_2 opacity only plays a major role near $15\,\mu\mathrm{m}$, and H_2O opacity yields very few spectral windows probing deep into the lower, hot layers.

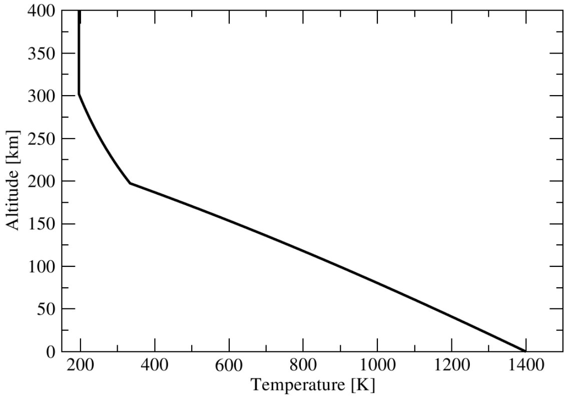

Figure 2: Temperature profile in the standard case. The structure in three layers is especially noticeable.

4 Future work

This atmospheric model, although already at an operational stage, can and will be improved. Some microphysics could be implemented to predict the exact vertical extent of the aerosol and cloud cover, thus enabling their inclusion in the radiative transfer model and providing a better estimate of the albedo in the solar wavenumber range. Ultimately, solar radiation can be taken into account, and the temperature profile could then be derived from local radiative and convective equilibrium rather than prescribed.

Also, besides the aforementioned improvements to the atmospheric model and to the interior model, coupling with an escape and impact module is envisionned so that some depletion in the volatile inventory will be taken into account, as well as heat deposition from impacts. Application to other plants than primitive Earth will then be possible and help in turning this model into a powerful tool for comparative planetary science.

Acknowledgements

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