PROSPECTS FOR AN ANCIENT DYNAMO AND MODERN CRUSTAL REMANENT MAGNETISM ON VENUS. J. G. O'Rourke[1], C. Gillmann[2], and P. Tackley[3], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ (jgorourk@asu.edu), [2]Royal Observatory of Belgium, Brussels, Belgium, [3]Department of Earth Sciences, ETH Zurich, Institute of Geophysics, Zurich, Switzerland.

Introduction: Venus is the only major planet without evidence for an internally generated magnetic field either now or in the past. Every other planet (and also Ganymede) besides Mars hosts a dynamo today. Spacecraft and meteorites have revealed ancient remanent magnetism produced on Mercury, Mars, Earth's Moon, and myriad asteroids [1]. Venus rotates fast enough—albeit slower than Earth—to produce a dynamo in convecting, liquid metal alloy like Earth's core. Determining whether Venus ever hosted a magnetic field has myriad implications for its accretion and habitability.

Three broad explanations have been proposed for the modern absence of a magnetic dynamo in Venus. First, canonical models assume that Venus indeed has an "Earth-like" core (i.e., at least partially liquid and chemically homogenous) that has been cooling too slowly to convect since a transition in mantle dynamics possibly associated with catastrophic resurfacing. [e.g., 2]. Second, recent work argues that the tidal Love number measured by the Magellan mission is not precise enough to exclude complete solidification of the core [3]. Third, a relative paucity of giant impacts during the accretion of Venus may result in a chemically stratified core (i.e., stable Si/O gradients) that never convects [4].

We evaluate these possibilities using simulations built on a previous investigation of coupled atmospheric and mantle dynamics on Venus [5]. Our approach is to model an "Earth-like" core always for simplicity. Simulations that predict a modern dynamo are taken as evidence for complete solidification or stratification.

Methods: Our simulations include three modules to handle the dynamics of the atmosphere, mantle, and core. We use the StagYY code in 2-D, spherical annulus geometry to track the evolution of the mantle—including partial melting, depth-dependent phase transitions in the pyroxene-garnet and olivine systems, and radiogenic heating. All melt generated above 300 km depth in the mantle is assumed to rise to the surface and release greenhouse gases CO_2 and H_2O. Hydrodynamic escape (most relevant at early times) and various non-thermal escape processes remove H and O over time. Surface temperature changes in response according to a one-dimensional, grey model of the radiative-convective atmosphere [5], and thus the mantle transitions between the mobile, episodic, and stagnant lid regimes.

Core dynamics: We constructed a one-dimensional model for the core based on a fourth-order parameterization of the radial density profile [6]. We include conventional energy sources for the dynamo like secular cooling, radioactivity, and the exclusion of light elements from an inner core. We also consider heat loss from the inner core and novel power sources like the precipitation of light species such as MgO [7, 8] and/or SiO_2 [9]. The thermal conductivity of iron-rich alloys under core conditions is critical yet poorly constrained by theory and experiments. High conductivity raises the core/mantle heat flow required to drive a dynamo. Fortunately, repeating simulations is not necessary to test the full range of plausible values since conductivity only affects entropy production—and not the global heat budget. We calculate the critical thermal conductivity below which each simulation would predict positive dissipation and thus a dynamo in an "Earth-like" core.

Sensitivity tests: We run many simulations to examine factors that are likely to strongly affect the dynamo while still producing realistic atmospheric evolution and surface volcanism. Including a primordial layer of dense material at the bottom of the mantle greatly reduces core/mantle heat flow at early times. Adjusting the equation of state for basalt to increase its density relative to harzburgite by a few percent at the core/mantle boundary produces a ~1000 km thick layer of basalt that provides progressively more insulation for the core over time. [e.g., 10]. We run most of our simulations with a viscoplastic rheology and a yield strength of 90 MPa at

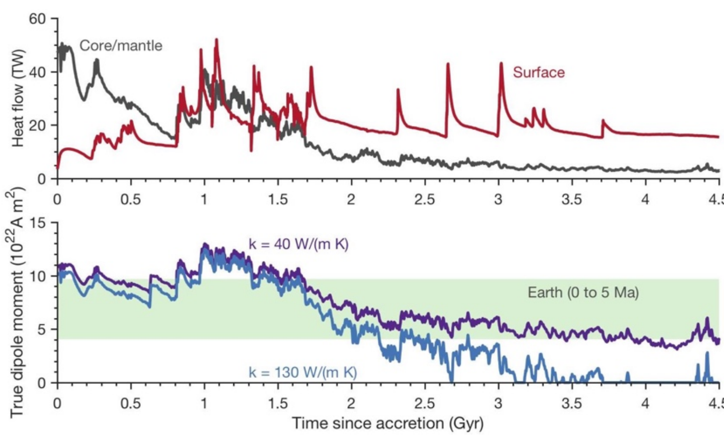

Figure 1 | Example simulation. Cooling rates of the mantle and core and the estimated magnetic field strength over time for upper and lower limits on the thermal conductivity (k) in the core.

the surface so that recent mantle evolution is in the episodic lid regime with regional—but not globally catastrophic—resurfacing events that are consistent with the cratering record [e.g., 11]. But we also test cases with higher yield stress (300 MPa) and thus recent evolution in the stagnant lid regime. Finally, we ran simulations with constant surface temperature and thus no transitions away from the episodic lid regime in the mantle.

Results: Given available constraints, all three proposed scenarios remain possible. Heat loss from the mantle of Venus during quiescent periods in the episodic lid regime is reduced to less than half the modern value for Earth (~15 vs. 44 TW). Therefore, the mantle is plausibly heating up today [12]. But core cooling is not completely suppressed. Our simulations still predict core/mantle heat flow >2 TW at present following a "hot start" in the core. Every 200 ppm of potassium added to the core increases the CMB heat flow by ~2 TW today.

Any simulation initialized with a liquid, homogenous core predicts a global magnetic field with Earth-like strength at the surface for the first ~2–3 billion years after accretion. If the lowest estimates for thermal conductivity (~40–50 W/m/K) are confirmed [e.g., 13], then the core of Venus must have completely solidified or preserved a compositional stratification. We predict that Venus would otherwise have a dynamo today. Higher conductivities (>100 W/m/K) are consistent with the conventional view that Venus has an "Earth-like" core that is cooling too slowly to convect.

Complete solidification: At least some inner core growth seems inevitable unless [K] > 600 ppm in the core—in comparison, [K] < 100 ppm is favored for Earth by geochemical constraints and mineral physics experiments. However, complete solidification only occurs in our simulations if there is no radiogenic heating in the core, and the primordial layer and any density difference between basalt and harzburgite are both eliminated. An initial temperature close to when inner core nucleation occurs is also required. Even under these conditions, the core remains partially liquid until <500 million years ago. We do not run any "Earth-like" simulations with a primordial inner core because any scenario for accretion that produces such cold conditions is likely to create substantial compositional stratification.

Search for crustal remanent magnetism: Future missions should perform the first-ever magnetometer measurements below the ionosphere to search for magnetized rocks in the crust. Atmospheric interactions with the solar wind complicate observations from orbit [14], so an aerial platform in the lower atmosphere is perhaps ideal for a global survey. Our simulations often predict dynamo activity within the surface age (i.e., <750 Ma) while the surface always remains at or below the current temperature—which is well under the Curie point of magnetite (~740 vs. 858 K) —for the last ~2.5 billion years. Any detection of crustal remanent magnetism would strongly support similar conditions and impact rates during the accretion of Earth and Venus.

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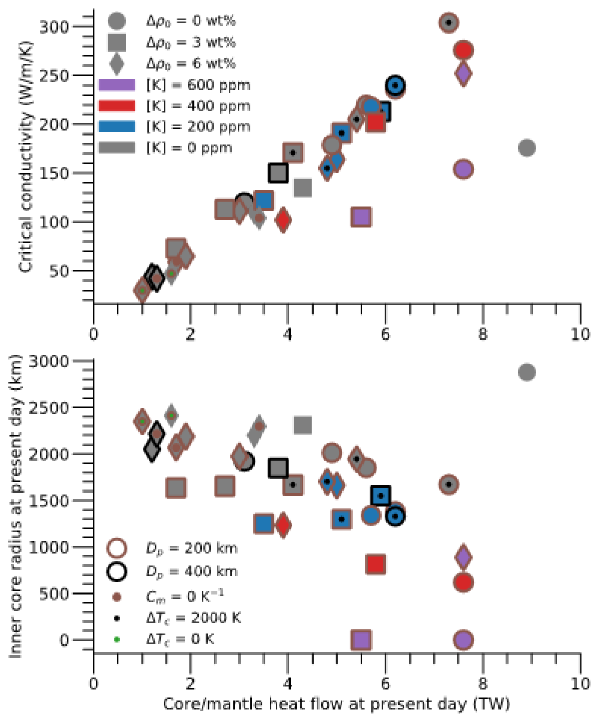

Figure 2 | Summary of sensitivity tests. Critical conductivity that prevents a dynamo versus present-day cooling rate of the core and size of the inner core. Symbols show combinations of initial conditions including the basalt-harzburgite density contrast ($\Delta\rho_0$), the thickness of the primordial, dense layer at the bottom of the mantle (D_p), the rate of MgO and/or SiO_2 precipitation (C_m), and the initial temperature excess in the core above inner core nucleation (ΔTc). No simulation with a "hot start" or precipitation is consistent with the modern lack of a dynamo if k < 40–50 W/m/K, but several sets of initial conditions are compatible with the plausible upper limit k ~ 130 W/m/K.