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Unveiling the characteristics of a potential super-Mercury exoplanet family

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Abstract

The growing number of terrestrial-sized exoplanet discoveries sheds light on an emerging category of bodies: high-density planets. A feature recalling Mercury in the solar system, which presents several unique properties among terrestrial planets. To investigate how far the similarities extend between Mercury and these potential super-Mercuries, we perform a study of their possible interiors. We use an Earth-based model updated in regard to the latest outcomes on Mercury's bulk and layer compositions, and improved to follow correct extrapolation in the super-Earth domain. As Mercury, several considered exoplanets show a compositional deviation relative to their host star. We then extend our study to other characteristics such as orbital parameters, to provide a global picture of this exoplanet family. Super-Mercuries have the potential to improve our understanding of Mercury's uniqueness, and consequently of planetary formation.

1. The peculiar case of Mercury

The first hint on Mercury's peculiar situation among solar system terrestrial planets came from the knowledge of its mass and radius only. Its high derived bulk density, relative to its size, led early studies to suggest that the whole planet was enriched in dense materials, mostly iron. Over the years, numerous additional features strengthened the uniqueness of Mercury in the solar system [4]. These discoveries kept challenging theories of the planet's formation, an event that remains puzzling as of today. In the past few years, ongoing characterization of exoplanets –most of them discovered by the *Kepler* mission– has revealed the existence of outer worlds with particularly high bulk densities, echoing the early studies of Mercury. Due to current observational biases, these exoplanets are larger and more massive than the terrestrial planets in our solar system, hence the name "super-Mercuries".

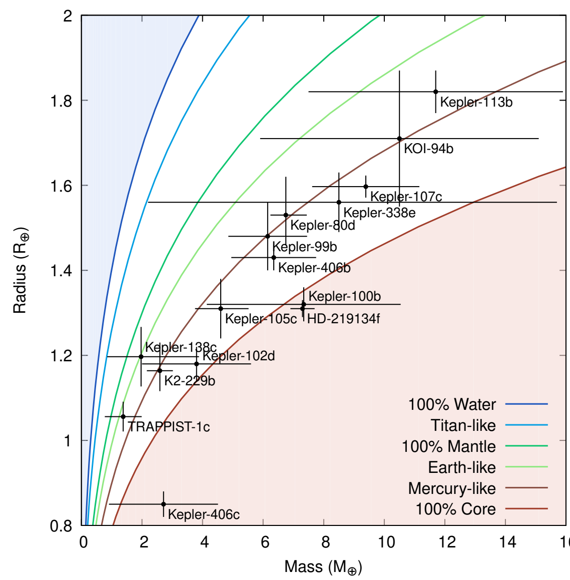

Figure 1: Locations of potential super-Mercuries in the mass-radius diagram. Compositional curves are computed using the model from [1, 2] with updated equations of state (see text).

We select fifteen potential super-Mercuries from the NASA Exoplanet Archive database. Their measured fundamental parameters are all compatible with a simplified Mercury-like internal structure (i.e., a rocky planet with a 70% core mass fraction; see Fig. 1). The selected set spans large ranges in both mass and radius, and the latter correctly matches the subset of *Kepler* exoplanets interpreted as rocky bodies, with an upper radius limit around 1.6–1.8 $R_\oplus$ [3]. In addition to their high bulk densities, this feature supports the assumption that these potential super-Mercuries do not possess significant budgets of volatile materials, i.e. large H-He atmospheres or water envelopes.

So far, only a few of these fifteen planets have been studied, separately, using different interior models solely based on Earth-like compositions. We aim at performing an extensive and consistent investigation of their possible interiors, taking into account state-of-the-art modeling of Mercury's bulk and layer compositions, in order to derive a global interpretation of this potential new exoplanet family.

2. Adapting interior models

A recently inferred key feature of Mercury is its formation in a chemically reducing environment. Such conditions impact the behavior of specific materials, especially during the planet's differentiation. As such, Mercury is thought to have different core and mantle compositions than the Earth's. For instance, iron and silicon become siderophile under reducing conditions, and thus migrate more easily to the core of the planet. We update the Earth-based interior model developed by [1] with finer descriptions of both the core and the mantle, to be able to account for these compositional differences. This updated model is calibrated in a study of Mercury's interior using the latest MESSENGER and laboratory results [2].

Yet, by applying this model to planets more massive than the Earth, we raise the issue of extrapolating equations of state that are limited in pressure, because calibrated on laboratory experiments. This is the main source of uncertainty in interior modeling of super-Earths, and is thus also relevant for super-Mercuries. Therefore, we perform a review study of available equations of state for core- and mantle-forming materials. We find a formulation that meets theory predictions in the high-pressure regime, unlike commonly used formulations, while requiring the same thermodynamic parameters derived from experiments.

3. Properties of a new family

In correlation with its high bulk density, Mercury shows a strong deviation from the chondritic composition, unlike the remaining terrestrial solar system planets. The relative abundances of refractory materials in chondrites are similar to the solar values. Therefore, models of terrestrial interiors commonly use stellar abundances as proxies for planetary composition. The validity of this assumption is strongly questioned in the case of potential exo-Mercury worlds, as was shown for K2-229b [5]. We compute the probability that each of the fifteen selected super-Mercuries shows a compositional discrepancy to its host star. When stellar abundances are unknown, we use a distribution of values representative of stars who host Earth- to super-Earth-sized exoplanets among the *Kepler* sample. We show that several of these potential super-Mercuries indeed present a deviation from the stellar abundances.

Secondly, we review orbital and system properties of exoplanets in our set. We look for features that could be specific to super-Mercuries, and that could help identify members of this family in the future. We also study the habitability potential of super-Mercuries compared to super-Earths. Because of their different core compositions, the latter are less likely to have a liquid shell in this layer, and thus to generate their own magnetic field. Finally, we discuss the relevance of the different formation scenarios invoked for Mercury, in light of these exoplanet discoveries, as each planet in our set is a potential new test case. One mechanism able to account for the variety of bodies observed here would provide constraints for the formation of Mercury itself. On the other hand, this variety might require different formation mechanisms working at different scales.

As more terrestrial exoplanets are discovered, the properties of the super-Mercury family will keep on being refined, and its diversity will be revealed. Our study shows one more time the importance of measuring stellar abundances for the study of terrestrial exoplanets. Super-Mercuries have the potential of improving our understanding of the link between stellar and planetary composition, and thus of terrestrial planet formation.

Acknowledgements

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