A Basal Magma Ocean in Venus: Implications for Gravity, Heat Flow, Magnetism, and Noble Gases.
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Introduction: Magma oceans were ubiquitous during the formation of rocky planets. Crystallization of the mantle of Earth and Venus may have proceeded from the middle outwards. Liquid silicates are gravitationally stable near both the surface and core/mantle boundary (CMB) [1,2]. The surficial magma ocean of Venus solidified within ~100 Myr via rapid cooling to space [3]. However, a basal magma ocean (BMO) could survive for billions of years—and, perhaps, still exist as global layer within Venus today.

Earth's putative BMO has been invoked to solve various geochemical puzzles [1]. In particular, the BMO is a "hidden reservoir" for incompatible elements including heat-producing isotopes. Seismology hints that iron-rich melt and compositional anomalies at the base of the mantle are the last residua of a BMO.

Why would Earth but not Venus have a BMO? These planets are assumed to have similar compositions because their bulk densities are nearly identical. Assuming that Venus and Earth accreted under similarly energetic conditions, a BMO on Earth would be mirrored by one with a comparable initial size on Venus.

Many models predict that the interior of Venus cools slowly relative to Earth. A popular story is that the proximity of Venus to the Sun led to desiccation of the surface and atmosphere [3]. Mantle dynamics on Venus may have transitioned between different regimes over time [4]. However, any period of mobile-lid convection (i.e., plate tectonics) was likely short-lived. Other modes of mantle dynamics such as stagnant- or episodic-lid convection are relatively less efficient at cooling the mantle. Roughly speaking, the total heat flow from the solid mantle of Venus to the surface has been estimated at ~20 TW versus ~44 TW for Earth.

This study [5] argues that the lifetime of a BMO in Venus plausibly stretches until today. In other words, Venus has an internal *structure* resembling that of Earth ~2 Gyr ago. However, the internal *dynamics* of Earth and Venus are different because middle-aged Earth cooled faster than modern Venus.

Methods: Parameterized models of Earth [1,2] were adapted to track the thermal evolution of the BMO and core inside Venus. These models are one-dimensional (radial). Relative to Earth, structural parameters for the core and mantle of Venus were adjusted to reflect lower internal pressures (i.e., ~125 vs. 130 GPa at the CMB) [6]. The initial condition for the model is the starting thickness of the BMO. Temperatures within the BMO and core are determined self-consistently from the thickness of the BMO based on the assumed liquidus. In contrast to the situation with a fully solid mantle, temperature cannot change dramatically across the CMB while the basal mantle is a low-viscosity fluid.

The heat flow into the base of the solid mantle (Q_{BMO} in Fig. 1) controls the thermochemical evolution of the BMO and core. By definition, the total heat flow (Q_{BMO}) is the sum of energy terms related to specific and radiogenic heat in both the BMO and core, along with latent heat and gravitational energy associated with the freezing of the BMO from above and of the inner core.

Scaling laws determine when and where a dynamo could exist. The BMO and/or core are assumed to create a strong magnetic field if they are vigorously convecting. Critically, recent studies show that liquid silicates are electrically conductive under extreme pressures and temperatures. "Slow" rotation of Venus relative to Earth does not preclude dynamo activity because it is "fast" in the context of dynamo physics.

Results: Benchmark models for Earth were initialized with the thickness of the BMO equal to 750 km [1,2,5]. The thickness of the BMO shrinks to <10 km over 4.5 Gyr if Q_{BMO} linearly decreases from 55 to 15 TW over geologic time. This result agrees with the seismic constraint that there is no thick, global layer of liquid silicates at the base of Earth's mantle today.

Nominal model for Venus. As a crude approximation of the differences between mantle dynamics on Venus and Earth, Q_{BMO} for Venus was reduced by half at all times relative to Q_{BMO} for Earth. In other words, Q_{BMO} decreased linearly from 27.5 to 7.5 TW over 4.5 Gyr. Figure 2 illustrates the thermal evolution of the deep interior. The BMO cools by only ~233 K over 4.5 Gyr because radiogenic and latent heat dominate its energy budget. That is, there is not enough total heat flow to rapidly change the specific heat of the BMO. The thickness of the BMO remains ~230 km today—clearly thick enough to constitute a global, detectable layer. Temperatures at the liquid-solid interface atop the BMO were estimated by averaging the

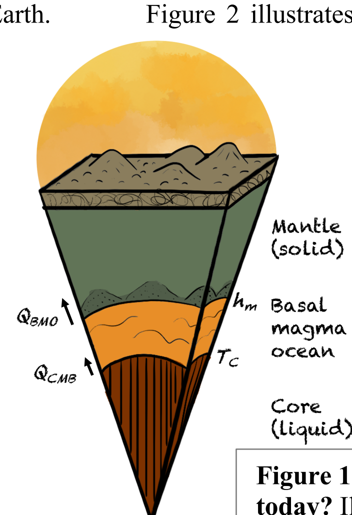

Figure 1. Internal structure of Venus today? Illustration by JoAnna Wendel [5].

solidus and liquidus of peridotite. A thermal boundary layer should exist at the base of the solid mantle. Otherwise, the mantle would likely have an extremely high potential temperature and produce unrealistic amounts of volcanism.

This model is consistent with available constraints on the magnetic history of Venus. Neither the BMO nor the core are cooling fast enough at present day to drive a dynamo. The BMO acts to suppress a dynamo in the core. However, a dynamo may have existed until recently in the BMO. Its lifetime is highly sensitive to the scaling law chosen for convective velocities in the BMO. The favored (CIA) scaling predicts that a dynamo lasted until ~1 Gyr ago (i.e., within the age of surface units) and had Earth-like strengths (i.e., ~10–30 μT).

Sensitivity analyses for Venus. The chemistry of the BMO influences how fast it cools. This study uses a simple, linear phase diagram [1]. Varying the density contrast between the BMO and the solid mantle can change the present-day size of the BMO by a factor of ~2. Future work should include a better phase diagram with partition coefficients [2] and track compositional layering in the BMO and solid mantle [7].

Implications: *Gravity*. A BMO is potentially detectable via future measurements of the tidal Love number (k_2) and the tidal phase lag. Measuring a high k_2 (>0.27 versus 0.295 ± 0.066 from Magellan) would indicate that the deep interior remains liquid, although the detection limit for a BMO needs definition [8].

Heat flow. The present-day thickness of a BMO is an integrated signal of the cooling history of Venus. Future missions may provide better constraints on the modern cooling rate of the mantle via analyses of high-resolution gravity, imagery, and topography. Such data are essential to verifying the *assumption* that Venus has cooled slowly relative to Earth over time.

Magnetism. Crustal remanent magnetism is a potentially observable consequence of an early dynamo in either the core or BMO [9]. In the absence of a BMO, the core could power a dynamo for billions of years [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. With a BMO, the prospects for a dynamo in Venus are less sensitive to assumed properties of the core. A dynamo is predicted to exist for similar timescales—but it would be located in the BMO, not in the core. The BMO gives, and the BMO has taken away.

Alternatively, Venus could have accreted under low-energy conditions where any BMO solidified quickly and chemical stratification blocked convection in the core forever [10]. Any detection of crustal remanent magnetism would disprove this alternate story.

Noble gases. 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].

Ultimately, the prospect that a major feature such as a BMO could lurk undetected within Venus is one of many indications that new missions are needed.

References: [1] Labrosse et al. (2007) *Nature*, *450*, 866–9. [2] Blanc et al. (2020) *EPSL*, *534*, 116085. [3] Hamano et al. (2013) *Nature*, *497*, 607–10. [4] Gillmann & Tackley (2014) *JGR:P*, *119*, 1189–217. [5] O'Rourke (2020) *GRL*, 47(4). [6] O'Rourke et al. (2018) *EPSL*, *502*, 263–72. [7] Laneuville et al. (2017) *PEPI*, *276*, 86-92. [8] Dumoulin et al. (2017) *JGR:P*, *122*, 1338–52. [9] O'Rourke et al. (2019) *GRL*, *46*, 2019GL082725. [10] Jacobson et al. (2017) *EPSL*, *474*, 375–386. [11] Kaula (1999) *Icarus*, *139*, 32–39.

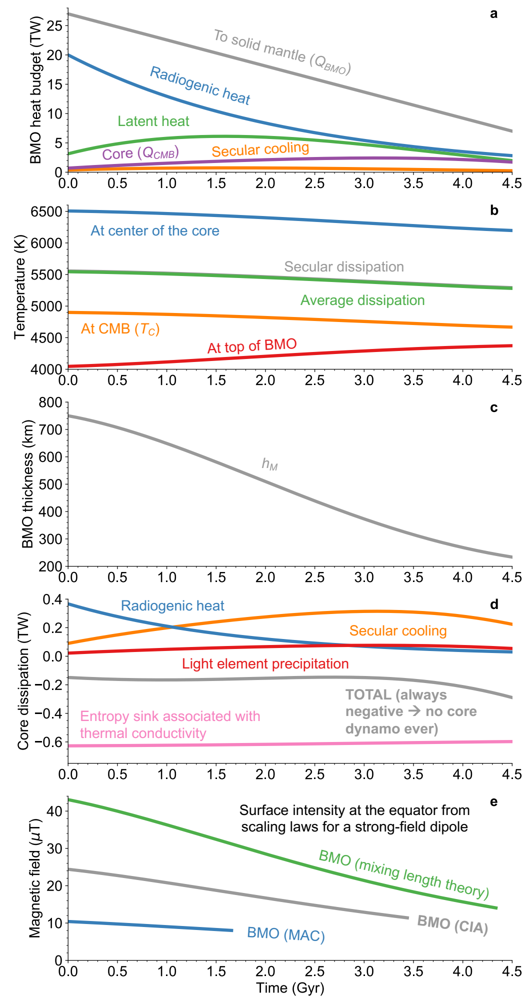

Figure 2. Nominal model for Venus [5].