Energetic Requirements for Dynamos in the Metallic Cores of Super-Earth and Super-Venus Exoplanets

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Abstract

Super-Earth and super-Venus exoplanets may have similar bulk compositions, but their surface conditions and mantle dynamics are vastly different. Vigorous convection within their metallic cores may produce dynamos and thus magnetospheres if the total heat flow out of the core exceeds a critical value. Earth has a core-hosted dynamo because plate tectonics cools the core relatively rapidly. In contrast, Venus has no dynamo and its deep interior probably cools slowly, potentially due to a lack of plate tectonics. It is not fully known how or if magnetic fields affect habitability, but the size of a magnetosphere might indirectly constrain the habitability of a surface. In this study, we developed scaling laws for how planetary mass affects the minimum heat flows required to sustain both thermal and chemical convection, which we compared to a simple model for the actual heat flow of both super-Earth and super-Venus exoplanets conveyed by solid-state mantle convection. We calculated three critical thresholds for heat flow based on varying the size of an inner core, the rate at which light elements precipitate at the core-mantle boundary, and the thermal conductivity of the core. We found that the required heat flows increase with planetary mass (to a power of ˜0.8–0.9), but the actual heat flows of both super-Earths and super-Venuses could increase even faster (to a power of ˜1.6) (Figure 1). Massive super-Earths are likely to host a dynamo in their metallic cores if their silicate mantles are entirely solid. Super-Venuses with relatively slow mantle convection could host a dynamo if their mass exceeds ˜1.5 (with an inner core) or ˜4 (without an inner core) Earth-masses. However, the mantles of massive rocky exoplanets might not be completely solid. Basal magma oceans may reduce the heat flow across the core-mantle boundary and smother any core-hosted dynamo. Detecting a magnetosphere at an Earth-mass planet probably signals Earth-like geodynamics. In contrast, magnetic fields may not reliably reveal if a massive exoplanet is a super-Earth or a super-Venus. We eagerly await direct observations in the next few decades. Published in JGR, doi:10.1029/2020JE006739

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Are Massive Exoplanets More Likely to Have Magnetic Fields?

- Super-Earth and Super-Venus exoplanets are defined as planets with Earth (Venus)-like densities, but their masses scale from 1-10 Earth-masses.
- Convection in a metallic core can produce a magnetic field [e.g.,1-6].
- Detecting a magnetic field might help us constrain models of mantle dynamics.
- Any detection of a magnetic field could help us learn more about the habitability of the planet's surface [2].

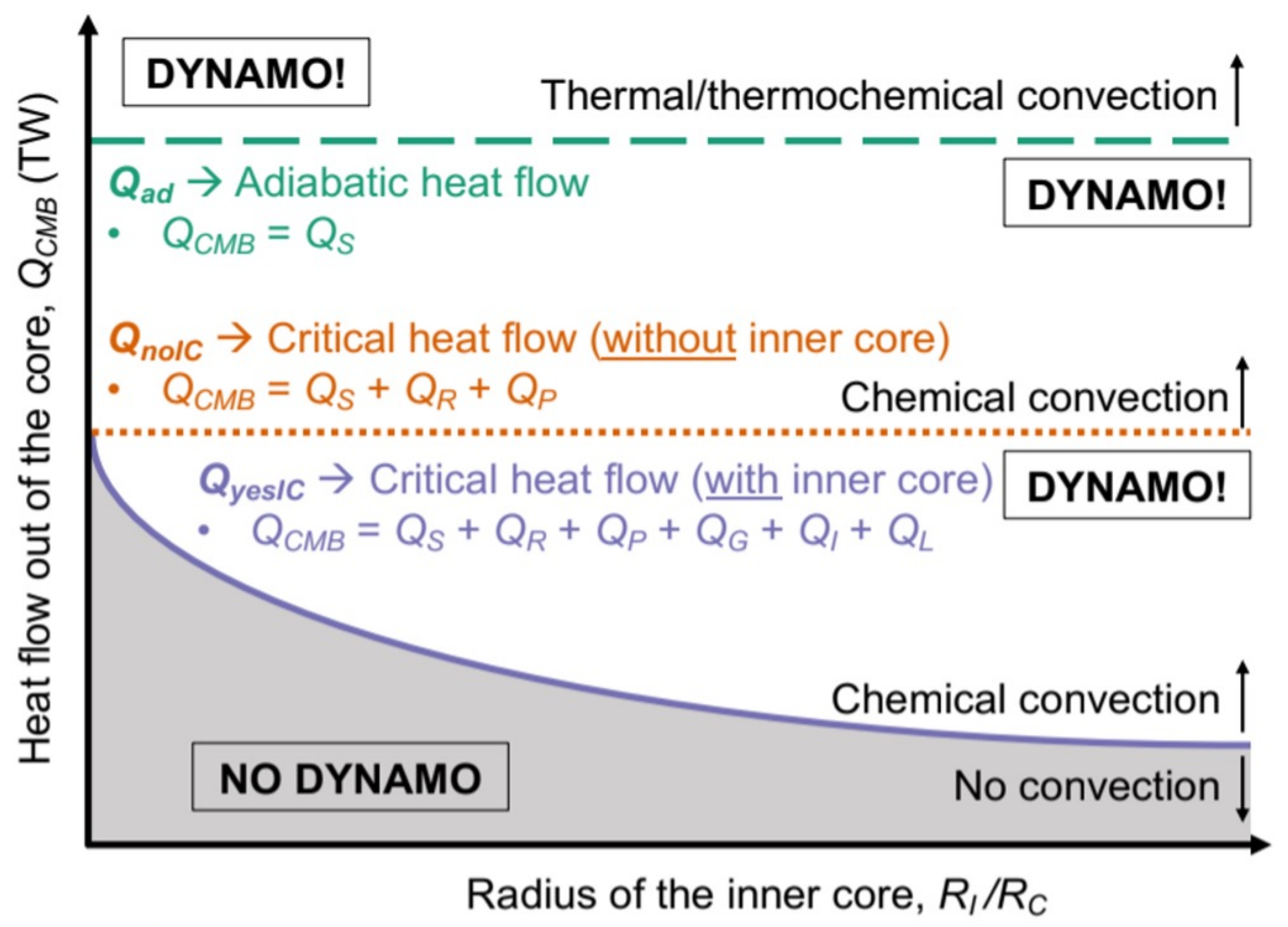
What Do We Know About Earth and Venus?

- **Earth** has plate tectonics and a core-hosted dynamo. The heat flow out of the core may be super- or sub-adiabatic.
- **Venus** has no plate tectonics, and no dynamo due to a low total heat flow relative to Earth, or a different core composition/structure

Earth has a magnetic field
Credit: Discover Magazine

Venus does not
Credit: NASA/JPL-Caltech

Scaling Law #1 – Required Heat Flow

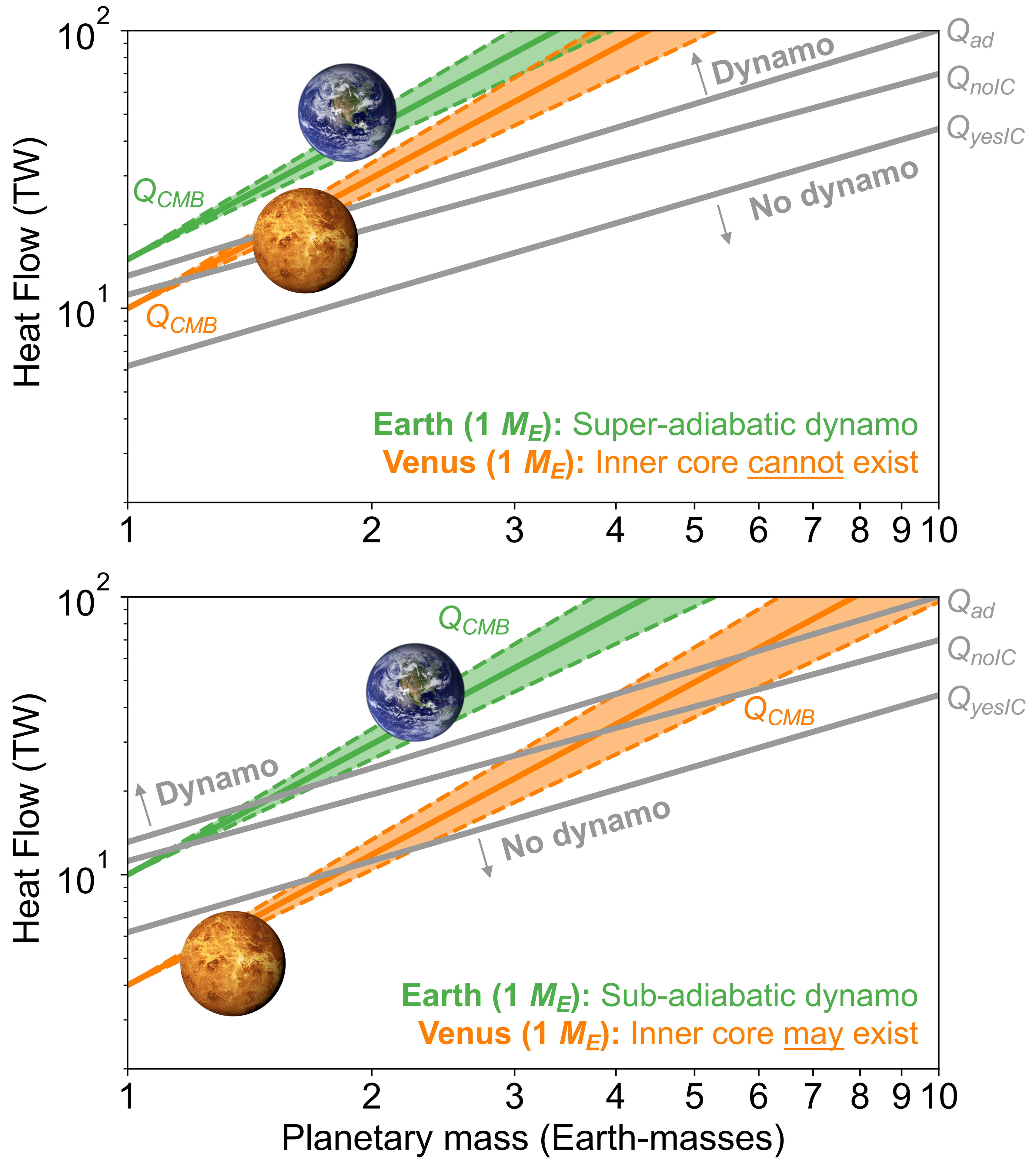


- We calculated **3 possible threshold values** of the total heat flow required to drive convection depending on available sources [3,4].

Q_S = Secular cooling of the outer core
Q_R = Radiogenic heating in the outer core
Q_P = Chemical precipitation at the core-mantle boundary
Q_G = Gravitational energy driven from convection below
Q_I = Heat flux associated with cooling at inner core boundary
Q_L = Latent heat associated with freezing of inner core

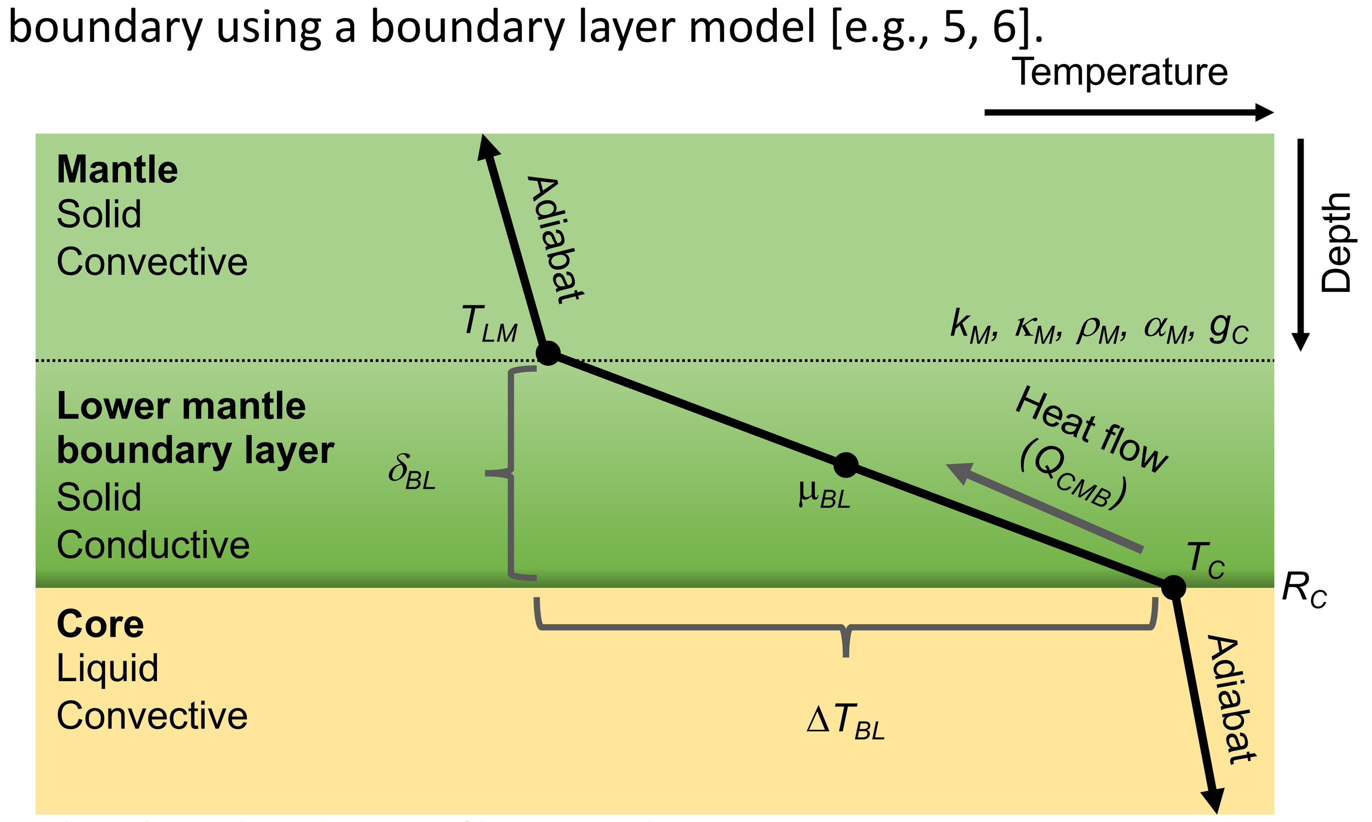
Q_{CMB} is the heat flow across the core-mantle boundary.
  - Dependent on the thermal conductivity of the mantle, **not** the thermal conductivity of the core!

Results: Required vs. Actual Heat Flow Across the CMB



Scaling Law #2 – Actual Heat Flow

- We estimated the actual heat flow across the core-mantle boundary using a boundary layer model [e.g., 5, 6].



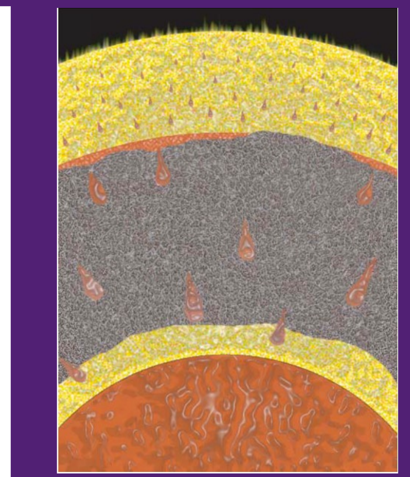
k_M = thermal conductivity of lower mantle
κ_M = thermal diffusivity
α_M = coefficient of thermal expansion
ρ_M = density
g_C = gravitational acceleration at CMB
R_C = radius of the core
T_{LM} = temperature of lower mantle
δ_{BL} = thickness of boundary layer
μ_{BL} = average viscosity
ΔT_{BL} = thermal contrast across mantle base
T_C = temperature at CMB

Yes! Massive Exoplanets are More Likely to Have Magnetic Fields.

- The **actual heat flow** out of the metallic cores of exoplanets may **increase faster** with planetary mass than the values required for a dynamo.
- Super-Earth exoplanets may have ubiquitous magnetospheres—even without inner cores.
- Super-Venus exoplanets may also host dynamos in their cores if they are sufficiently massive—even without plate tectonics.
- Overall, magnetic fields may not provide a unique test for plate tectonics at massive exoplanets.

Future Work

- Determine if basal magma oceans can host dynamos in massive exoplanets and their effects on cores
- Test a wider range of assumptions about mantle dynamics and the composition of the core
- Further out: Detect magnetic fields in exoplanets to constrain models



Credit: Labrosse et al. 2007

Credit: ESA

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