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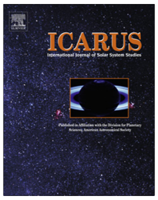

Effect of a single large impact on the coupled atmosphere-interior evolution of Venus

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ABSTRACT

We investigate the effect of a single large impact either during the Late Veneer or Late Heavy Bombardment on the evolution of the mantle and atmosphere of Venus. We use a coupled interior/exterior numerical code based on StagYY developed in Gillmann and Tackley (Gillmann, C., Tackley, P.J. [2014]. J. Geophys. Res. 119, 1189–1217). Single vertical impacts are simulated as instantaneous events affecting both the atmosphere and mantle of the planet by (i) eroding the atmosphere, causing atmospheric escape and (ii) depositing energy in the crust and mantle of the planet. The main impactor parameters include timing, size/mass, velocity and efficiency of energy deposition. We observe that impact erosion of the atmosphere is a minor effect compared to melting and degassing triggered by energy deposition in the mantle and crust. We are able to produce viable pathways that are consistent with present-day Venus, especially considering large Late Veneer Impacts. Small collisions (<100 km radius) have only local and transient effects. Medium-sized impactors (100–400 km) do not have much more consequence unless the energy deposition is enhanced, for example by a fast collision. In that case, they have comparable effects to the largest category of impacts (400–800 km): a strong thermal anomaly affecting both crust and mantle and triggering melting and a change in mantle dynamics patterns. Such an impact is a global event and can be responsible for volcanic events focused at the impact location and near the antipode. Depending on the timing of the impact, it can also have major consequences for the long-term evolution of the planet and its surface conditions by either (i) efficiently depleting the upper mantle of the planet, leading to the early loss of its water or (ii) imposing a volatile-rich and hot atmosphere for billions of years.

1. Introduction

The surfaces of the terrestrial bodies show that impact craters are a common feature in the Solar System. That is especially true for the Moon, Mercury and Mars, but craters can also be found on Earth. Venus is certainly no exception, although the present-day surface of Venus displays a relatively small number of craters due to the young surface age of 300–1000 Ma (Schaber et al., 1992; Herrick, 1994; Strom et al., 1994; McKinnon et al., 1997). In fact, a large early collision is considered to be a possible reason for Venus' slow and retrograde rotation (Baines et al., 2013; Raymond et al., 2013). While the present-day surface of Venus gives us few definite clues about its past impact history, comparison with the Earth and the other terrestrial bodies and numerical simulations indicates that the terrestrial planets experienced early on an intense bombardment by all types of bodies ranging from small sizes to impactors on the 100 km scale or even larger. The final stages of Earth's accretion involved bodies with up to Mars' mass (Hartmann and Davis, 1975; Cameron and Ward, 1976; Canup and Asphaug, 2001; Canup, 2004) or even larger (Canup, 2012), while afterwards, impacting bodies tend to decrease in size, mass and frequency.

Geochemical data indicate that after the formation of both the Earth's Moon and the Earth's core siderophile elements must have been introduced via chondritic impactors into the Earth's mantle. This Late Veneer (LV) arises from the clearing of leftover planetesimals from planetary accretion declining for several hundred million years, typically occurring between the time of the Moon forming impact and 500 Ma after the start of the accretion (Raymond et al., 2013). Numerical simulations of the LV phase by Raymond et al. (2013) imply the delivery of a total mass around $9 \cdot 10^{-3}\ M_{\mathrm{Earth}}$. Jacobson et al. (2014) find a slightly lower value

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around $5 \cdot 10^{-3}$ M_{Earth}. Models by both Bottke et al. (2010) and Raymond et al. (2013) suggest that the majority of the LV material was delivered by a few large impactors with up to lunar-size. The results of Raymond et al. (2013) also show that during this epoch Venus must have accreted comparable amounts of material as did Earth.

After the end of the LV, an impact spike, the so-called Late Heavy Bombardment (LHB), occurred. It has been suggested that this spike is correlated with the change of orbital architecture of the giant planets occurring around 500 Ma after the start of the Solar System (Tsiganis et al., 2005; Levison et al., 2011) and ending around 3.8 Ga ago. The total mass of impact material during the LHB phase is controversial (Levison et al., 2001; Ryder, 2002; Dauphas, 2003; Bottke et al., 2007; Marty and Meibom, 2007; Frey, 2008; Jørgensen et al., 2009). Due to age uncertainties in crater counting the use of scaling laws can only provide estimates. However, a total mass of about 10^{-4} M_{Earth} was suggested by various authors (Levison et al., 2001; Gomes et al., 2005; Jørgensen et al., 2009; De Niem et al., 2012). Since models indicate that much of the impactor material comes from the asteroid belt, models using the size–frequency distribution of the present-day asteroid belt suggest that during this epoch most material was delivered by few larger impactors with up to a few hundred km size (e.g. Abramov and Mojzsis, 2009).

It is believed that impactors of ~500 km diameter affect the habitability of a planet since they boil away oceans, thus affecting water and surface conditions at the large scale. Zahnle et al. (2007) discuss a qualitative scenario for the outcome of such an impact. The short-term effects are cataclysmic, with the production of a rock vapor atmosphere of 100 bar of sublimated silicates. Surface temperatures can immediately (within a timescale of hours to days) reach very high values (~1000 K). However, heat is efficiently radiated into space. In the medium-term, a steam atmosphere is present, limiting heat loss to space at the top of the cloud layer. This way, surface temperatures can stay high for a few 10^3 years and liquid water cannot be sustained. The long-term effects of such an impact are, however, less certain. Possible climatic consequences of impacts through the release of volatiles into the atmosphere are important and complex (Solomon et al., 1999; Bullock and Grinspoon, 2001; Segura et al., 2013). In the particular case of Venus, the chemistry of the atmosphere would be largely influenced by an impact, affecting the regular greenhouse effect, but more importantly cloud formation and albedo changes (Segura et al., 2013). At the moment, however, the precise effects of an impact are still unclear.

Here we use the newly developed coupled mantle-atmosphere methodology presented by Gillmann and Tackley (2014) to study these uncertain long-term effects of large impacts occurring during the LV and LHB epoch. For this purpose we choose to neglect the more immediate effects of impacts described above and to work on long-lasting volatile and energy exchanges. Such an approach fits better with the rest of our numerical model, employing time steps around 10^4 years, whereas most of the effects described above tend to settle down on a 10^3 years timescale. Such a high time resolution would only be needed to study the climatic effects during the presence of a steam atmosphere. Additionally, most numerical simulations used to study the long-term evolution of terrestrial planets are not able to adjust to such quick changes or uncommon conditions (for example rock vapor is a very specific situation that has no consequence for the rest of the evolution) while the calculation time is acceptable.

The structure of the manuscript is as follows: In the next section we describe the coupled model, the applied impact heating model and the atmosphere erosion model. This is followed by a discussion of the model setup. The last three sections contain our findings, the discussion and the conclusions.

2. Model

2.1. Basic coupled model

Our model for the evolution of Venus encompasses various components that represent different aspects of the history of the planet. Here we focus on volatile exchange, as this appears to be the most important feature. The coupling is two-way. Mantle activity leads to degassing, releasing volatiles into the atmosphere and contributing to the greenhouse effect. On the other hand, the greenhouse effect governs the surface temperature, which acts as a boundary condition for mantle convection.

The model is composed of four different parts (Fig. 1): (i) the mantle convection model, (ii) the atmospheric escape module, (iii) the atmosphere model and (iv) the impact module. Part 4 will be described in more detail in a dedicated section below, as it is the latest extension. A detailed description of parts (i), (ii) and (iii) of the coupled model can be found in our previous work (Gillmann and Tackley, 2014). However, for completeness, we present here a brief summary.

Section (i) deals with mantle dynamics, melting and volcanic production. It is based on an adapted version of the state-of-the-art code StagYY (Tackley, 2008; Hernlund and Tackley, 2008). Specifically, we use the same model setup as Armann and Tackley (2012) for Venus, employ similar parameters and apply the same grid resolution in a 2D spherical annulus layout.

A compressible anelastic, infinite Prandtl number mantle is assumed. We solve the mass, momentum and energy conservation equations. Physical properties like density, thermal expansivity, and thermal conductivity are depth-dependent and are calculated as described in Tackley (1996, 1998). Radiogenic heating decays exponentially with time, based on Earth-like concentrations of heat producing elements (Janle et al., 1992; Turcotte, 1995; Nimmo and McKenzie, 1997). The phase transitions in the olivine system and in the pyroxene-garnet system are included as discussed in Xie and Tackley (2004).

The assumed rheology is viscous diffusion creep and plastic yielding (viscoplastic rheology). Diffusion creep parameters are based on laboratory experiments for the upper mantle (Karato and Wu, 1993) and other estimates for the lower mantle (Yamazaki and Karato, 2001). Viscosity is both temperature- and depth-dependent:

$$\eta(T,d) = \eta_0 \exp[(E+Bd)/(RT) - E/(RT_0)] \quad (1)$$

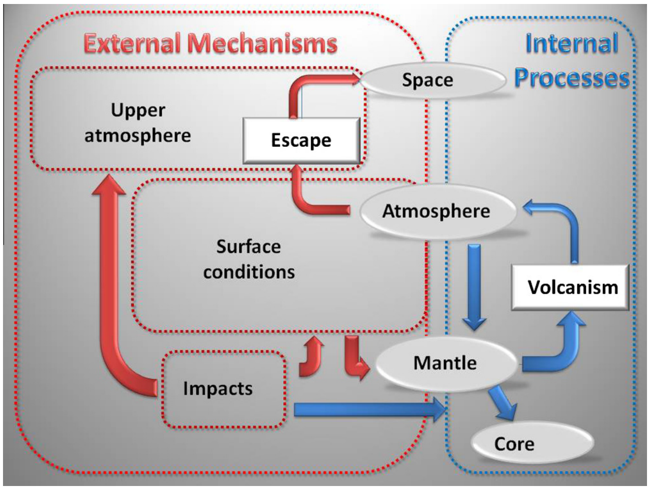

Fig. 1. Layout of the coupled model and interactions between the different parts described in the text.