Could the Migration of Jupiter have Accelerated the Atmospheric Evolution of Venus?

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Abstract: In the study of planetary habitability and terrestrial atmospheric evolution, the divergence of surface conditions for Venus and Earth remains an area of active research. Among the intrinsic and external influences on the Venusian climate history are orbital changes due to giant planet migration that have both variable incident flux and tidal heating consequences. Here, we present the results of a study that explores the effect of Jupiter's location on the orbital parameters of Venus and subsequent potential water loss scenarios. Our dynamical simulations show that various scenarios of Jovian migration could have resulted in orbital eccentricities for Venus as high as 0.31. We quantify the implications of the increased eccentricity, including tidal energy, surface energy flux, and the variable insolation flux expected from the faint young Sun. The tidal circularization timescale calculations demonstrate that a relatively high tidal dissipation factor is required to reduce the eccentricity of Venus to the present value, which implies a high initial water inventory. We further estimate the consequences of high orbital eccentricity on water loss, and estimate that the water loss rate may have increased by at least ~5% compared with the circular orbit case as a result of orbital forcing. We argue that these eccentricity variations for the young Venus may have accelerated the atmospheric evolution of Venus toward the inevitable collapse of the atmosphere into a runaway greenhouse state. The presence of giant planets in exoplanetary systems may likewise increase the expected rate of Venus analogs in those systems.

Introduction: The current state of the Venusian atmosphere and the pathway through which it arrived there is an exceptionally complicated topic. Numerous studies have provided insights into the climate evolution of Venus and discussed primary influences on the atmospheric dynamics (Bullock & Grinspoon 1996; Taylor & Grinspoon 2009; Taylor et al. 2018). The evolutionary history of the atmosphere of Venus, and its potential divergence from a temperate "Earth-like" climate, depends heavily upon assumptions regarding the initial conditions. For example, Hamano et al. (2013) proposed that Venus may have never had surface liquid water oceans due to an extended magma surface phase. Alternatively, some models suggest that Venus may have had temperate surface conditions that allowed the persistence of surface liquid water until as recently as ~0.7 Ga (Way et al. 2016), depending upon assumptions regarding rotation rates and convection schemes (e.g., Leconte et al. 2013; Ramirez 2018). Such potential for past Venusian surface habitability has been the basis for defining the empirically derived inner edge of the "Habitable Zone" (Kasting et al. 1993; Kopparapu et al. 2014; Kane et al. 2016). The connection to planetary habitability has further fueled the relevance of Venus to refining models of exoplanets (Kane et al. 2019), both in terms of studying atmospheric chemistry (Schaefer & Fegley 2011; Ehrenreich et al. 2012) and detection prospects for potential Venus analogs (Kane et al. 2014; Ostberg & Kane 2019).

In the consideration of climate evolution, the orbital parameters of a planet can play a key role in the energy budget distribution over the surface of the planet (Kane & Torres 2017). In particular, it has been demonstrated that the orbital eccentricity can have significant consequences for the climate evolution of terrestrial planets (Way & Georgakarakos 2017; Palubski et al. 2020). Overall planetary system architectures can also play a role, such as the effect of Jupiter on impact rates (Horner & Jones 2008) and refractory elemental abundance (Desch et al. 2018) in the early inner solar system. Correia et al. (2012) showed that the eccentricity of planetary orbits can be increased by the excitation effects of outer planets that exceed the dampening effects of tidal heating. For those planets where the eccentricity contributes to significant tidal heating, the additional surface energy flux can trigger a runaway greenhouse for an otherwise temperate terrestrial planet (Barnes et al. 2013). Furthermore, the current rotation rate of Venus appears to be impacted by eccentricity and resulting solar tidal torques (Ingersoll & Dobrovolskis 1978; Green et al. 2019), in addition to interactions between the atmosphere and topography (Fukuhara et al. 2017; Navarro et al. 2018)

Results: Using the results of our extensive suite of dynamical simulations, we extracted the minimum and maximum orbital eccentricities attained by Venus for the full range of Jupiter semi-major axis values. Our eccentricity data show that the most powerful perturbations to the Venusian orbit occur when Jupiter is located in the vicinity of 4.3 AU. The maximum Venusian eccentricity of 0.31 occurs at a Jupiter semi-major axis of 4.31 AU. If Venus once had an orbital eccentricity as high as 0.31, then the question remains as to how the orbit circularized to its current state. One of the most efficient mechanisms to circularize a planetary orbit is through tidal interactions between the planet and its host star. Our tidal dissipation calculations suggest that the effects of tides may have played a key role in circularizing and stabilizing Venus's orbit. We found that the current value of Venus's tidal dissipation is not enough to achieve this, suggesting that Venus was not as dry in the past as it is today. To circularize its orbit over the timescale of the age of the solar system (~4000 Myr, post gas phase and migrations), the dissipation factor needed is 1.5 current Earth values. This suggests that Venus might have had a water-rich past, possibly in the form of surface or sub-surface oceans.

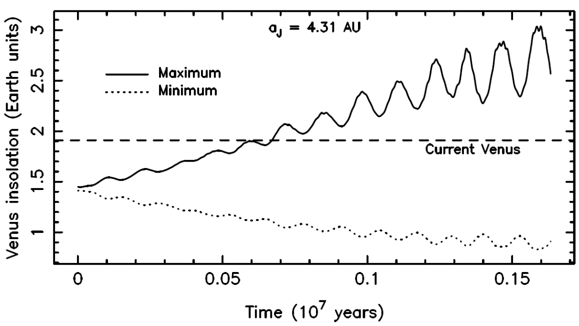

Figure 1: Maximum insolation (perihelion passage) and minimum insolation (aphelion passage) at Venus as a function of time.

To simulate the expected insolation flux of Venus during a possible early era with a high eccentricity, we adopt a solar luminosity that is 75% of the current value. At the semi-major axis of Venus, this results in an insolation flux of S/S0 = 1.43, where S0 is the present-day solar flux received at Earth. The evolution of the maximum flux (perihelion) and minimum flux (aphelion) received by Venus is represented in Figure 1. Venus starts in a circular orbit, then the rise in eccentricity results in a maximum insolation flux that rapidly starts to oscillate high above its present value, indicated by the horizontal dashed line.

Conclusions: The study presented here specifically investigates the effect of possible orbital dynamical scenarios on the evolution of an early Venus. Our simulations and subsequent analyses demonstrate that (1) the eccentricity of the Venusian orbit is dramatically increased for particular locations of Jupiter and (2) the consequences of the increased eccentricity would have included a significantly increased rate of surface liquid water loss. Our investigations of tidal dissipation and circularization timescales show that damping the eccentricity perturbations of Venus to their current value requires a larger initial water inventory than that for the current Earth, lending credence to the notion of substantial water delivery to an early Venus.

These results have been published in the Planetary Science Journal and are available on arXiv (arXiv:2008.04927).

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