VENUS: A THICK BASAL MAGMA OCEAN MAY EXIST TODAY. J. G. O'Rourke, School of Earth and Space Exploration, Arizona State University, Tempe, AZ (jgorourk@asu.edu).

Introduction: Magma oceans were ubiquitous during the formation of rocky planets. Crystallization of the mantle proceeded from the middle outwards because melt is gravitationally stable near both the surface and core/mantle boundary (CMB) [1,2]. Surficial magma oceans solidify within ~100 Myr via rapid cooling to space [3]. However, a basal magma ocean (BMO) can survive for billions of years because cooling through the solid mantle is orders-of-magnitude less efficient.

Earth's putative BMO has received scrutiny because liquid silicates are a reservoir of incompatible elements. A long-lived BMO in Earth could explain differences in $^{142}Nd/^{144}Nd$ ratios between terrestrial rocks and chondritic meteorites and solve the so-called "missing heat source" problem [1]. Primordial iron-rich melt and compositional anomalies in the basal mantle are possibly the last residua of an ancient BMO.

Models that feature a terrestrial BMO predict suppressed cooling of the core and a delayed start for the geodynamo. Because the BMO has low viscosity, the BMO and uppermost core should have the same temperature and must cool in tandem. Latent and radiogenic heat in the BMO buffers its cooling rate. In models with a well-mixed BMO [1], Earth's core would not convect and drive a dynamo until ~3.4–4 Gyr ago.

Why would Earth but not Venus have a BMO? These two planets have nearly identical sizes and bulk densities that reflect similar bulk compositions. The proximity of Venus to the Sun may have delayed solidification of the surficial magma ocean and desiccated the surface and atmosphere [3]. In the absence of colder surface temperatures and water oceans, Venus entered a geodynamic regime that is less efficient at cooling the mantle than plate tectonics [4]. Most models indicate that the heat flow from the solid mantle to the surface in Venus is roughly half Earth's modern value, i.e., ~20 TW versus 44 TW. A BMO should have formed inside Venus and would solidify at a slower rate.

This study argues that the lifetime of a BMO in Venus extends to the present. The structure of the deep interior of Venus thus resembles that of Earth from ~2–3 Gyr ago [5]. Structural similarities give way to dynamical differences because modern Venus cools slowly compared to middle-aged Earth. Ultimately, the prospect that such a major feature awaits detection highlights the pressing need to explore Venus.

Methods: Parameterizations of energy sources and sinks—adapted from previous studies of Earth [1] and Venus [6]—track the thermochemical evolution of the basal magma ocean and core (Figure 1). Scaling laws determine when and where a dynamo could exist. The BMO may host a dynamo [2] if liquid silicates become semi-metallic at extreme pressures and temperatures. Although the rotation of Venus is "slow" relative to Earth, it is "rapid" in the context of dynamo physics. Relative to Earth, structural parameters for the core and mantle of Venus were adjusted to reflect lower internal pressures (e.g., ~125 versus 130 GPa at the core/mantle boundary). Then, the heat flow out of the basal magma ocean was roughly halved at all times to reflect relatively slow cooling of Venus relative to Earth.

Results: Benchmark models for Earth were initialized with the initial thickness of the BMO equal to 750 km [1]. The thickness of the BMO shrinks to <10 km over 4.5 Gyr if the heat flow out of the BMO into the solid mantle linearly decreases from 55 to 15 TW. Assuming that Earth and Venus accreted in an equivalently energetic environment, expecting that the BMO in Venus began with a similar size seems logical.

Nominal model for Venus. Figure 2 illustrates the thermal evolution of the deep interior. Radiogenic and latent heat dominate the energy budget of the BMO, which only cools by ~233 K over 4.5 Gyr. The thickness of the BMO decreases to ~234 km—clearly constituting a global layer. Temperatures at the liquid-solid interface atop the BMO are estimated by averaging the solidus and liquidus of peridotite. A thermal boundary layer must exist at the base of the solid mantle. Otherwise, the very high potential temperature of the mantle would then imply unrealistically high rates of surface volcanism [4]. Magnetic

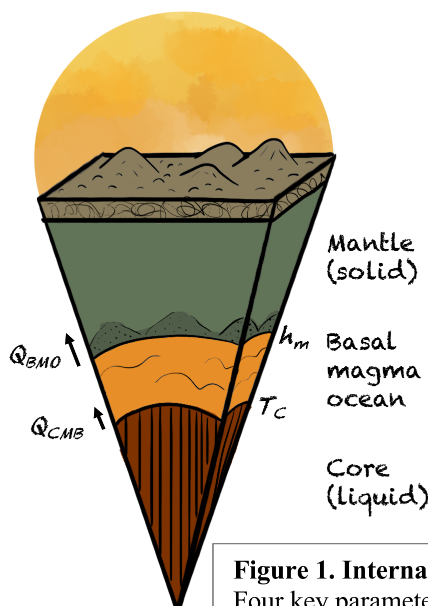

Figure 1. Internal structure of Venus today? Four key parameters: heat flow from the BMO to the solid mantle (Q_{BMO}), heat flow across the CMB (Q_{CMB}), temperature at the CMB (T_C), and BMO thickness (h_M). Illustration by JoAnna Wendel [5].

dissipation in the core is negative always even with the thermal conductivity set to the lowest plausible value (40 W/m/K). If there were no BMO, then $Q_{CMB} \sim Q_{BMO}$ and the core would produce a dynamo. The BMO may have hosted a dynamo until recently, although the predicted lifetime is highly sensitive to the flow velocity scaling law. The favored Coriolis-Inertial-Archimedean (CIA) scaling predicts a magnetic field with surface strengths of ~10–30 μT until ~1 Gyr ago—roughly the estimated average age of surface units.

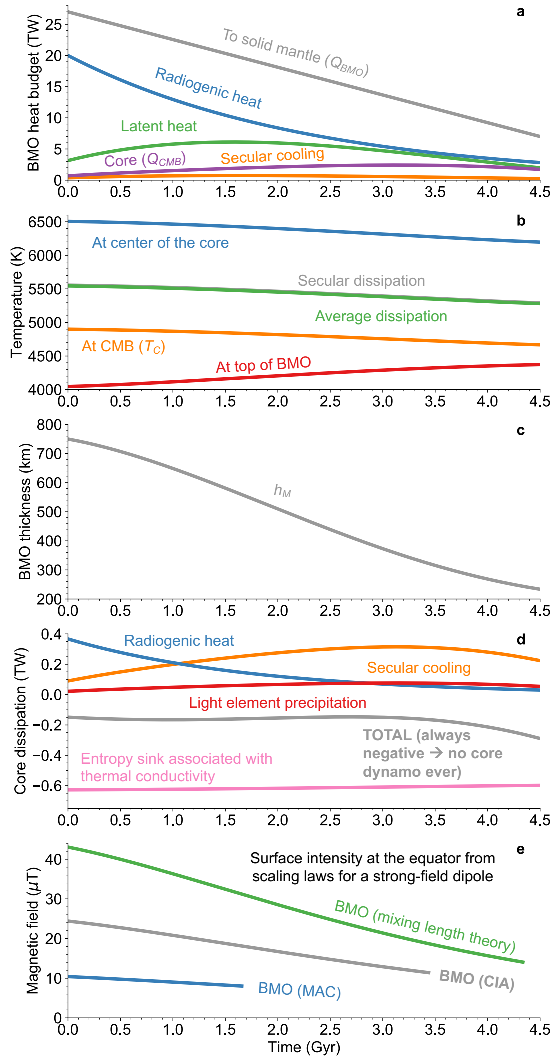

Figure 2. Nominal model for Venus. A long-lived basal magma ocean is the natural outcome of slow cooling through the solid mantle relative to Earth. (a) Heat budget of the BMO. (b) Temperatures at the top of the BMO and CMB, and deeper in the core. (c) Thickness of the BMO. (d) Dissipation budget for the core and the total deficit in energy available for a dynamo. (e) Estimated strength of the surface magnetic field produced by a dynamo in the BMO from three flow velocity scalings [5].

Sensitivity analyses for Venus. Cooling timescales depend on assumptions about the chemistry of the solidifying BMO. This study uses a simplified linear phase diagram [1]. Varying the density contrast between the BMO and the solid mantle can plausibly change the present-day size of the BMO by a factor of ~2. Future work should include a more detailed phase diagram with partition coefficients [2] and track any compositional layering in the BMO and solid mantle [7].

Implications: The likelihood that a BMO persisted until now within Venus has myriad implications.

Geochemistry. Incompatible elements from the lowermost ~650–1250 km of the primitive mantle (e.g., ~11–25% of the mantle's total volume), especially potassium, could remain hidden in a reservoir unsampled by volcanism and degassing. Future work should investigate whether the BMO could explain why Venus has less atmospheric argon-40 than Earth [8].

Tidal response. Measuring a high k_2 (>0.27 versus 0.295 ± 0.066 from Magellan) with a new mission would prove that the core remains partially liquid [9]. In principle, a BMO could decouple the solid mantle from the core and lead to a high k_2 even if the underlying core were completely solid. In reality, the solidus of the core is far lower than that of the basal mantle. No realistic thermal history features a BMO and a solid core [6].

Magnetic history. Venus could have accreted under low energetic conditions where any BMO solidified quickly and chemical stratification blocked convection in the core forever [10]. Alternatively, Venus may have sustained an Earth-strength global magnetic field until recently. The core could power a dynamo for billions of years absent a BMO [6]. High thermal conductivity for the core (>100 W/m/K) was previously invoked because simulations using lower conductivities over-predicted the dynamo's lifetime. Here, a dynamo exists instead in the BMO but survives for similar timescales. The basal magma ocean gives, and the basal magma ocean has taken away. The thermal conductivity of the core is then no longer a critical uncertainty because the cooling rate of the core is sub-adiabatic regardless. Crustal remanent magnetism is a potentially observable consequence of an early dynamo in either the core or BMO [11].

References: [1] Labrosse et al. (2007) *Nature*, *450*, 866–9. [2] Blanc et al. (2019) *EPSL* (in review) doi: 10.31223/osf.io/cmgef. [3] Hamano et al. (2013) *Nature*, *497*, 607–10. [4] Gillmann & Tackley (2014) *JGR:P*, *119*, 1189–217. [5] O'Rourke (2020) *GRL* (in review) doi: 10.1002/essoar.10501095.2. [6] O'Rourke et al. (2018) *EPSL*, *502*, 263–72. [7] Laneuville et al. (2017) *PEPI*, *276*, 86-92. [8] Kaula (1999) *Icarus*, *139*, 32–39. [9] Dumoulin et al. (2017) *JGR:P*, *122*, 1338–52. [10] Jacobson et al. (2017) *EPSL*, *474*, 375–386. [11] O'Rourke et al. (2019) *GRL*, *46*, 2019GL082725.