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# Prospects for an ancient dynamo and modern crustal remanent magnetism on Venus

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ABSTRACT

Venus lacks an internally generated magnetic field today. Whether one existed in the past is unknown, but critical to atmospheric evolution and potential habitability. Canonical models assume the core of Venus is cooling too slowly for convection and thus a magnetic dynamo to occur today. Core/mantle heat flow is suppressed in these models after a putative transition in mantle dynamics associated with widespread, volcanic resurfacing. However, recent studies of impact craters and other surface features support more steady heat loss over geologic time. Precipitation of MgO and/or $SiO_2$ from the core can also drive compositional convection even with slow cooling. Here we reevaluate the likelihood that Venus has an "Earth-like" (at least partially liquid and chemically homogeneous) core using numerical simulations of the coupled atmosphere–surface–mantle–core evolution. An Earth-like core is only compatible with the modern lack of a dynamo if the thermal conductivity of core material is towards the higher end of modern estimates (i.e., >100 $\mathrm{W\,m^{-1}\,K^{-1}}$). If lower estimates like ∼40–50 $\mathrm{W\,m^{-1}\,K^{-1}}$ are actually correct, then we favor recent proposals that the core has completely solidified or preserved primordial stratification. Any simulation initialized with a homogeneous, liquid core predicts a global magnetic field with Earth-like surface strength for >2–3 billion years after accretion—consistent with all available observations—and also sporadic activity within the surface age while temperatures remain below the Curie point of magnetite. Therefore, future spacecraft missions should prioritize the first-ever magnetometer measurements below the ionosphere to search for crustal remanent magnetism.



## 1. Introduction

Venus stands alone as the only major planet without evidence for an internally generated magnetic field either now or in the past. Vigorous convection of liquid iron alloy in Earth's outer core has sustained our geodynamo for at least 3.45 Gyr (e.g., Tarduno et al., 2010). Venus is presumably differentiated like Earth into a silicate mantle and metallic core, but Pioneer Venus Orbiter constrained the magnetic moment of Venus to less than $\sim 10^{-5}$ times the modern value for Earth (e.g., Phillips and Russell, 1987). Determining whether Venus ever hosted a global magnetic field has myriad implications for its surface habitability (e.g., Driscoll and Bercovici, 2013; Foley and Driscoll, 2016) and the ongoing debate over the general relationship between magnetic shielding and atmospheric erosion (e.g., Tarduno et al., 2014).

Generally speaking, there are two basic requirements for a magnetic dynamo. First, the Coriolis force must strongly affect the fluid flow as indicated by a small Rossby number at the equator: $\mathrm{Ro} = v/(2L\Omega)$, where $v$ is fluid velocity, $L$ is the length scale of the dynamo region, and $\Omega$ is the angular rotation speed. Venus has the longest rotational period of the major planets, but $\mathrm{Ro} \approx 10^{-5} \ll 1$ (versus $\sim 10^{-6}$ for Earth) should still support dynamo action (e.g., Stevenson, 2003). Second, the magnetic Reynolds number $\mathrm{Re}_m = vL/\lambda$—where $\lambda$ is magnetic diffusivity (inversely proportional to electrical conductivity)—must exceed a critical value ∼10–100. In the absence of other fluid motions like tidal stirring, this criterion mandates vigorous convection in a low viscosity (i.e., liquid) core. Dynamos constantly require energetic input—any global magnetic field would dissipate within $\sim 10^4$ yr after convection ceases (Stevenson, 2003).

Canonical models assume Venus has an "Earth-like" core—at least partially liquid and chemically homogeneous—that is currently cooling too slowly for a dynamo. Thermal convection only occurs if the heat flow across the core/mantle boundary (CMB)

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exceeds that which conduction would transport up an adiabatic temperature gradient. Nimmo (2002) argued that a transition from plate tectonics to the stagnant lid regime of mantle convection at ∼500 Ma decreased CMB heat flow to nearly zero. Dramatic, global changes in mantle dynamics are commonly invoked to produce "catastrophic resurfacing" and explain the random distribution of impact craters on the surface (e.g., Strom et al., 1994; McKinnon et al., 1997). Ongoing debate over whether catastrophic resurfacing actually occurred hinges on the fraction of craters that suffered post-impact volcanic modification. Only ∼10% of craters were classified as obviously embayed during the first analysis of radar images from Magellan (e.g., Strom et al., 1994). Monte Carlo models of cratering and non-catastrophic resurfacing can reproduce this low percentage (Bjonnes et al., 2012), but cannot explain the clustering of obviously embayed craters (O'Rourke et al., 2014). However, radar-dark floors found in ∼80% of craters may indicate volcanic modification that is not otherwise obvious in low-resolution Magellan imagery (Wichman, 1999; Herrick and Rumpf, 2011). O'Rourke et al. (2014) showed that non-catastrophic resurfacing by thin, localized flows—matching some stratigraphic histories (Guest and Stofan, 1999)—would produce a volcanically modified population with the same size and spatial distributions as the dark-floored craters.

Even models without catastrophic resurfacing rely on low CMB heat flow to explain the absence of a dynamo today. One-dimensional, parametrized models agree that stagnant lid convection suppresses mantle and core cooling if melt migration to the surface is relatively inefficient (e.g., Stevenson et al., 1983; Solomatov and Moresi, 1996; Driscoll and Bercovici, 2013, 2014; O'Rourke and Korenaga, 2015; Foley and Driscoll, 2016). However, Armann and Tackley (2012) predicted that magmatic heat pipe dominates in the stagnant lid regime, which leads to unrealistically high rates of crustal production and Earth-like core/mantle heat flow. An episodic lid mode, in contrast, suppresses core cooling during quiescent periods and better matches the present-day amplitude of the geoid and topography. Recent work demonstrates that atmosphere–surface coupling causes transitions between different mantle convective regimes that ultimately stabilize surface conditions (Noack et al., 2012; Gillmann and Tackley, 2014). Factors affecting dynamo action have not been fully investigated in these new simulations.

Compositional buoyancy produced by chemical processes is potentially key to dynamo action in terrestrial planets. For example, the plausible range for the energy sink associated with thermal conduction in Earth's core (∼4–11 TW) overlaps with the estimated ∼5–15 TW total heat flux across the CMB today (Lay et al., 2008). There is no problem explaining Earth's dynamo at present, however, because exclusion of light elements from the solidifying inner core provides compositional buoyancy. Core/mantle heat flow need not exceed the conductive flux along the adiabat once the inner core nucleates since compositionally dense (but relatively hot) material can sink and carry heat downwards. Precipitation of light elements from the core may provide compositional buoyancy before nucleation of an inner core. O'Rourke and Stevenson (2016) first proposed that magnesium could provide an early power source for Earth's dynamo. Later, Badro et al. (2016) presented supportive results from diamond-anvil cell experiments. Magnesium is delivered in the ∼10% of core-forming iron alloy that chemically equilibrates with mantle silicate at extremely high-temperature conditions in the aftermath of giant impacts. The solubility of magnesium in metal decreases rapidly with temperature, so cooling rates under ∼50 K Gyr$^{-1}$ still provide sufficient mass flux to drive convection. Hirose et al. (2017) subsequently suggested that crystallization of silicon dioxide may also occur at similar rates even if metal/silicate equilibration occurs at more moderate temperatures near mid-mantle depths. Additional mineral physics experiments are required to clarify many details about these new mechanisms. Regardless, Venus could possibly sustain a dynamo with sub-adiabatic heat flow in an Earth-like core even prior to inner core nucleation.

Two recent studies offer alternatives to canonical models of the core. First, Earth-sized planets are expected to form with stratified cores where the abundances of light elements increase with radius (Jacobson et al., 2017). Metal added later to the core during accretion chemically equilibrates with silicates at higher temperature/pressure conditions where silicon and oxygen are more soluble in metal. Earth's Moon-forming impact presumably eliminated this stratification through mechanical mixing. In the absence of a late energetic impact with appropriate geometry, this stratification may survive and completely prevent convection even with extremely rapid cooling. Second, the core of Venus may have completely solidified (e.g., Stevenson et al., 1983; Dumoulin et al., 2017). Doppler tracking of Magellan and Pioneer Venus Orbiter measured the tidal Love number as $k_2 = 0.295 \pm 0.066$ (Konopliv and Yoder, 1996). Elastic deformation models based on a one-dimensional seismological model of Earth's interior implied that a solid core would have $k_2 \approx 0.17$ compared to $0.23 < k_2 < 0.29$ for a liquid core (Konopliv and Yoder, 1996). However, Dumoulin et al. (2017) used a viscoelastic solution for mantle deformation to argue that the core must be fully solid if future spacecraft find $k_2 < 0.27$. Verifying either of these scenarios would profoundly alter theories for the accretion of Venus and Earth.

In this paper, we address two fundamental questions. First, does slow cooling alone explain the modern absence of a global magnetic field? Second, should we prioritize a search for crustal remanent magnetism on Venus? We run numerical simulations built on recent models of Earth's dynamo (O'Rourke and Stevenson, 2016; O'Rourke et al., 2017) and a previous investigation of coupled atmospheric and mantle dynamics on Venus (Gillmann and Tackley, 2014). For simplicity, we always assume that the core lacks significant compositional stratification and has an Earth-like bulk composition. Simulations that predict enough core cooling to drive a dynamo at present are taken as evidence for primordial stratification of the core (Jacobson et al., 2017), unless the core has completely solidified.

## 2. Model

Our simulations of the evolution of Venus include three modules to handle the energy balance of the atmosphere and the dynamics of the mantle and core. We consider two-way coupling between the atmosphere and mantle based on how melt production in the mantle releases greenhouse gases and then surface temperature determines the regime of mantle convection. This study includes some coupling between the mantle and core because the temperature of the core influences mantle convection, which controls the cooling rate of the core. However, we have not yet formulated a model for the influence of a magnetic field on atmospheric composition. Table 1 defines critical parameters that we use or track in our simulations, along with values for some important constants.

### 2.1. Evolution of the mantle

We continue to use the StagYY code to simulate mantle convection (Armann and Tackley, 2012; Gillmann and Tackley, 2014; Gillmann et al., 2016). Briefly, we assume a compressible, anelastic mantle with infinite Prandtl number in 2D, spherical annulus geometry with a resolution of 512 azimuthal by 64 radial cells plus 1 million tracers to track composition and melt fraction. Heat-producing elements are uniformly distributed initially but partition into melt as in some cases from Armann and Tackley (2012). We