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Linking the evolution of terrestrial interiors and an early outgassed atmosphere to astrophysical observations

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Abstract

Current and future exoplanet observations will favour the detection and characterisation of hot and warm planets, potentially with large outgassed atmospheres. An interior–atmosphere model is combined with static structure calculations to track the evolving radius of a hot rocky mantle that is outgassing CO_2 and H_2O. Synthetic emission and transmission spectra are generated for CO_2 and H_2O dominated atmospheres. Atmospheres dominated by CO_2 suppress the outgassing of H_2O to a greater extent than previously realised, since previous studies have applied an erroneous relationship between volatile mass and partial pressure. Furthermore, formation of a lid at the surface can tie the outgassing of H_2O to the efficiency of heat transport through the lid, rather than the radiative timescale of the atmosphere. Contraction of the mantle as it cools from molten to solid gives $\sim 5\%$ radius decrease, which can partly be offset by addition of a relatively light species (e.g., H_2O versus CO_2) to the atmosphere.

1. Introduction

The earliest secondary atmosphere of a rocky planet originates from extensive volatile release during one or more *magma ocean* epochs that occur during and after the assembly of the planet. Magma oceans set the stage for the long-term evolution of terrestrial planets by establishing the major chemical reservoirs of the iron core and silicate mantle, chemical stratification within the mantle, and outgassed atmosphere. Therefore, understanding the whole life-cycle of a terrestrial planet, from its magma ocean origins to potentially a mature state with a solid mantle, has fundamental implications for the thermal and chemical evolution of terrestrial planets. In this study, we highlight the potential to combine models of coupled interior–atmosphere evolution with static structure calculations and modelled atmospheric spectra (transmission and emission). By combining these components in a common modelling framework, we acknowledge planets as dynamic entities and leverage their evolution to bridge planet formation, interior-atmosphere interaction, and observations. By considering the earliest stage of terrestrial planet evolution (the magma ocean epoch), we can investigate the consequences of large variations in temperature, material phase, and atmospheric properties on observations. This has immediate application for characterising hot and close-in rocky planets.

2. Model

We use the SPIDER code [1] to model the interior evolution of an Earth-like planet coupled to an atmosphere. We include volatile species (H_2O and CO_2) that form an atmosphere as a consequence of outgassing as a magma ocean cools and crystallises. The partial pressure of each volatile species relates to its atmospheric mass [2]:

$$m_v^g = 4\pi R_p^2 \left(\frac{\mu_v}{\bar{\mu}}\right) \frac{p_\mathrm{v}}{g} \tag{1}$$

where m_v^g is the mass of the volatile in the atmosphere, R_p radius of the planetary surface, μ_v molar mass of the volatile, $\bar{\mu}$ mean molar mass of the atmosphere, p_v the (surface) partial pressure of the volatile, and g gravity. In some previous studies that focus on magma oceans, the ratio of molar masses is incorrectly omitted, but this is only appropriate if a single volatile species is considered.

3 Results and Discussion

For *early outgassing* models, outgassing occurs largely unimpeded and magma ocean cooling generates a large outgassed atmosphere within a few million years. For *extended outgassing* models the formation of a viscous lid at the surface prevents efficient outgassing, particularly of H_2O which has a higher solubility in silicate melt than CO_2. This is because the cooling timescale is dictated by heat transport through the lid, and eventually the viscous flow of the solid mantle, rather than the radiative timescale of the atmosphere. In general, 90% of the H_2O inventory remains in the interior and only readily outgasses once the global melt fraction drops below 10%. This melt fraction occurs after the surface reaches the viscous lock-up point, suggesting that a large reservoir of H_2O can be retained in the interior until the very last stages of magma ocean crystallisation. Therefore, the formation of a surface lid that restricts heat transport could control the outgassing of volatile species from the interior.

In the model, we fix the final (fully outgassed) partial pressure of H_2O to 220 bar and vary the final volume mixing ratio of CO_2 between 0.1 (Case 1c) and 0.9 (Case 9c) to explore the connection between outgassing and planetary radius (Fig. 1). Our results demonstrate that a hot molten planet can have a radius several percent larger ($\sim 5\%$, assuming Earth-like core size) than its equivalent solid counterpart, which may explain the larger radii of some close-in exoplanets. Outgassing of a low molar mass species (such as H_2O, compared to CO_2) can combat the continual contraction of a planetary mantle and even marginally increase the planetary radius. We further use our models to generate synthetic transmission and emission data to aid in the detection and characterisation of rocky planets via transits and secondary eclipses. Atmospheres of terrestrial planets around M-stars that are dominated by CO_2 versus H_2O could be distinguished by future observing facilities that have extended wavelength coverage (e.g., JWST). Incomplete magma ocean crystallisation, as may be the case for close-in terrestrial planets, or full or part retention of an early outgassed atmosphere, should be considered in the interpretation of observational data from current and future observing facilities.

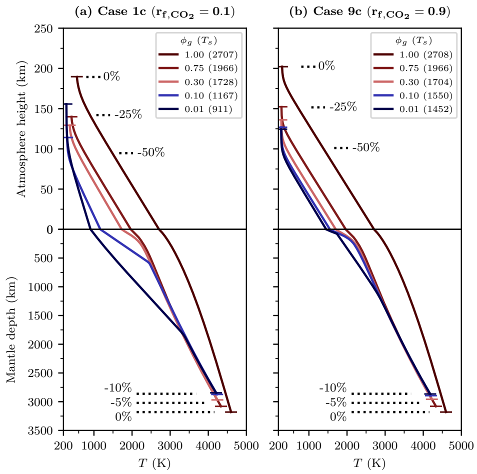

Figure 1: Combining the integrated interior–atmosphere evolutionary model with structure calculations. The planetary surface is fixed at 0 and the atmospheric height and mantle depth are plotted relative to this coordinate. Horizontal dotted lines indicate the percentage change in height (atmosphere) and depth (mantle) relative to the initial height and depth of the respective reservoir at 0 Myr. (a) Case 1c, (b) Case 9c.

4. Summary and Conclusions

A molten silicate mantle can increase the radius of a terrestrial planet by around 5% compared to its solid counterpart, or equivalently account for a 13% decrease in bulk density. An outgassing atmosphere can perturb the total radius according to its speciation, notably the abundance of light versus heavy volatile species. Atmospheres of terrestrial planets around M-stars that are dominated by CO_2 or H_2O can be distinguished by observing facilities with extended wavelength coverage (e.g., JWST)

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