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Diving Deep into Rocky Exoplanets
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Summary

DIVING DEEP INTO ROCKY EXOPLANETS

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In the third century BC, the Greek philosopher Epicurus scribed an almost prophetic statement in his letter to his disciple, Herodotus: "There is an infinite number of worlds, some like this world, others unlike it". About four thousand planets outside our solar system (exoplanets) have been discovered in the past 25 years and tens of thousands or more are likely to be discovered in the next 25 years. A large fraction of these exoplanets are likely to have a solid or rocky surface, similar to the inner solar system planets; Mercury, Venus, Earth, and Mars. Astronomical observations indicate that rocky exoplanets are much more diverse in their physics and chemistry than the planets of our solar system. For individual rocky exoplanets, however, the only information available at the moment is their mass and/or radius and there is no direct way to study their interiors. Nevertheless, it is possible to characterize them in a general sense. Some of the most intriguing questions are: What is the composition and structure of these diverse rocky exoplanets? What are their surfaces like? Can they sustain life?

Planets born orbiting their host stars are byproducts of the birth of the star itself. The formation of rocky planets takes place in the protoplanetary disk, a circumstellar nebula made of gas and solids (in the form of dust grains). These dust grains eventually become part of rocky planets as a result of accretion processes. The chemical composition of dust grains varies both with the distance from the newly-born star and with time. This chemical composition is strongly controlled by the relative abundances of major rock-forming elements such as magnesium, silicon and iron as well as carbon and oxygen. The bulk composition of a rocky planet depends on the chemical compositions of dust grains that acquired during formation.

Because the interiors of rocky planets are under immense pressures and temperatures, these dust grains undergo chemical reactions to produce a set of minerals in equilibrium. Due to gravity and the high temperatures associated with planetary accretion processes, the planets differentiate: denser minerals sink to the center of the planet and lighter minerals rise to the surface. This process leads to a stratified structure inside the planet. For a planet such as Earth or Mars, the inner layer is made of iron-rich metal and is called the core, and the outer layer comprises silicates and is called the mantle.

The heat acquired by a planet during its formation and produced during the natural decay of radioactive elements in its interior is slowly released during its evolution. Due to this internal heating, planetary interiors can remain dynamic for billions of years. The rate of cooling of a planet depends on the physical and chemical properties of its different layers which determine the style and vigor of heat transport to the surface. The mantle can behave like a fluid over geological timescales. This leads to motion of material and transfer of heat resulting in convection, which is similar to the motion of water in a boiling pot (but extremely slow, at rates of centimeters per year). The material not taking part in convection transfers heat via conduction, which is the reason why the tail of a metallic spoon in the boiling pot becomes hot even though only the head is dipped.

Geosciences for exoplanets

In this thesis, I study the mineralogy, structure and evolution of chemically diverse rocky exoplanets using the tools mentioned below.

The deepest man-made hole on Earth reaches only 12 km below its surface, while the diameter of Earth is 12 742 km. Nonetheless, geoscientists still manage to study the Earth's interior using different tools from geophysics and geochemistry. Similarly, it is possible to study the interiors of rocky exoplanets using some of these tools. The high-pressure high-temperature conditions of planetary interiors can be reproduced in a high-pressure device using synthetic chemical powders to simulate interior bulk composition. Such experiments tell us about the minerals that form in the interiors of rocky exoplanets (Chapters 3 and 4). To describe the properties of these minerals we use the equation of state, which describe show the density of a mineral changes with pressure and temperature. The equation of state can either be measured directly from experiments or derived from the principles of quantum mechanics like we do in Chapter 2. With the information about mineral properties and physical laws, the stratified interior structure of rocky exoplanets is computed (Chapters 2, 3 and 5). For a generalized study of rocky exoplanets, theoretical mass-radius relations are also computed from the interior structure calculations (Chapter 2). The heat transport and thermal evolution in a rocky exoplanet are calculated using Rayleigh-Bénard convection (Chapter 5).

Mineralogy

Studies modeling the chemical evolution of protoplanetary disks have found that the car-bon content in some rocky exoplanets can be up to 50% of the planet mass (Earth contains less than 0.01%). But the phase(s) in which this carbon is present are not known. We per-formed piston-cylinder experiments on chemical mixtures representative of carbon-enriched rocky exoplanets, exposing them to 1–2 GPa (10 000 times the atmospheric pressure) and 1523–1823 K, high enough to start melting rocks (Chapter 3). Our results show that these exoplanets, when fully differentiated (stratified), consists of a metallic core, a silicate mantle, and a graphite layer on top of the silicate mantle. Graphite (or diamond at higher pressures) is the dominant carbon-bearing phase in these exoplanets. The silicate mineralogy is similar to that in carbon-poor planets such as the Earth, and Mg/Si, Al/Si, Ca/Si ratios and oxygen fugacity (which essentially gives the oxygen content) determine the silicate phases and their compositions. Iron-rich metals show immiscibility (implying that there would be a two-layer core or a one-layer core) depending on the ratio of sulfur to iron and the core pressure. Our results show that if a rocky exoplanet contains more carbon than on the order of one percent, graphite forms as a separate phase. Since the surface of these exoplanets may lack essential elements for life other than carbon such as oxygen, nitrogen, hydrogen and others, these exoplanets might be inhospitable for life.

Silicon carbide, another carbon-bearing phase discussed in several astronomical studies about carbon-enriched rocky exoplanets, which was present in the initial chemical mixture, disappeared by the end of our experiments. To understand the reason behind the vanishing of silicon carbide, we performed an experiment by reacting a silicon carbide layer with a layer representative of carbon-enriched rocky exoplanets (Chapter 4). Our experiment captures a reaction leading to the oxidation of silicon carbide in an exoplanetary interior. We show that, in order to stabilize silicon carbide in a planetary interior, all of the oxidized iron (Fe^{2+} and Fe^{3+}) should be reduced to Fe^0, suggesting future spectroscopic detection of Fe^{2+} or Fe^{3+} on the surface of rocky exoplanets may imply the absence of silicon carbide in the interior.

Structure

For the calculation of the interior structure of massive rocky exoplanets, equations of state of iron, the major constituent of the core, have been historically extrapolated to pressures more than an order of magnitude beyond their range of validity. In Chapter 2, we compute a new ab initio equation of state of solid iron up to pressures more than two orders of magnitude higher than the pressures reproducible in laboratories. The comparison of our equation of state with other equations shows that extrapolations lead to errors in the density of iron of up to 20% at a pressure of 10 TPa. This suggests that the implementation of extrapolated equations of state lead to a discrepancy of up to 20% in the masses of the most massive rocky exoplanets.

With the help of interior structure calculations, we quantify the effect of extreme core and mantle compositions and of the thermal profile on the mass-radius relations of massive rocky exoplanets (Chapter 2). Our results show that core and mantle compositions are capable of affecting the derived mass by up to 50%, whereas the temperature has a small effect of only a few percent. Our application to Kepler-36b shows that its maximum core radius is 64% of the total radius.

We also perform interior structure calculations for rocky exoplanets with an iron-rich core, a silicate mantle and a graphite outer shell (Chapter 3). Our application to Kepler-37b, a planet with a known radius but unknown mass, shows that a model with 10% graphite has 7% less mass than the model with no graphite. This implies that the presence of graphite, due to its low density, can have a significant effect on the mass of the planet.

Evolution

Our experiments showed that it is possible for rocky exoplanets to consist of an iron-rich core, a silicate mantle, and a graphite outer shell (Chapter 3). But the thermal evolution of such planets is unknown. We apply a parameterized model of mantle convection to determine the heat transport in the graphite shell and the thermal evolution of these exoplanets (Chapter 5). We find that conduction is the dominant heat transport mechanism in graphite shells. Our results show that the outer graphite shell produces a thermal shielding effect which reduces the cooling rate of the planetary interior. This thermal shielding effect becomes significant for the long-term evolution of planets with a graphite outer shell thickness larger than 500 km. Our application to a known exoplanet, Kepler-37b, assuming that it is covered by a graphite shell, shows that the thermal shielding effect dominates over the effect of reduced internal heating. Plate tectonics and the presence of water on these exoplanets may increase the potential for habitability, especially for exoplanets with thin graphite shells.

The work presented in this thesis represents an effort to characterize rocky exoplanetary interiors by implementing laboratory and computational tools from geosciences. In my view, this is a first step towards establishing exogeoscience as a distinct discipline.