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Thermal evolution of rocky exoplanets covered with graphite

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Abstract

Laboratory and computational studies discussing the mineralogy of fully differentiated carbon-enriched rocky exoplanets have indicated the presence of a graphite outer shell. We evaluate to first order the effects of a graphite outer shell on the thermal evolution of rocky exoplanets containing a metallic core and a silicate mantle. We apply a parameterized model of mantle convection to determine the thermal evolution of Mars-size rocky exoplanets with a graphite outer shell. Our results show that, due to graphite's high thermal conductivity, conduction is the dominant heat transport mechanism in graphite shells. We find that a graphite outer shell behaves like a stagnant lid essentially slowing down planetary cooling due to thermal inertia (dominant only in the earliest stages), thermal resistance and a lower temperature contrast at the top of the silicate mantle due to a third layer (collectively, thermal shielding).

1. Introduction

Studies modeling the mineral condensation chemistry in protoplanetary disks of high C/O ratio stars have discussed the existence of carbon-enriched rocky exoplanets [1, 2]. Laboratory experiments and interior structure modeling have shown that these exoplanets are comprised of a graphite outer shell because of 40% lower density of graphite than common mantle silicates [3]. Graphite has other peculiar properties such as extremely high melting temperature (4000 K), metal-like heat capacity and about an order of magnitude higher thermal conductivity than mantle silicates. Consequently, a planet with a graphite outer shell is likely to have a direct impact on planetary cooling, interior and surface dynamics as well as surface habitability. Here we address to first order the impact of graphite on the thermal evolution of rocky exoplanets with an iron core, a silicate mantle and a graphite outer shell.

2. Methods

We implement a one-dimensional parameterized thermal evolution model to the main layered reservoirs in carbon-enriched rocky exoplanets. The temperature of each layer is described by an equation for the conservation of thermal energy [5]. For the graphite outer shell, as we find that convection is not important for long-term evolution, we implement another equation for the conservation of thermal energy describing time-dependent conductive heat transport [5].

3. Results

Our calculations for Mars-size planets with an iron core and a graphite shell show that the duration of convective cooling (the time for the Nusselt number to reach unity) is between $3-200$ Myr depending on the thickness of the shell (Fig. 1). This result is in contrast to the planets with an iron core and a silicate shell where the duration of convective cooling ($0.04-2.7$ Gyr) is more than an order of magnitude higher. Consequently, for modeling three-layer planets with an iron core, a silicate mantle and a graphite outer shell, we assume conduction to be the heat transport mechanism in the graphite shell.

For three-layer planets, we find that the graphite shell behaves like a stagnant lid essentially slowing down planetary cooling which is mainly due to thermal inertia (dominant only in the earliest stages), thermal resistance [4], and a lower temperature contrast at the top of the silicate mantle due to a third layer (collectively, thermal shielding). For planets with thin graphite shells (<500 km), the thermal shielding ef-

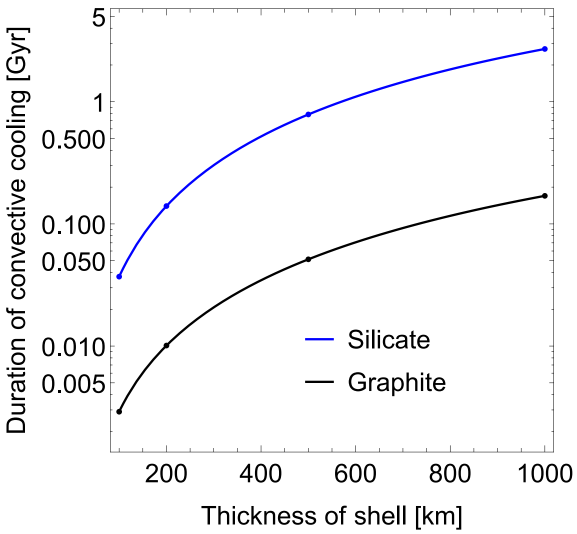

Figure 1: Comparison of the convective cooling duration of graphite and silicate shells for planets with a core radius of 1500 km and a shell thickness of 100−1000 km.

fect is small. Our models for Mars-size planets and Kepler-37b (Mercury-size) with graphite outer shells with thicknesses >500 km show that the cooling of the interior is delayed by up to several billion years (Fig. 2). For Earth-size and super-Earth-size planets, graphite shells cannot be thicker than 500 km before transforming into diamond and result in a small thermal shielding effect.

4. Conclusions

- Because of an order of magnitude higher thermal conductivity of graphite than silicates, conduction is the heat transport mechanism in graphite shells of carbon-enriched rocky exoplanets for all but the earliest stages of evolution.
- A graphite outer shell thermally shields the planetary interior essentially acting as a stagnant lid.
- The thermal shielding effect is small for thin graphite shells (<500 km) but can delay the cooling by billions of years for thick graphite shells (>500 km).
- Planetary thermal structure and its evolution depend on the mineralogy of different layers in the planet.
- Along with advancements in the characterization of rocky exoplanets using data from future telescopes, the understanding of their interior and surface dynamics also needs to advance with the help of theoretical studies such as this one.

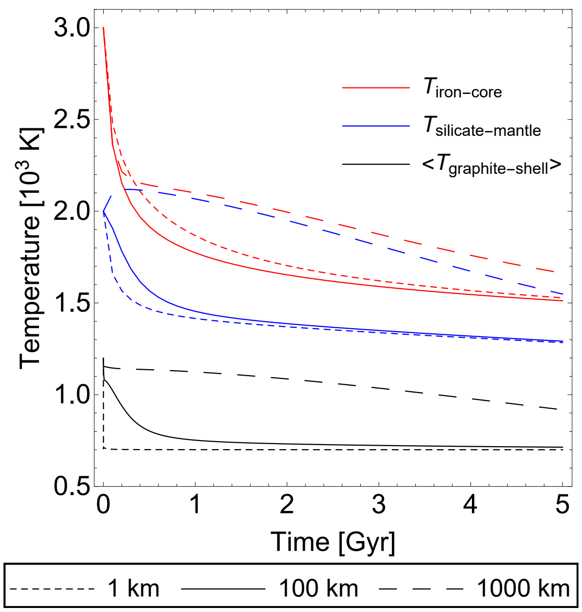

Figure 2: The evolution of temperature of three layers for planets with core and mantle radii of 1500 km and 3000 km, respectively and thicknesses of graphite shells of 1 km (reference case), 100 km and 1000 km.

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