EPSC Abstracts
Vol. 13, EPSC-DPS2019-1407-1, 2019
EPSC-DPS Joint Meeting 2019

EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

Unveiling the Formation and Magnetic History of Venus

Joseph G. O'Rourke
School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA (jgorourk@asu.edu)

Abstract

Planetary magnetic fields are unique probes of deep interiors and deep time. However, whether Venus ever hosted a dynamo is unknown. Canonical models assume the core of Venus has Earth-like structure and composition but is cooling too slowly today for convection and thus a dynamo to operate in the core. Simulations initialized with an Earth-like (i.e., hot, chemically homogeneous) core predict that a global magnetic field with Earth-like strength would have existed within the surface age. Crustal remanent magnetism is a potentially observable consequence of an ancient Venusian dynamo. Alternative models suggest that the core of Venus preserves a primordial chemical stratification that always inhibited a dynamo, which would imply that Venus and Earth trod different evolutionary paths from the start. Future missions would perform key tests of these scenarios and reveal the birth and evolution of Venus.

1. Introduction

Venus stands alone as the only major planet without evidence for an internally generated magnetic field either now or in the past. Pioneer Venus Orbiter (PVO) supplied the strictest upper limit on any present-day global magnetic field: ~10^{-5} times Earth's magnetic moment [1]. Venus is presumably differentiated like Earth into a silicate mantle and metallic core. Compared to Earth, Venus rotates slowly but still fast enough for a dynamo to operate if the core were convective [2]. Three explanations that are not mutually exclusive have been proposed for the absence of a dynamo at Venus. First, the core of Venus may cool slowly in the absence of plate tectonics at a rate that is insufficient to drive vigorous convection in the core [3]. Second, the core may have completely solidified [4]. Third, primordial chemical stratification that naturally arises if late energetic impacts do not mechanically mix the core may resist convection forever [5]. Deciding which explanation(s) are correct would have myriad implications for models of the internal evolution, recent climate history, and atmospheric loss processes on Venus [6]. Unfortunately, meaningful data are quite limited.

2. Prospects for an Ancient Dynamo at Venus

We revaluated the likelihood that Venus has an Earth-like core using numerical simulations of the coupled atmosphere-surface-mantle-core evolution [7]. Precipitation of MgO and/or SiO_2 from the core and solidification of an inner core over time can potentially drive compositional convection and thus a dynamo even if the core cools too slowly for purely thermal convection. Simulations that predict enough core cooling to drive a dynamo at present day are taken as evidence for primordial stratification of the core [6] unless the core has completely solidified [5].

Any simulation initialized with an Earth-like core predicts a global magnetic field with Earth-like surface strength for >2-3 billion years after accretion. Dynamo activity is suppressed today if the thermal conductivity is higher than the lower limit to the modern range of uncertainty (i.e., >50-100 W/m/K). Lower thermal conductivities lead to a modern dynamo that conflicts with observations. At least sporadic dynamo activity is predicted within the surface age (i.e., <1 billion years ago) for any thermal conductivity. At the same time, average surface temperatures are calculated to remain below the present-day value of ~737 K, which is >100 K below the Curie temperature of magnetite. Enough melt production is predicted to occur within the surface age to increase crustal thickness by >30 km. Therefore, substantial volumes of crust could acquire thermoremanent magnetization (TRM) if a dynamo existed, which would validate the assumption that the core of Venus (and thus its accretion) was Earth-like.

3. Detectability of Crustal Remanent Magnetism on Venus

Prior studies downplayed the likelihood of obtaining useful results from a search for crustal remanent magnetism on Venus. Retaining detectable amounts of TRM requires surface temperatures below the Curie points of common magnetic carriers such as magnetite (~858 K) and hematite (~948 K). Any

TRM would tend to decay once the Venusian dynamo disappeared as magnetic domains randomize.

However, decades of results from terrestrial paleomagnetic studies indicate that magnetite and hematite can retain TRM for billions of years at Venusian conditions [8]. Depths to the Curie temperature of magnetite on Venus are >5-10 km and potentially >20 km at regions with below-average heat flow. Plausible magnetization intensities mostly exceed the lower limit for detection by an orbiter or aerial platform for regions where the horizontal coherence scale of magnetization is greater than the observational altitude (~150 and 50 km, respectively). Previous orbiter spacecraft missions only constrained the coherence scale to <150 km northward of 50° South latitude for magnetization intensities >1-3 A/m.

4. Novel Constraints from Future Missions

Future missions should perform the first-ever magnetometer survey below the ionosphere to search for crustal remanent magnetism. Orbiters could search for strong, large-scale crustal magnetization in the southern hemisphere of Venus. Aerial platforms operating in clement regions of the atmosphere are ~27 times more sensitive than orbiters to small-scale magnetization, which could await detection almost anywhere on Venus except the Venera 4 landing site.

The ESA-NASA proposed EnVision Venus orbiter and NASA Discovery Venus missions would also provide critical information. Any orbiter would return a vastly improved estimate for the tidal Love number (k_2) and reveal whether the core remains partially liquid today. High-resolution radar imagery, topography, and gravity data would constrain crustal thicknesses and thermal gradients in the lithosphere, which determines the amount of crust that may retain TRM at present day. Missions that provide global coverage would feed forward into site selections for future searches. Targeted investigations of particular areas at higher resolution would be complementary.

5. Summary and Conclusions

Detecting crustal remanent magnetism on Venus would confirm multiple hypotheses that now lack direct support. First, surface temperatures would have remained below the Curie points of common magnetic minerals in recent times. Second, the core of Venus would have formed hot and chemically homogenous, meaning that Venus and Earth both suffered energetic giant impacts towards the end of accretion that mechanically mixed the core. The age of latest magnetization would be a key constraint on thermal evolution if the core has fully solidified.

Venus is potentially also a Rosetta Stone for terrestrial exoplanets. Atmospheric loss processes and thus habitability may depend on whether global magnetic fields mediate interactions with space weather. However, no general model can rest on a foundation of fundamental ignorance about the formation and evolution of Earth and Venus. Searching for crustal remanent magnetism on Venus would help determine if atmospheric escape from Venus occurred mostly in the absence of a magnetic field, and whether the Earth-Venus dichotomy originated from stochastic processes during accretion.

References

[1] Phillips, J. L. and Russell, C. T.: Upper limit on the intrinsic magnetic field of Venus, Journal of Geophysical Research, Vol. 92, pp. 2253, 1987.

[2] Stevenson, D. J.: Planetary Magnetic Fields: Achievements and Prospects, Space Science Reviews, Vol. 152, pp. 651-664, 2010.

[3] Nimmo, F.: Why does Venus lack a magnetic field?, Geology, Vol. 30, pp. 987-990, 2002.

[4] Dumoulin, C., et al.: Tidal constraints on the interior of Venus, Journal of Geophysical Research: Planets, Vol. 122, pp. 1338-1352, 2017.

[5] Jacobson, S., et al.: Formation, stratification, and mixing of the cores of Earth and Venus, Earth and Planetary Science Letters, Vol. 474, pp. 375-386, 2017.

[6] Foley, B. J. and Driscoll, P. E.: Whole planet coupling between climate, mantle, and core: implications for rocky planet evolution, Geochem. Geophys. Geosyst., Vol. 17, pp. 1885-1914, 2016.

[7] O'Rourke, J. G., Gillmann, C., and Tackley, P.: Prospects for an ancient dynamo and modern crustal remanent magnetism on Venus, Earth and Planetary Science Letters, Vol. 502, pp. 46-56, 2018.

[8] O'Rourke, J. G., Buz., J., Fu, R. R., and Lillis, R. J.: Detectability of Remanent Magnetism in the Crust of Venus, Geophysical Research Letters, in revision, 2019.