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Constraining the range of bulk terrestrial exoplanet compositions, and their effects on coupled interior-atmosphere evolution

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Abstract

One of the main goals of exoplanetary sciences is to reconcile our theoretical knowledge of terrestrial exoplanet systems with observations. Since the atmosphere is the only observable part of a terrestrial exoplanet, the interaction between it and the planetary interior should be studied to reach this goal. The bulk composition of the planetary interior affects this interaction in multiple ways and should therefore be considered when studying the coupled interior-atmosphere system. Our aim is to constrain the possible range of terrestrial planet bulk compositions, since this range prescribes the extent to which evolution of the atmosphere-interior system can vary between planets of different compositions.

We attempt to constrain this range by considering a range of exoplanet host star compositions, and applying devolatilization to these compositions. For this goal, we utilize the devolatilization model from [1], update it for new condensation temperature data, and apply it to exoplanet host stars contained by the TESS catalog [2]. The effect of galactic chemical evolution on the range of terrestrial planet bulk compositions is examined as well. Finally, we apply the resulting range to a simple model of atmosphere-interior interaction.

1 Introduction

One of the main goals of exoplanetary science is to understand the dynamics of formation and evolution of a planet, and to reconcile this understanding with observations. For terrestrial (exo)planets, the atmosphere is the only observable part of the planet. Their atmospheres form by degassing from a magma ocean, and evolve under interaction with the rocky interior, which means that the atmosphere and interior systems are coupled [3]. In our previous work (Spaargaren et al., in prep.), we explored a model capturing only the essential aspects of atmosphere-interior interaction. We found that the dependence of viscosity on composition affects the thermal evolution of the planet, and that stable stratification of the mantle, which affects the thermal evolution of the interior, is possible for realistic compositions. Furthermore, mantle composition has a strong influence on crustal formation and buoyancy, with as result that it may promote or inhibit initiation of plate tectonics [4]. And thus, the bulk composition of a planet has a significant effect on the interaction of the planetary interior and atmosphere.

However, this interaction is not fully understood yet, and many parameters involved in this interaction are not well constrained. Narrowing this space down will benefit future attempts at investigating this interaction. Since composition has a significant effect on the coupled interior-atmosphere system, it is important to constrain this part of the parameter space. No model has been published so far of bulk planet composition as a function of host star composition and distance from the star. Therefore, our aim is to present a model that allows us to constrain the possible range of bulk compositions that terrestrial planets can possess, based on host star compositions.

2 Constraining bulk composition

It is not possible to directly observe the composition of an exoplanet, but we are able to determine the elemental abundances in host stars, published in catalogs such as [2]. Most authors assume that the elemental abundances of a terrestrial planet agree well with those of its host star, which only holds for the more refractory elements [1]. The abundances of elements with lower condensation temperatures are smaller than in the host star, meaning that a devolatilization has occurred.

To compensate for this volatility-based element fractionation between a terrestrial planet and its host star, we will use a model created by [1]. This model applies devolatilization trends to stellar elemental abundances, which results in the composition of a hypothetical rocky planet. We apply this model to a large catalog of stellar abundances to create a dataset describing the range of bulk compositions of terrestrial planets. For this purpose, we use data from the TESS habitable zone star catalog [2], which contains stellar abundance data on 1822 stars that host at least one planet that receives Earth-like irradiation.

The work from [1] uses condensation temperature data from [5], which is a widely used reference for this purpose. We wish to update this data in the devolatilization model based on the work of [6], who present corrections on the data from [5].

3 Galactic Chemical Evolution

Planetary bulk compositions are subject to a trend of compositional changes with the planets' time of formation. From galactic chemical evolution, we know that the average metallicity in the Universe increases over time, and that stellar Fe/Mg increases and Mg/Si decreases over time. Furthermore, the relative abundance of radioactive material decreases over time, so planets forming later in the lifetime of the universe have a smaller initial radiogenic element abundance [7, 8]. We explore the effects of galactic chemical evolution on bulk planet compositions, to attain a more complete overview of possible compositions. Afterwards, we explore the first-order effects of the range of bulk compositions on the long-term evolution of the atmosphere-interior system with our atmosphere-interior system model (Spaargaren et al., in prep).

4 Future Work

Thus far, our work has focused on constraining the bulk composition of the entire planet. However, core-mantle differentiation redistributes this bulk composition in two reservoirs. To accurately model the properties of planetary interiors, a good understanding of metal-silicate and silicate-silicate partitioning during core formation and magma ocean crystallisation is required. We will consider element fractionation during metal-silicate partitioning by distributing available oxygen to elements in decreasing order of litophility. For silicate-silicate partitioning, we will employ magma ocean crystallisation models which consider fractionation of elements by their incompatibility with the solid phase. We will explore the likelihood of stable mantle stratification, which we found in our previous work (Spaargaren et al., in prep), for the compositional models found in this work.

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