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Modeling the albedo of magma ocean planets

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Abstract

1 Introduction

The modeling of telluric exoplanets at the beginning of their history, during their magma ocean stage, has been very active during the last decade. Such models usually consist in coupled models, with various submodules (interior, atmosphere) interacting with each others through matter and/or energy fluxes[1, 2, 3].

Here we present the newest updates to the 1d radiative-convective atmospheric submodule[7, 8] of a coupled interior-atmosphere model developed since 2010[9, 12]. These newest updates consist in the inclusion of Rayleigh scattering, but mainly in the modeling of the reflectivity of the atmosphere in order to determine its albedo. This updated atmospheric model is therefore able to compute both the thermal outgoing longwave radiation ($\mathrm{OLR} = \sigma {T_{\mathrm{eff}}}^4$) of the planet, and the absorbed stellar flux ($\mathrm{ASF} = \sigma {T_{\mathrm{eq}}}^4$), thus allowing a self-consistent estimation of the secular cooling heat flux originating from the interior through the atmosphere, given by $\sigma \left({T_{\mathrm{eff}}}^4 - {T_{\mathrm{eq}}}^4\right)$. Also, the determination of both thermal emission spectra and spectral reflectivity could help in constraining future exoplanet observations that would happen to currently experience their magma ocean stage.

2 Improvements

2.1 Rayleigh scattering

Rayleigh scattering opacity was added to the most recent version of the atmospheric submodule[8]. Cross-sections of N_2, CO_2 and H_2O were assumed to follow a λ^{-4} spectral dependency so that spectral averaging within each of the 36 bands in both thermal (0-$10^4\,\mathrm{cm}^{-1}$) and stellar (2000-33000 cm^{-1}) components could be computed analytically. Preliminary testing shows that the influence of Rayleigh scattering for the thermal component was indeed negligible for $\lambda > 1\,\mu\mathrm{m}$.

2.2 Spectral reflectivity

In the 36 stellar bands, opacity due to Rayleigh scattering (see above), clouds and gaseous species (CO_2 and H_2O) was considered. Clouds properties ($\varpi_0(\lambda)$, $Q_{\mathrm{ext}}(\lambda)$ and $g(\lambda)$ assuming a Henyey-Greenstein phase function) were parameterized from Mie calculations given by [4], in the same way than for the already modeled thermal component. Gaseous opacities were extracted from the MT_CKD database [6] for the H_2O-H_2O continuum, and from Venusian observations for CO_2-CO_2. Line opacities were computed using KSPECTRUM [10], using the spectra already computed for similar pressures, temperatures and atmospheric composition by M. Turbet [11].

Spectral reflectivity in each of these bandes is then computed using a k-correlated code with 16 quadrature points in g-space, running DISORT [5] in the 4 streams approximation. Once spectral reflectivty is computed, the resulting albedo can be computed by weighting each band's reflectivity according to the Planck function for the star temperature.

3 Preliminary results

The work is still underprogress, but two features appear robust in our preliminary simulations: (1) for a given atmosphere (H_2O and CO_2 total pressures, surface temperature), the albedo is increasing with increasing stellar temperature. This is due to a global decrease in reflectivity with increasing wavelengths, since Rayleigh and/or cloud scattering becomes dominated by near IR absorption from H_2O (and CO_2 to a lesser extent); (2) for a given atmospheric inventory, a transition between a high albedo regime for relatively low surface temperatures and a lower albedo at higher surface temperatures can be observed. The transition temperature is close to the one observed for the OLR[8]: for higher surface temperature, clouds are optically thin, and therefore the condensation cold trap becomes neglible, enabling “dark” water vapor to reach higher levels where it can efficiently absorb stellar light.

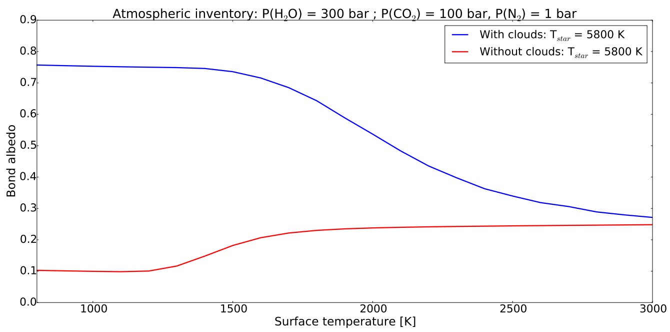

Figure 1: Preliminary modeling of the albedo of a H_2O-dominated atmosphere around a solar analog wrt. its surface temperature

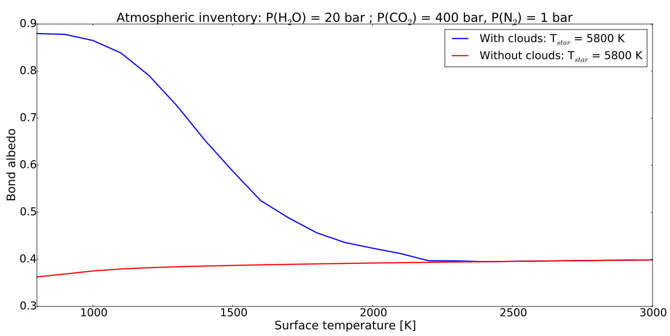

Figure 2: Preliminary modeling of the albedo of a CO_2-dominated atmosphere around a solar analog wrt. its surface temperature

4 Conclusion

Once finalised, the results from this model will be used as a benchmark for a new PhD project, aiming at using the LMD generic global circulation model in order to better model the transition between magma ocean planets (with a very high internal heat flux on par with stellar absorption) and mature telluric planets (with negligible internal heat flux) and thus investigate their habitability once atmospheric escape is taken into account.

Acknowledgements

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