



The effects of mantle dynamics and atmospheric escape on the atmosphere of terrestrial planets.

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Abstract

Mars, Venus and the Earth exhibit very diverse surface conditions as the result of the 4.5 billion years evolution that led to the planets we observe today.

We propose to study the interaction between the atmosphere and the inner dynamics of terrestrial planets by modeling the long term evolution of Mars and Venus. This lets us investigate both the history of the surface conditions of these planetary bodies and the way mantle dynamics and atmospheric evolution are linked.

We generate histories of the state of the atmosphere of these planets as a function of time. We propose to use the recent advances due to observation and modeling to constrain possible evolutions of the atmosphere of terrestrial planets with the help of isotopic data from Carbon, Nitrogen and Argon. CO₂ is the main object of our study.

The processes that are of interest here are atmospheric escape, both hydrodynamic (for early evolution) and non-thermal (during the late history of the planets) and mantle degassing.

1. Method

In order to simulate the global evolution of the atmospheres of terrestrial planets, we need to estimate the fluxes of volatiles entering and leaving those atmospheres. The incoming flux is obtained by modeling the degassing of the planetary mantle. We use several sources to constrain this flux over time. First, several studies have been published, that model the behavior of stagnant-lidded terrestrial planets and their volcanic activity or crust production (for Mars, [2], [5]). The second source for this data, and our main path, is the direct modeling of the mantle dynamics adapting the advanced StagYY code developed by Tackley, [6]. This modeling gives a realistic account of the mantle convection processes

and also includes, among other parameters, mineralogical phase transition and partial melting. Finally, in the case of Mars, we consider the observation of the surface of the planets and the study of different volcanic landforms as a way to constrain our numerical results [4].

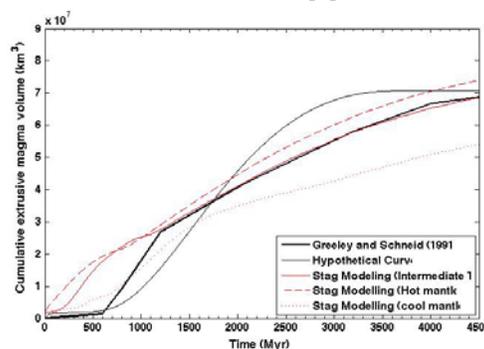


Figure 1: Evolution of the volcanic production on Mars for different models, from observation and numerical modeling.

The atmospheric escape is the main drain of volatiles considered in our model. The main phase evolution of the planet (post 4 Ga) is dominated by non thermal escape. Four different mechanisms are involved in this escape: sputtering, dissociative recombination, ionospheric outflow and ion pick-up. We model the evolution of the outgoing volatile fluxes associated with those processes based on present-day ASPERA (Analyzer of Space Plasma and Energetic Atoms) measurements [3] and the decrease of the Extreme UV (EUV) flux with time. Recent studies of the non-thermal escape fluxes provide a comparison [1]. Thermal escape is important early in the evolution of the planets when EUV flux was higher and the energy brought to the atmosphere by solar emissions was large enough to induce a global outflow of the atmosphere: hydrodynamic escape. This mechanism is important during the first few hundred million years but can be very efficient. We model its behavior and effects on the early conditions.

By combining atmospheric escape, volcanic production and lava composition, we can first operate an integration backward in time, starting with the present day state of the atmosphere, to investigate its past. We are also able to obtain surface conditions and estimate surface temperatures. These surface temperatures can be used to link the state of the atmosphere and the dynamics of the mantle both ways with feedback.

2. Results

The results we obtain allow us to propose different scenarios for the long term evolution of the atmospheres of Mars and Venus depending on parameters such as abundance of volatiles in the mantle and atmospheric escape efficiency. In the case of Mars, our model is able to reproduce present day ^{36}Ar abundance and $^{40}\text{Ar}/^{36}\text{Ar}$ ratio. We also show that the present-day atmosphere of Mars is likely to be constituted by a large part of volcanic gases. With a low CO_2 concentration in the magma (150 ppm), present atmosphere is constructed of 50% of volcanic gases emitted since 3.7 billion years ago, which corresponds to an age of 1.9 to 2.3 Gyr. The variations of CO_2 pressure over this period seem relatively low (50 mbars at most) when we only take into account degassing and non-thermal escape. This seems in line with the assumption of a heavy loss of volatiles during the first 500 Myr.

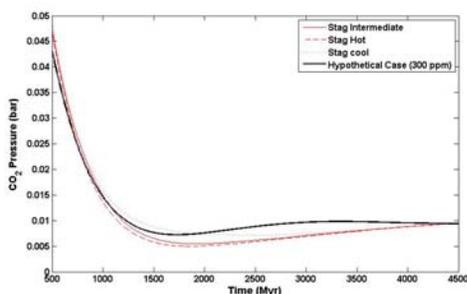


Figure 2 : Evolution of CO_2 pressure over time for Mars depending on the volcanic production (three initial temperatures are used for the modelling : 1600 K, 1800K and 2000K).

The evolution of the isotopic ratio of Nitrogen allow us to hypothesize that it decreased from high primordial values to its present state due to atmospheric escape and that what nitrogen is left in the atmosphere of Mars is old. On the contrary, the CO_2 would be much younger and volcanic degassing would have had a strong effect on the CO_2 isotopic ratio over the last four billion years. Surface

temperature variations are likely to be small (several Kelvin) when we take into account the CO_2 pressure variations and would not be responsible for periods of flowing liquid surface water by themselves. Water is, however, abundant on Mars during the whole 4 billion years evolution (between 30% and 150% of the present day water) but is unlikely to reside in the atmosphere or in liquid form.

In the case of Venus atmospheric escape is much lower than on Mars during the late evolution, in particular when considering the high mass of the atmosphere. This is due to the larger gravity of the planet. Moreover, even early on CO_2 escape at a lower rate by hydrodynamic escape. Other species, such as water, however, are lost efficiently, which could be the cause of the dry state of the present day atmosphere. This is in agreement with calculated isotopic ratios for noble gases such as Neon and Argon.

Acknowledgements

This work was done thanks to the ETH Fellowship program. We would like to thank ETH Zurich and the ETH Zurich research committee for their support.

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