New Thermodynamic Constraints on Internal, Thermal, and Magnetic States of Super-Earths

M. Zaghoo

Laboratory for Laser Energetics, University of Rochester

The discovery of exoplanetary systems orbiting host stars has revolutionized planetary astronomy. As we begin to understand the diversity of these planets' architectures across a wide range of planet–star separation, we rely on transit-based methods to characterize their masses, radii, albedo, and soon, atmospheres. Ascertaining planetary structure, evolution, and habitability require, however, a better understanding of key internal geophysical and geochemical processes that drive the planetary geochemical differentiation, internal composition, core sizes, and heat budgets, all of which depend on the behavior of planetary constituent materials, particularly silicates and iron, at extreme conditions.

In the past few years, advances in high-pressure physics experiments, particularly those employing ramp-dynamic compression tools, have addressed this challenge.[1] The experiments provided precise data on the compressibility of iron, its Grüneisen parameter,[2,3] and the solidus line of $MgSiO_3$ (Ref. 4) as well as its conductive behavior at conditions comparable to 4 to 5 M_E (Ref. 5). Additionally, recent static high-pressure experiments revealed that liquid iron's thermal conductivity at conditions corresponding to Earth's core mantle boundary (CMB) is substantially higher than values previously used in the geophysics literature.[6,7]

In this work, we derive new thermodynamic data using recent experimental results on both iron and silicates to better model the internal states for super-Earth (SE) planets ranging from 1 to 10 M_E (see Fig. 1). We combine the state-of-the-art equation of state and melting experimental data with parametric thermal evolution models to obtain new pressure, density, and temperature radial profiles of these planets. We reveal that for planets more massive than 3 M_E, a thick layer of deep magma oceans surrounding solid iron cores will develop. We present new theoretical data on the thermal conductivity of SE's iron cores at extreme conditions, based on the revised estimates for Earth's values, and carefully assess the power requirements required to maintain the convective state of these cores. We show that the drastic rise in the conductive losses along the CMB will dominate the heat

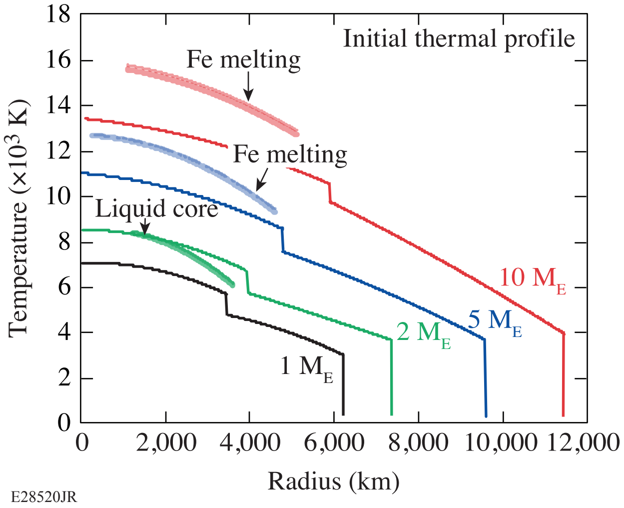

Figure 1
Radial thermal structure profiles of rocky SE planets ranging from 1 to 10 M_E calculated within the thermal boundary layer model. Also shown are the pure-Fe liquidus lines. The shaded area represents the reduction in the melting line caused by added impurities. The intersection of the thermal profile with the liquidus denotes the onset of iron crystallization, the inner core boundary. For planets 4 to 10 M_E, the liquidus does not cross the planetary thermal profile, meaning that these planets will likely lack an iron fluid core.

flux in the more-massive planets, driving their cores into a sub-adiabatic and non-convective state. Absent substantial intrinsic heat sources, the cessation of convection will consequently shut down the dynamo action in their cores. Our results lend support to the recently proposed concept of "super habitability," employed to describe terrestrial-like planets with enhanced characteristics amenable to their habitability.[8] We have shown that it most likely extends up to only ~4 M_E; beyond which, a new paradigm that describes the suitability of carbon-based life forms on more-massive rocky planets might be needed.

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1. T. Duffy, N. Madhusudhan, and K. K. M. Lee, in *Treatise on Geophysics*, 2nd ed., edited by C. Schubert (Elsevier, Oxford, 2015), Vol. 2.
2. R. F. Smith *et al*., Nat. Astron. **2**, 452 (2018).
3. J. K. Wicks *et al*., Sci. Adv. **4**, eaao5864 (2018).
4. D. E. Fratanduono *et al*., Phys. Rev. B **97**, 214105 (2018).
5. R. M. Bolis *et al*., Geophys. Res. Lett. **43**, 9475 (2016).
6. H. Gomi *et al*., Phys. Earth Planet. Inter. **224**, 88 (2013).
7. K. Ohta *et al*., Nature **534**, 95 (2016).
8. R. Heller and J. A. Armstrong, Astrobiology **14**, 50 (2014).