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# The Consequences of Late Accretion Volatile Delivery and Loss Mechanisms on Venus' Evolution

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The evolution of surface conditions on Venus has recently made a return to the forefront of planetary sciences questions. Due to both the striking similarities and the obvious differences between Earth and Venus, understanding Venus might hold some of the keys to how terrestrial planets become habitable, either in our solar system or beyond. The question of the origin and persistence of water at the surface/in the atmosphere of Venus determines, in a large part what the planet's evolutionary path has been. The critical difference between Earth and Venus might even be settled during their primordial evolution. Since no sample of Venus can be studied yet, as would be the case for Earth, we turn on alternative methods of investigation. We 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 and derive limits on maximum amounts of volatiles in the atmosphere of Venus through time, on volatile exchanges, and on water delivery.

We have developed coupled numerical simulations of the evolution of Venus, modeling mechanisms that govern its surface conditions and atmosphere composition. Currently, the simulations include modeling of mantle dynamics, core evolution, volcanism, surface alteration, atmospheric escape (both hydrodynamic and non-thermal), greenhouse effect, and the feedback mechanisms between the interior and the atmosphere of the planet. Focusing on Late Accretion, we have 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 transfer. The models are constrained by present-day observation and atmosphere composition, with the requirement that scenarios fit reasonnably the current state of the planet.

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, water outgassing during late evolution could be dampened by high surface pressures. Therefore, 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, 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. Likewise, the likely mass received by Venus during volatile-rich Late Accretion, if completely outgassed into the planet's atmosphere, could lead to masses of $CO_2$ and $N_2$ 3-6 times higher than observed at present-day.

Simulations show that the maximum contribution of wet material impactors (carbon-chondrites-like) is about 5-10% (mass.) of the total accreted mass during Late Accretion (the larger portion of the Late accretion being composed of enstatite-chondrite-like 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. Water should have been delivered early to the terrestrial planets in the solar system, during main accretion, before the last giant impact, as is suggested for Earth from isotopic measurements.

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