The early evolution of Venus controlled by hydrodynamic escape

C. Gillmann[1], E. Chassefière[2] and P. Lognonné[1]

[1] Institut de Physique du Globe de Paris (IPGP), 4 av de Neptune, 94100, Saint Maur, France
[2] CNRS/UPS UMR 8148 IDES Interactions et Dynamique des Environnements de Surface

The atmospheres of Venus and the Earth are quite similar, despite the different ways the planets evolved. Their compositions show an impressive similarity, if we take into account the fact that for the Earth oxygen has been produced by photosynthesis and that CO_2 has been trapped into carbonate deposits, as they are mostly composed of CO_2, nitrogen and noble gases. This similitude points toward a common origin for those three atmospheres and a usual theory is that these atmospheres are secondary, created by the degassing of volatiles from the bodies that constituted the early planet. The atmosphere of Venus could then represent a primitive state of the evolution of terrestrial.

We wish to study the evolution of the primitive atmosphere of Venus and investigate the possibility of an early habitable Venus with a possible liquid water ocean on its surface. We therefore developed a time dependent model of hydrodynamic escape of hydrogen during the first few hundred million years. Oxygen is the second major species in the early atmosphere and we study it through its linked escape with hydrogen. The energy powering the escape comes from solar EUV (Extreme UV) and solar wind and decreases with time (unlike the luminosity of the sun). It is consumed by both H and O, with oxygen using most of it, due to its higher mass.

We track the loss of hydrogen over time and relate it to the equivalent amount of “initial” water it represents. We apply the same principle to the slower escape of oxygen. This enables us to compare the losses to the initial global water content of the planet. We also study specifically the isotopic fractionation of noble gases resulting from hydrodynamic escape. The fractionation’s primary cause is the effect of diffusive/gravitational separation between the homopause and the base of the escape. We compare this fractionation to the Venera data available in order to constrain our scenarios. Heavy noble gases such as Kr and Xe are not fractionated. Ar is only marginally fractionated whereas Ne is moderately fractionated.

Our model suggests that during the first 100 Myr of the evolution of Venus, the content of approximately five terrestrial oceans (5 TO) of water have been lost to space, while reaching present day values for the fractionation of noble gases. Our preferred scenario shows that around 60% of the oxygen contained in this water was left behind in the atmosphere.

We argue that hydrodynamic escape could have controlled the solidification rate of the magma ocean during the end of the accretion period by pumping the water out of the magma. This way, the atmosphere would have been able to maintain a pressure of around 300 bar despite losses. After most of the water in the magma has been extracted, the atmosphere progressively dried up, and the magma ocean crystallized, leading to a final collapse of the hydrodynamic escape around 100 Myr after the beginning of the accretion.

We propose that the dissolution of oxygen in the magma ocean as been able to efficiently remove large amounts of oxygen from the atmosphere. From 100 Myr to 500 Myr, the hydrogen delivered by a late veneer of comets could have been removed by continued thermal escape. The energy available then would have been insufficient to allow oxygen to be escape. At 500 Myr, on Venus would be left a water global equivalent layer of a few meters depth and a dense molecular oxygen atmosphere of around 15 bar. At later times non-thermal mechanisms may have removed most of the remaining water and led to the present D/H ratio. The 15 bar of oxygen may have been lost to crustal oxidation if the resurfacing and oxidation rates have been high enough during the last past 4 billion years.