## Evolution of Atmospheres, Outgassing History, and Water Inventories of terrestrial planets

H. Lammer

*Austrian Academy of Sciences, Space Research Institute, Graz, Austria*

### 1. Introduction

The origin and evolution of the terrestrial planet atmospheres are discussed since their protoplanets have been released from the protoplanetary disk a few million years after the Sun/star and the planets originated. The early disk-embedded phase of the evolution of protoplanetary cores, that can accumulate nebular gas and form thin planetary hydrogen-envelopes, is discussed. As illustrated in Fig. 1, this formation scenario is compared to cases of late stage planet formation where terrestrial planets accrete from large planetary embryos after the protoplanetary gas disk already disappeared.

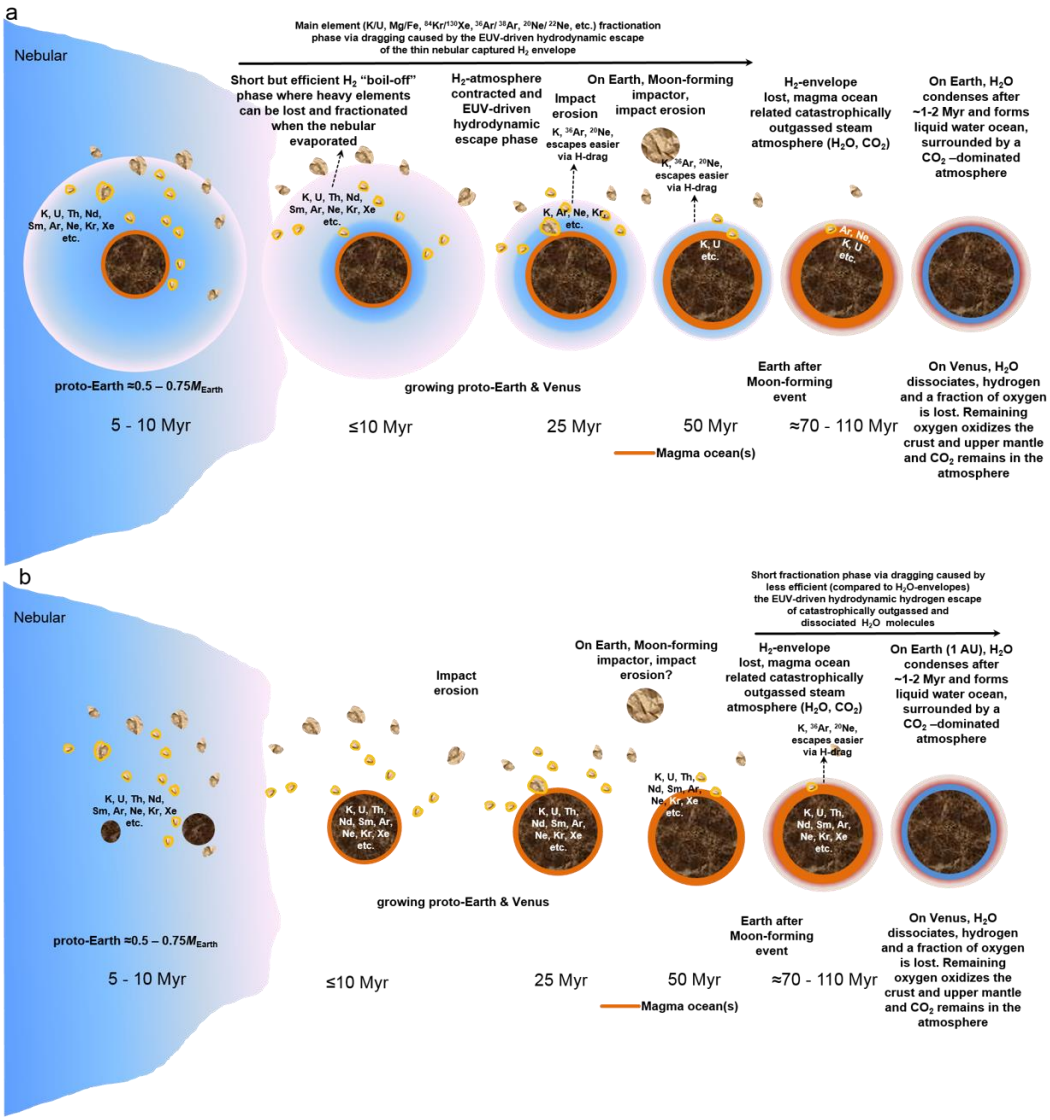


Figure 1: a) Protoplanetary cores accrete fast while they are embedded in the gas disk. A $H_2$-envelope can be captured and should be lost during a short boil-off phase, the young Sun/stars high EUV radiation and impacts. b) Late-stage accretion means that the planet forms mainly after the gas disk disappeared. Both scenarios are accompanied by the solidification of magma oceans and related catastrophic outgassing, leading to steam atmospheres and later to secondary outgassed atmospheres.

After the loss of the primordial atmospheres caused by the EUV radiation of the active young Sun/star, the catastrophic outgassing of volatiles (i.e., $H_2O$, $CO_2$) and the formation and cooling of steam atmospheres after the solidification of magma oceans is addressed together with the geochemical evidence of additional delivery of volatile-rich (i.e., $H_2O$, $NH_3$, HCN, $CO_2$, etc.) chondritic materials to early planets (i.e., Venus, Earth, Mars) during the main stages of their formation. On early Earth and possible similar exoplanets, the

complex interplay between the atmosphere-surface-interaction related $CO_2$ carbonate-silicate cycle and surface weathering of atmospheric constituents is discussed. The differences that occurred on early Earth are then compared with the atmosphere evolution of one-plate planets like Venus or Mars during the first few hundred million years. The diversity between early terrestrial planets related to their geochemical, geodynamical and geophysical conditions, including plate tectonics, crust and mantle oxidation processes and the role of outgassed secondary $N_2$ atmospheres is also addressed.

## 2. Summary

A discussion on the implications of understanding Earth's and Venus geophysical and related atmospheric evolution in relation to the discovery of potential habitable terrestrial exoplanets finalizes and concludes the talk.

## Short Summary

The origin and evolution of the terrestrial planet atmospheres are discussed since their protoplanets have been released from the protoplanetary disk. A discussion on the implications of understanding Earth's/Venus geophysical and related atmospheric evolution in relation to the discovery of potential habitable terrestrial exoplanets finalizes and concludes the talk.