ENERGETIC REQUIREMENTS FOR DYNAMOS IN THE METALLIC CORES OF SUPER-EARTH AND SUPER-VENUS EXOPLANETS.

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Introduction: Super-Earths are massive exoplanets with Earth-like bulk compositions but surfaces that could be habitable like Earth or hellish like Venus [1]. Observationally, planets with radii larger than ~1.5 Earth-radii (~5 Earth-masses, M_E) are mostly "mini-Neptunes" with thick volatile envelopes, although some very massive super-Earths (up to ~10 M_E) probably exist. Magnetic fields could potentially reveal whether a super-Earth is truly an Earth-analogue. Having a magnetic field can protect a planet's surface from the solar wind as well as increase the longevity of the atmosphere [2,3]. Moreover, the presence of a magnetosphere reveals that a planet's deep interior is cooling quickly enough to sustain a dynamo. On Earth, plate tectonics helps sustain habitability [4] and also rapidly removes heat from the core, driving vigorous convection. It is probably not a coincidence that Venus lacks both plate tectonics and a dynamo [5]. Detections of magnetic fields from super-Earths may happen in the next few decades. Would such a detection also serve as a clear signal of plate tectonics on an alien world?

In this study, we build new models for thermal and chemical convection in the metallic cores of super-Earths. A dynamo can exist if the overlying silicate mantle cools fast enough to provoke a heat flow across the core-mantle boundary (CMB) that exceeds a critical value [6]. Driving a dynamo with thermal convection alone requires a relatively large heat flow. Chemical buoyancy can vastly reduce the critical heat flow. We assume that Earth- and Venus-analogues have metallic cores with the same bulk compositions—the only difference between the two here is that the cores of true super-Earths cool relatively rapidly.

Previous studies are divided about whether the likelihood of a dynamo increases with planetary mass. One paper [7] argued that inner cores would not form in planets with masses >2–3 M_E, leading to short-lived (or entirely absent) dynamos. Super-Earths could still produce dynamos via thermal convection if mantle convection is quite efficient [8]. Moreover, recent mineral physics data on the liquidus and adiabat of iron alloys at extreme conditions actually supports the formation of inner cores within super-Earths [9]. All in all, the existing literature could be read to support the idea that, like Earth and Venus in our Solar System, convection that produces a dynamo is expected for massive Earth-analogues but doubtful if not impossible for super-Venus exoplanets [10].

Methods: We first created one-dimensional models for the radial structure of metallic cores assuming an Earth-like core mass fraction of 0.325 for planetary masses from 1–10 M_E. We integrated the fundamental equations of planetary structure (mass conservation, hydrostatic equilibrium, and an equation of state) from the center to the CMB. Finally, we fit radial profiles of density to fourth-order polynomials that are amenable to integration over the volume of the outer core [11].

Energetic Criteria for a Dynamo. The energy budget for the core is roughly $Q_{CMB} = Q_S + Q_R + Q_P + Q_G + Q_L$, where Q_{CMB} is the heat flow across the CMB, Q_S represents secular cooling, and Q_R is radiogenic heating. Precipitation of light elements at the CMB releases gravitational energy (Q_P), while crystallization of the inner core produces both latent heat (Q_L) and more gravitational energy (Q_G). Given a specified Q_{CMB}, we can analytically solve for each term in the heat budget, plus the rate of temperature change and, if applicable, inner core growth. We use the entropy budget for the core to calculate the total dissipation available (Φ)—a dynamo may exist if Φ > 0 W. We calculate three types of critical thresholds for Q_{CMB} (Figure 1):

1. Q_{ad} — Adiabatic heat flow in the core, the minimum value for thermal convection without radiogenic heating or any chemical buoyancy.

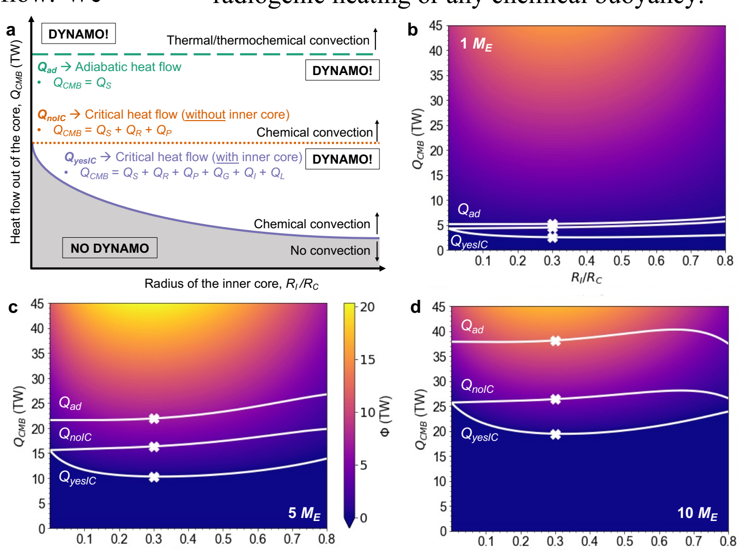

Figure 1. Regime diagram for dynamos in metallic cores. The heat flow required for convection increases with planetary mass.

2. Q_{noIC} — Critical heat flow for thermochemical convection before the inner core nucleates (i.e., including radiogenic heating and precipitation).
3. Q_{yesIC} — Critical heat flow with an inner core.

By definition, $Q_{ad} \geq Q_{noIC} \geq Q_{yesIC}$ always. We consider inner core radii (R_I) from 0 km to 80% of the total core radius (R_C)—values at $R_I = 0.3R_C$ are representative.

Scaling Laws. We used power laws to describe how Q_{CMB}, Q_{ad}, Q_{noIC}, and Q_{yesIC} vary with planetary mass:

$$Q(M_P) = Q(M_E)\left[\frac{M_P}{M_E}\right]^{\Gamma}, \qquad (1)$$

where M_P is the planetary mass and Γ is a best-fit exponent. We used a boundary layer model for Q_{CMB}:

$$Q_{CMB} = 4\pi R_C^2 k_M \left(\frac{\rho_M \alpha_M g}{\kappa_M Ra_c}\right)^{\frac{1}{3}} \mu_{BL}^{-\frac{1}{3}} \Delta T_{BL}^{\frac{4}{3}}, \qquad (2)$$

where R_C is the radius of the core, g is gravitational acceleration at the CMB, and Ra_c is the critical Rayleigh number. In the lower mantle, we have thermal conductivity (k_M), density (ρ_M), thermal expansion (α_M), and thermal diffusivity (κ_M), along with the average viscosity in (μ_{BL}) and thermal contrast across (ΔT_{BL}) the thermal boundary layer immediately above the CMB. We estimated the individual scaling relationships for these parameters by scouring the existing literature.

Results: As planetary mass increases, the heat flow across the CMB is predicted to increase—but so do the critical values required for convection and a dynamo. We found a best-fit $\Gamma = 1.7$ for Q_{CMB}, compared to $\Gamma \sim 0.75$–0.9 for Q_{ad}, Q_{noIC}, and Q_{yesIC}. We conducted a sensitivity test to explore the importance of three properties of the core: thermal conductivity, abundance of potassium, and the precipitation rate of light elements. We found that these three parameters can dramatically change the absolute values of the critical heat flows at a certain M_E. However, they do not significantly affect the exponent Γ in each power law.

Figure 2 shows how the prospects for a dynamo in massive Earth- and Venus-analogues may change with planetary mass. Crucially, we do not know the exact value of Q_{CMB} for either Earth or Venus or if Venus has an inner core. However, $Q_{CMB} > Q_{yesIC}$ for Earth and $Q_{CMB} < Q_{noIC}$ for Venus by definition. Dynamos seem more likely to exist in the metallic cores of super-Earths. Even if Q_{CMB} is sub-adiabatic in Earth, a ≥ 2 M_E super-Earth could have a dynamo powered by thermal convection alone in the core. Likewise, a ≥ 2 M_E super-Venus could have a core-hosted dynamo if an inner core exists. A ≥ 3 M_E super-Venus might have a dynamo in any case, even in the absence of plate tectonics.

Conclusions: Massive rocky exoplanets may have core-hosted dynamos even if mantle convection operates in a less efficient regime than plate tectonics. While the lack of a dynamo at Venus is a key clue to the Earth-Venus dichotomy, future observations of a magnetic field probably should not be considered a sure sign that a "super-Earth" is a real Earth-analogue.

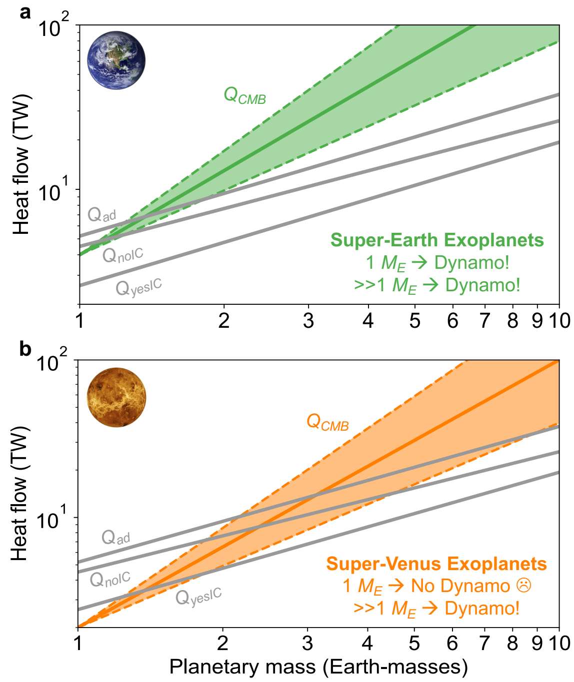

Figure 2. Massive exoplanets are more likely to host dynamos in their metallic cores. We assume that the key distinction between super-Earth (above) and super-Venus (below) exoplanets are the values to which Q_{CMB} is pinned at ~1 M_E.

Future work should go beyond the simplifications used here. Modeling non-Earth-like bulk compositions and core mass fractions (i.e., analogues to Mercury and Mars) is a straightforward next step. More importantly, basal magma oceans (i.e., thick layers of molten silicates) are perhaps ubiquitous in massive rocky exoplanets. They could suppress the heat flow out of the core relative to our predictions, which assumed a solidified mantle. However, convection within the basal magma ocean itself could also produce a dynamo because silicates become electrically conductive under extreme conditions [12]. We must continue the quest to learn what helps or hinders dynamos in rocky planets.

References: [1] Tasker et al. (2017) *Nature Astro.*, *1*, 1–2. [2] Driscoll (2018) *Handbook of Exoplanets,* 1–18. [3] Dong et al. (2020) *ApJ*, *896*, L24. [4] Korenaga (2012) *Annals NY Acad. Sci.*, *1260*, 87–94. [5] Nimmo (2002) *Geology*, 30, 987–990. [6] Stevenson (2003), *EPSL*, *208*, 1–11. [7] Gaidos et al. 92010) *ApJ*, *718*, 596–609. [8] Driscoll & Olson (2011) *Icarus*, *213* 12–23. [9] Boujibar et al. (2020), *JGR:P*, *125*. [10] Van Summeren et al. (2013) *JGR:P*, *118*, 938–951. [11] Labrosse (2015) *PEPI*, *247*, 36–55. [12] Stixrude et al. (2020) *Nature Comm.*, *11*, 935.