

**LATE ACCRETION WATER DELIVERY ON VENUS AND VOLATILE HISTORY** C. Gillmann<sup>1</sup>, G. Golabek<sup>2</sup>, S. Raymond<sup>3</sup>, M. Schonbachler<sup>4</sup>, P. Tackley<sup>4</sup>, V. Dehant<sup>5</sup>, V. Debaille<sup>6</sup>. <sup>1</sup>Rice University, Earth Environmental and Planetary Sciences, MS-126, 6100 Main Street, Houston, TX 77005, USA ([cg62@rice.edu](mailto:cg62@rice.edu)). <sup>2</sup>Bayreuth University, <sup>3</sup>Laboratoire d'astrophysique de Bordeaux, <sup>4</sup>ETH Zurich, <sup>5</sup>Royal Observatory of Belgium, <sup>6</sup>Free University of Brussels.

**Summary:** We use numerical simulations to study the bulk atmospheric content evolution over the 4.5 Gyr of the history of Venus, from the Late Accretion up to present-day [1]. We try to quantify Late Accretion delivery of water based on present-day observation of the atmosphere, since isotopic measurements (the usual method of study for the Earth) are unavailable for Venus. We consider volatile exchanges on the global scale. Multiple mechanisms are included in the study, such as all types of atmospheric escape processes, volcanic degassing and mantle dynamics, surface alteration, impact erosion, delivery and melting of the surface and mantle. We investigate the relative importance of those mechanisms for the long term evolution of Venus and their interactions.

We show that Venus, in the most straightforward scenario, is unlikely to have possessed a very large amount of water in its atmosphere for most of its evolution. Only during Late Accretion would this amount be significant and even then, it implies that i) Late Accretion was mostly dry and ii) putative water oceans on Venus were limited to less than a fraction of an Earth Ocean.

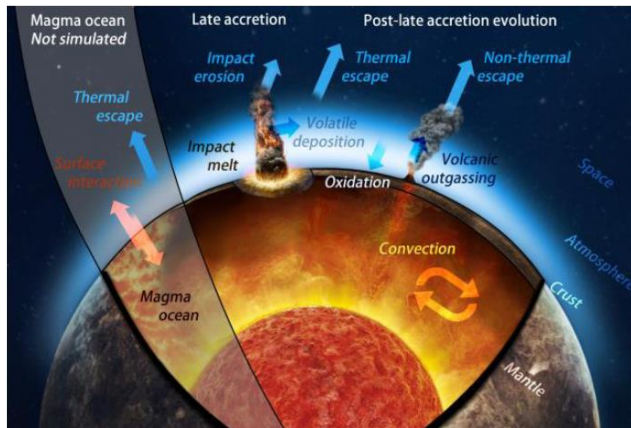


Figure 1: Mechanisms and feedback cycles in the evolution of Venus affecting volatile history, after the end of the magma ocean phase.

**Introduction:** With the eye of the scientific community turning back toward Venus, the question of the evolution of surface conditions on Venus has gathered considerable interest [2, 3].

Due to both the striking similarities and the obvious differences between Earth and Venus,

understanding Venus might hold some of the keys to how planets become habitable. The question of the origin persistence of water in the atmosphere of Venus is directly linked to that of habitability. In the primitive evolution of water reservoirs, could lay a difference between Earth and Venus. Since no sample of Venus can be studied as would be the case for Earth, we turn on alternative methods of investigation and track the evolution of volatiles at the surface of the planet during its history since the end of the magma ocean phase. We compare these scenarios with present-day observation. This allows us to put limits on maximum amounts of volatiles in the atmosphere of Venus through time, on volatile exchanges, and on water delivery.

**Modeling:** We have developed a coupled numerical simulation of the evolution of Venus [1, 4], striving to identify and model mechanisms that are important to the behavior of the planet and its surface conditions. Currently, the simulations include modeling of mantle dynamics, core evolution volcanism, surface alteration, atmospheric escape (both hydrodynamic and non-thermal), the evolution of atmosphere composition, and surface conditions (greenhouse effect), and the coupling between the interior and the atmosphere of the planet.

In an effort to study Late Accretion, we have now modeled the effects of large meteoritic impacts on long term evolution through three aspects: atmosphere erosion, volatile delivery and mantle dynamics perturbation due to energy deposition. Of particular interest are the limits to the volatile exchanges set by present-day observation: we reject any scenario that deviates far from present-day Venus at the end of its simulated history.

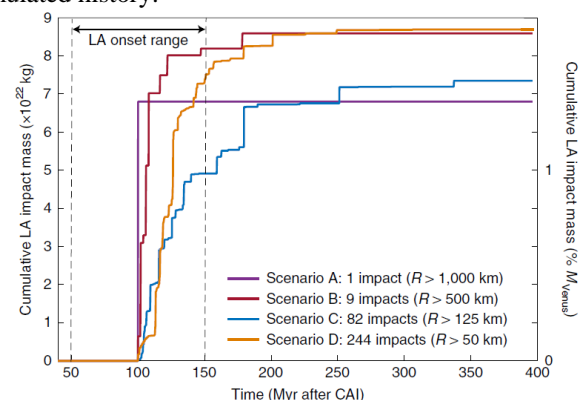


Figure 2: Late Accretion scenarios (mass-radius distributions) and timing used in the simulations.

**Results:** Volatile fluxes between the different layers of the planet are critical to estimate how Venus changed over time. This is especially important as we have highlighted the strong role played by mantle/atmosphere coupling in regulating both mantle dynamics and surface conditions through surface temperature evolution.

Mantle convection regime evolves with time and depends on surface conditions. We produce scenarios that fit present-day conditions and feature both early mobile lid regime (akin to plate tectonics) as well as late episodic lid regime with resurfacing events. However, it is during the early history of Venus, in particular, that we observe the largest volatile exchanges. That era seems to have large repercussions on long term evolution and present-day state, as it determines volatile inventories and repartition.

The effects of impacts dominate the volatile and mantle evolution during Late Accretion. Large impacts are shown to have essential consequences for volatile repartition. The atmosphere erosion they cause is marginal and doesn't deplete the atmosphere as much as swarms of smaller bodies could [5], they instead act as a significant source of volatiles. Indeed, if Late Accretion is mainly composed of volatile-rich bodies; it is very difficult to reach the observed present-day state of Venus; instead the atmosphere may become too wet.

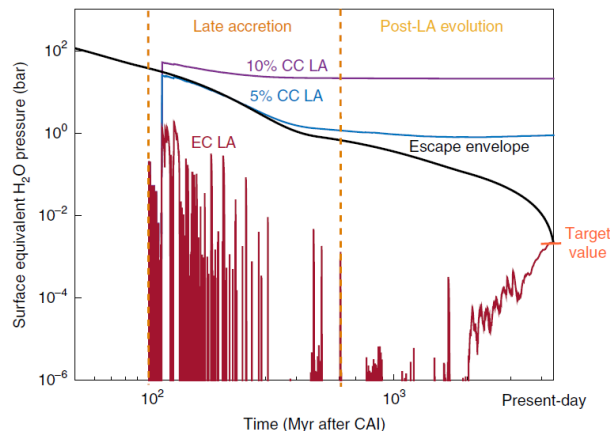


Figure 2: evolution of equivalent water content of the atmosphere of Venus after magma ocean phase up to present-day. Three scenarios are shown depending on late accretion volatile content 100% Enstatite chondrite-like (red), with 5% Carbon chondrites (blue), and with 10% Carbon chondrites (purple).

Simulations show wet material (carbon chondrites) contribution limit at a maximum of 5-10% (mass.) of the total accreted mass during Late Accretion (the larger portion of the Late accretion being composed of enstatite chondrite bodies). In less volatile rich scenarios, water brought by collisions is then lost,

either quickly or over billions of years. A small amount of water is then slowly reinserted in the atmosphere by volcanic outgassing.

In wet scenarios, water is efficiently brought to the surface of Venus and loss mechanisms are not able to remove it later, through solid surface oxidation and atmospheric escape. This then leads to water-rich atmosphere, unlike what we observe today.

Those results are consistent over a large range of simulations with variations of late accretion timing, impactors mass-size distribution, composition, efficiency, mantle parameters and so on.

**Conclusions:** Impact delivery has the potential to be the major source of volatiles for both the interior and the atmosphere of a terrestrial planet like Venus. However, given the present-day observation, the Late Accretion delivery flux has been limited by low volatile concentrations in the impactors, akin to enstatite chondrite bodies. Higher Late Accretion volatile delivery is incompatible with the present-day atmosphere, which is dry and mostly devoid of  $O_2$ . Instead, water should have been delivered earlier, during main accretion, before the last giant impact, as is suggested for Earth from isotopic measurements. Other mechanisms marginally affect early volatile evolution (4.5-3.5 Gyr ago) but are likely to govern later history.

Venus' apparent lack of strong water and  $O_2$  sink means it is more and more difficult to accommodate water oceans at the surface as time passes. Instead, during the last 4 Gyr, a maximum of 2 bar water could have stayed in the atmosphere, most of it more than 3 Gyr ago, corresponding to no more than a 20 m global equivalent layer of liquid water. In such a scenario, earlier oceans could have been somewhat larger, but no more than 0.1 Earth Oceans.

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