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EVOLUTION OF THE MARTIAN ATMOSPHERE.

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Evolution of Mars' noble gases through two stages of hydrodynamic escape early in planetary history has been proposed previously by the author [1]. In the first evolutionary stage of this earlier model, beginning at a solar age of ~50 m.y., fractionating escape of a H_2-rich primordial atmosphere containing CO_2, N_2, and the noble gases in roughly the proportions found in primitive carbonaceous (CI) chondrites is driven by intense extreme-ultraviolet (EUV) radiation from the young evolving Sun. Hydrogen exhaustion then leads to a long (~80 m.y.) period of quiescence, followed by abrupt degassing of remnant H_2, CO_2, and N_2 from the mantle and of solar-composition noble gases lighter than Xe from the planet's volatile-rich accretional core. Degassed H refuels hydrodynamic loss in a waning but still potent solar EUV flux. Atmospheric Xe, Kr, and Ar remaining at the end of this second escape stage, ~4.2 G.y. ago, have evolved to their present-day abundances and compositions. Residual Ne continues to be modified by accretion of solar wind gases throughout the later history of the planet.

This model does not address a number of processes that now appear germane to martian atmospheric history. One, gas loss and fractionation by sputtering, has recently been shown to be relevant [2,3]. Another, atmospheric erosion, appears increasingly important [4–6]. In the absence then of a plausible mechanism, the model did not consider the possibility of isotopic evolution of noble gases heavier than Ne after the termination of hydrodynamic escape. Subsequent nonthermal loss of N [7] was assumed, in an unspecified way, to account for the elevation of $\delta^{15}N$ from the model value of ~250‰ at the end of the second escape stage to ~620‰ today. Only qualitative attention was paid to the eroding effects of impact on abundances of all atmophilic species prior to the end of heavy bombardment ~3.8 G.y. ago. No attempt was made to include precipitation and recycling of carbonates [8] in tracking the pressure and isotopic history of CO_2.

All these evolutionary processes, and others, can in fact be modeled in a straightforward way along with hydrodynamic escape. However, their inclusion requires a different mathematical architecture than the closed-form integration of analytic equations across entire escape episodes utilized in [1] to determine the effects of hydrodynamic loss acting alone. An approach in which each of several mechanisms operates independently over short time intervals serves very well [3,9], although at the cost of some computational complexity. In this approach martian atmospheric history is divided into small timesteps, Δt, in the present model of average duration ~0.5 m.y. and ~4 m.y. respectively for times earlier and later than 3.8 G.y. ago. Evolutionary tracking begins ~4.5 G.y. ago at a solar age of ~100 m.y., when a H-rich primordial atmosphere containing CO_2, N, and noble gases of mixed CI-solar composition, degassed by impact from accreting meteoritic and cometary planetesimals during planetary growth, is presumed to surround the planet [1]. The first and subsequent timesteps include evolution from initial atmospheric abundances and isotopic compositions by whichever of the following loss and addition mechanisms are judged to be operative during that interval: EUV-driven hydrodynamic escape, atmospheric erosion by impact, planetary outgassing, sputtering from the exobase by exospheric "pick-up" ions, photochemical escape (for N), and carbonate formation and recycling (for CO_2). Each of these processes is assumed to act independently on the volatile inventories present at the beginning of each Δt timestep. Initial abundances and isotopic compositions for the following timestep are adjusted to reflect losses, gains, and isotopic shifts generated in the atmospheric and carbonate reservoirs during the preceding interval.

This more general procedure has been used to track the noble gases, CO_2, and N from primordial inventories to their present compositional states in a revised model of atmospheric evolution on Mars [9]. Atmospheric history is divided into early and late evolutionary periods, the first characterized by high CO_2 pressures and a possible greenhouse [8] and the second by a low-pressure cap-regolith buffered system [10] initiated by polar CO_2 condensation [11], assumed for illustration to have occurred ~3.8 G.y. ago. During early evolution the Xe isotopes are fractionated to their present composition by hydrodynamic escape, and CO_2 pressure and isotopic history is dictated by the interplay of losses to erosion, sputtering, and carbonate precipitation, additions by outgassing and carbonate recycling, and perhaps also by feedback stabilization under greenhouse conditions. Atmospheric collapse leads to abrupt increases in the mixing ratios of preexisting Ar, Ne, and N_2 at the exobase and their rapid removal by sputtering [3]. Current abundances and isotopic compositions of these light species are therefore entirely determined by the action of sputtering and photochemical escape on gases supplied by planetary outgassing during the late evolutionary epoch. The present atmospheric Kr inventory also derives almost completely from solarlike Kr degassed during this period. Consequently, among current observables, only the Xe isotopes and $\delta^{13}C$ survive as isotopic tracers of atmospheric history prior to its transition to low pressure. With the possible exception of $\delta^{13}C$, this baseline model generates very satisfactory matches to current atmospheric abundances and isotopic compositions.

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EARLY MARS: THE INEXTRICABLE LINK BETWEEN INTERNAL AND EXTERNAL INFLUENCES ON VALLEY NETWORK FORMATION.

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The conditions under which the valley networks on the ancient cratered terrain on Mars formed are still highly debated within the scientific community. While liquid water was almost certainly involved (although this has recently been questioned [1]), the exact mechanism of formation is uncertain. The networks most resemble terrestrial sapping channels [2], although some systems exhibit a runoff-dominated morphology [3]. The major question in the fomation of these networks is what, if anything, do they imply about early martian climate?