

THE ATMOSPHERIC EVOLUTION OF MARS INDICATED BY C, N, AR, AND H ISOTOPES

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Introduction:

The initial thickness, evolution, and loss of the Martian atmosphere have been the subject of much debate, as these have major implications for the evolving climate and habitability potential of the red planet. Recently, new clues to this problem have been found by integrating atmospheric and geological processes into the models of the isotope budget of the planet. The isotopic composition of carbon, nitrogen, argon, and hydrogen in Mars's atmosphere, together with the extent of carbonates, nitrates, and hydrated minerals found on the planet, provides information about its atmospheric evolution. We have developed a comprehensive model to trace the evolution of the Martian atmosphere, including the impacts of outgassing, escape to space, and sequestration into the crust (Figure 1). As new features, the model integrates the atmospheric and geological sources and sinks and enables the joint analysis of the C, N, Ar, and H isotopes. Recognizing that evolution involves a trajectory in a multi-dimensional phase space of many variables, we have used a million-model approach to rigorously perform quantitative tests against the isotopic composition of the atmosphere and the size of crustal volatile reservoirs.

Results:

The current atmospheric $^{13}\text{C}/^{12}\text{C}$ ratio points to an evolutionary history of CO_2 that started from a moderately dense atmosphere (i.e., $< \sim 1$ bar) at approximately 3.8 billion years before present (i.e., when most valley networks are thought to have been formed). Only scenarios with large amounts of carbonate formation in open lakes permit higher pressures up to 1.8 bar. We also show that a previously unknown family of evolutionary solutions can explain the isotopic composition of nitrogen, without invoking a multi-bar early CO_2 atmosphere or excessive outgassing in the Amazonian. This new family of solutions suggest that Mars had an N_2 -rich early atmosphere, with a partial pressure of ~ 0.3 bar. The outgassing models are consistent with the constraints from Ar's isotopic composition and suggest mantle sources with the oxygen fugacity more reduced than IW. Furthermore, we show that ocean-scale volumes of water on ancient Mars are simultaneously compat-

ible with the evidence of widespread hydrated minerals, H escape rate estimates, and D/H measurements.

Implications:

Collectively, these empirical constraints indicate a multi-component atmosphere in the late Noachian, with the CO_2 partial pressure not much larger than about 1 bar and N_2 as an important component of the atmosphere. Additionally, the crustal sequestration of water and the outgassing from reduced mantle sources may give rise to a substantial component of H_2 in the atmosphere. This new picture of the Martian paleoatmosphere provides a new path forward to explain the geologic records that suggest intermittent conditions for liquid water on ancient Mars's surface and to understand the redox conditions of these past surface environments.

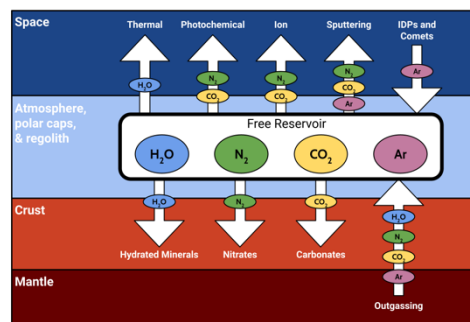


Figure 1: A comprehensive model for the evolution of the Martian atmosphere, including the impacts of outgassing, escape to space, and sequestration into the crust. The model traces the mass and isotopic composition of the volatile reservoirs to the present day, and the results are compared with the isotopic composition of the current atmosphere. The model also takes into account the information about the content of carbonates, nitrates, and hydrated minerals in rock and soil from in situ and remote sensing measurements, and MAVEN's characterization of the upper atmosphere processes.