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Thermal evolution of Venus with argon degassing

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ABSTRACT

Decades-old measurements of atmospheric and elemental surface composition constrain the history of Venus. In this study, we search for a model featuring continuous evolution in the stagnant-lid regime that predicts the present-day atmospheric mass of radiogenic argon and satisfies the other available constraints. For comparison, we also consider the end-member scenario of a single catastrophic resurfacing event. Thermal evolution simulations are performed that track the mass transport of argon and potassium and include a simple model of upwelling mantle plumes. Sensitivity analyses and linear regression are used to quantify the range of initial conditions that will produce desired values for key model output parameters. Decompression melting of passively upwelling mantle causes considerable mantle processing and crustal growth during the early evolution of Venus. Mantle plumes have negligible effects on recent crustal production, but may be important to local surface features. For a wide range of initial conditions, continuous evolution in the stagnant-lid regime predicts the correct amount of argon degassing, along with the absence of a global magnetic field, crustal and lithosphere thicknesses matching modern estimates, and volcanism consistent with the cratering record. Argon degassing does not uniquely constrain mantle dynamics, but the success of simple stagnant-lid models diminishes the need to invoke dramatic changes like catastrophic resurfacing.

1. Introduction

Venus, like Earth, is an engine that converts heat into interesting phenomena. Given their comparable orbital parameters, masses, and radii, Venus likely also differentiated into a silicate mantle and an iron-rich core, although its moment of inertia is not actually known (Bills et al., 1987). Dichotomous surface conditions are the most obvious proof that the evolution of Venus and Earth sharply diverged at some point. Earth is habitable and even clement, but greenhouse gases have raised surface temperatures on Venus to roughly 740 K (e.g., Bullock and Grinspoon, 2001). Whereas mantle dynamics cause frequent surface recycling on Earth through plate tectonics, mantle convection on Venus currently occurs below a rigid lithosphere that encompasses the entire planet (e.g., Kaula and Phillips, 1981; Solomatov and Moresi, 1996). In fact, all terrestrial planets in our Solar System besides Earth presently operate in this stagnant-lid regime of mantle convection (e.g., Schubert et al., 2001), which is perhaps natural because the viscosity of materials comprising terrestrial planets is strongly temperature-dependent (Solomatov, 1995). No consensus exists, however, as to whether Venus exhibited dramatically different internal dynamics in the past, complicating the interpretation of surface geology.

Some models attempt to couple the evolution of both the interior and atmosphere of Venus (e.g., Phillips et al., 2001; Noack et al., 2012; Driscoll and Bercovici, 2013; Gillmann and Tackley, 2014). Greenhouse warming of the atmosphere may cause periodic increases in surface temperature to ~1000 K, possibly sufficient to cause episodic transitions from the stagnant- to mobile-lid regime by reducing the viscosity contrast across the lithosphere (Noack et al., 2012). High surface temperatures are also suggested to favor an episodic or stagnant-lid regime over plate tectonics for three reasons. First, a hot surface may eventually result in increasing mantle temperatures, causing convective stress to drop below the lithosphere yield stress on a ~1 Gyr timescale (Lenardic et al., 2008). Second, a non-Newtonian rheology based on damage theory predicts that high temperatures strengthen the lithosphere through a higher healing rate within ~100 Myr (Landuyt and Bercovici, 2009). Finally, high surface temperatures preclude the presence of surface water, which may be important to the generation of plate tectonics through lowering the brittle strength of lithosphere (e.g., Moresi and Solomatov, 1998; Korenaga, 2007).

Impact craters revealed by synthetic aperture radar images collected during NASA's Magellan mission provide major constraints

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on the evolution of Venus. The spatial coordinates of the ~1000 craters are indistinguishable from a random distribution. Only a few (<10%) craters are obviously embayed by lava flows that breach their rims and cover their ejecta blankets. These two facts motivated the catastrophic resurfacing hypothesis, in which an episode of extreme volcanism lasting ~100 Myr covered the vast majority of the surface in km-thick flows (e.g., Schaber et al., 1992; Strom et al., 1994). According to studies of the likely impactor population and atmospheric screening, catastrophic resurfacing would have occurred between ~300 Ma and 1 Ga (e.g., McKinnon et al., 1997). Catastrophic resurfacing is also compatible with the so-called directional stratigraphy that categorizes morphologically similar terrains as globally synchronous units (e.g., Ivanov and Head, 2013). Theorists have invoked many mechanisms to explain catastrophic resurfacing, ranging from episodic subduction caused by lithosphere thickening above a warming mantle (Turcotte, 1993; Fowler and O'Brien, 1996) to brittle mobilization of the lithosphere (Moresi and Solomatov, 1998) to lid overturn caused by low yield stress (Armann and Tackley, 2012; Gillmann and Tackley, 2014). Transitions between the thick- and thin-lid branches of stagnant-lid convection (Reese et al., 1999) or a cessation of plate tectonics (e.g., Phillips and Hansen, 1998) have also been proposed. In any model, some recent volcanism is also required to explain the existence of young lava flows identified as high emissivity anomalies in Venus Express data (Smrekar et al., 2010) and sulfuric acid/water clouds, which would not persist without volcanic replenishment of SO_2 that is otherwise removed from the atmosphere within ~50 Myr (Fegley and Prinn, 1989; Bullock and Grinspoon, 2001).

Other evidence casts doubt on the idea of catastrophic resurfacing. Alternative stratigraphic studies suggest that local processes operating gradually throughout geologic time produced the surface features on Venus (Guest and Stofan, 1999). New mapping, for example, reveals that ribbon tesserae terrain records a geologic history that predates the formation of many other features attributed to catastrophic resurfacing (Hansen and Lopez, 2010). Non-catastrophic processes can also explain every characteristic of the cratering record. Localized resurfacing events can produce a random-looking distribution of craters and a low number of obviously embayed craters (Phillips et al., 1992; Bjonnes et al., 2012; O'Rourke et al., 2014). New studies argue that post-impact lava flows have partially filled the craters with radar-dark floors, which comprise ~80% of the total population (Wichman, 1999; Herrick and Sharpton, 2000; Herrick and Rumpf, 2011). Statistical modeling demonstrates that localized resurfacing events consisting of thin, morphologically indistinguishable flows can explain the number and spatial distribution of these dark-floored craters (O'Rourke et al., 2014). A minor amount of regionally concentrated volcanism can explain the relatively few, clustered craters that are obviously embayed in Magellan imagery.

Besides impact craters, the thicknesses of the crust and lithosphere of Venus provide important constraints on models of its history. Using gravity and topography data to construct a map of crustal thicknesses, however, requires an estimate of the mean crustal thickness, which is subject to large uncertainty. James et al. (2013) calculated the mean thickness of the crust as ~8–25 km, with an upper limit of ~45 km, using a two-layered crustal thickness inversion. Previous estimates of the present-day crustal thickness range from ~20 to 60 km (e.g., Smrekar, 1994; Simons et al., 1997; Nimmo and McKenzie, 1998). The observed topography may provide coarse upper bounds for crustal thickness because it would significantly relax if the curst were thick enough to cause lateral flow (Nimmo and Stevenson, 2001) or to undergo the phase transition from (metamorphosed) basalt to eclogite (e.g., Namiki and Solomon, 1993). Constraints on the thickness of the mantle lithosphere of Venus are likewise loose. Some authors favor a relatively thick lithosphere, usually ~200–400 km (e.g., Turcotte, 1993; Solomatov and Moresi, 1996), but data permit values as high as ~600 km (Orth and Solomatov, 2011). Thinner (~100 km) lithosphere allows a larger magnitude of melt generation to explain recent resurfacing (e.g., Schubert, 1994; Smrekar, 1994; Simons et al., 1997; Nimmo and McKenzie, 1998).

Observations suggest that the core of Venus is likely cooling, but not convecting with sufficient vigor to produce a dynamo. Features in gravity field and topography data that are associated with large volcanic rises, high radar emissivity anomalies, and stratigraphically young flows indicate the presence of several plumes upwelling from the lower mantle (Stofan et al., 1995; Smrekar et al., 2010; Smrekar and Sotin, 2012). The existence of plumes might imply, at minimum, a positive heat flux across the core/mantle boundary (e.g., Weizman et al., 2001). However, Venus today has no global magnetic field (Phillips and Russell, 1987). Paleomagnetic evidence indicates that Earth's dynamo, in contrast, has persisted for more than 3.4 Gyr (Tarduno et al., 2010). Perhaps Venus lacks an inner core and thus compositional convection or, less likely, the core is completely frozen solid (Stevenson et al., 1983; Stevenson, 2003). Stagnant-lid convection is inefficient compared to plate tectonics, so the mantle will tend to insulate the core and limit cooling (e.g., Driscoll and Bercovici, 2014). Recent theoretical and experimental work indicates that the thermal conductivity of iron alloys at core conditions is possibly very high, meaning that driving a dynamo with thermal convection alone is quite difficult (e.g., Pozzo et al., 2012; Gomi et al., 2013). Significant cooling still is required even if conventionally low values for thermal conductivity are actually correct (e.g., Zhang et al., 2015). Another possibility is that the core became compositionally stratified and thus convectively stable during accretion, since more light elements tend to enter core material as pressure/temperature conditions increase (e.g., Rubie et al., 2015).

Degassing of noble-gas elements has long been incorporated into thermal evolution models for Earth (e.g., Sleep, 1979; Tajika and Matsui, 1993), but few studies have applied the same techniques to Venus. Argon-40, in particular, is produced by the decay of radioactive ^{40}K in the interior of Venus and released to the atmosphere through volcanism. The present-day atmospheric abundance of ^{40}Ar has been measured as 3.3 ± 1.1 ppb relative to the mass of Venus or $1.61 \pm 0.54 \times 10^{16}$ kg (von Zahn et al., 1983). This datum has been used to test the plausibility of ad hoc crustal production histories for Venus (Namiki and Solomon, 1998) and to place more general constraints on crustal thickness and the evolution of Venus (Kaula, 1999). A 2D cylindrical model with strongly temperature- and pressure-dependent viscosity confirmed that a substantial fraction of argon could degas even without plate tectonics (Xie and Tackley, 2004). Different modes of mantle convection may cause varying amounts of volcanism and thus degassing (e.g., O'Neill et al., 2014). One experimental study potentially diminishes the utility of ^{40}Ar degassing as a constraint on planetary evolution, however, claiming that argon may be more compatible with basaltic melts than olivine and that argon diffusion takes place very slowly (Watson et al., 2007). But a more recent investigation with a different experimental approach suggests that the results of Watson et al. (2007) may not properly represent bulk crystalline properties, thus supporting the usual assumptions that argon is incompatible and that diffusion can occur quickly at high temperatures (Cassata et al., 2011).

The purpose of this study is to evaluate whether models of the evolution of Venus can predict the present-day atmospheric mass of radiogenic argon while satisfying other available constraints. We use parameterized models of stagnant-lid convection, which have long been applied to the terrestrial planets in our Solar System (e.g., Stevenson et al., 1983). A scaling law of stagnant-lid