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p. 1

**EVOLUTION OF THE MARTIAN ATMOSPHERE.** R. O. Pepin, School of Physics and Astronomy, University of Minnesota, Minneapolis MN 55455, USA.

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, $\Delta t$, 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 $\Delta t$ 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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p. 3

S22-91 N94-21681

**EARLY MARS: THE INEXTRICABLE LINK BETWEEN INTERNAL AND EXTERNAL INFLUENCES ON VALLEY NETWORK FORMATION.** S. E. Postawko[1] and F. P. Fanale[2], [1]School of Meteorology, University of Oklahoma, Norman OK 73019, USA, [2]Planetary Geosciences, University of Hawaii, Honolulu HI 96822, USA.

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?

There are typically two major theories advanced to explain the presence of these networks. The first is that higher internal regolith temperatures, associated with a much higher heat flow 3.8 b.y. ago, would cause groundwater to be closer to the surface than at present [4]. Just how close to the surface groundwater would have to exist in order to form these valley networks has recently been questioned [3]. The second major theory is that early Mars had a much thicker atmosphere than at present, and an enhanced atmospheric greenhouse may have increased surface temperatures to near the freezing point of water [5–7]. While recent calculations indicate that $CO_2$ alone could not have produced the needed warming [8], the presence of other greenhouse gases [8–10] may have contributed to surface warming.

It does not, in fact, make sense on physical grounds to consider these two mechanisms separately. The effectiveness of both atmospheric greenhouse warming and higher internal regolith temperatures on early Mars is dependent on high early heat flow. In the case of the atmospheric greenhouse effect, this is because the abundance of a greenhouse gas (or any gas) in the atmosphere will depend on the supply rate from the interior (which may include supply of both juvenile and recycled gases), which can be related to the heat flow. The depth to the liquid water level, which depends on internal regolith temperatures, can also be related to heat flow. We have derived a quantitative relationship between the effectiveness of an atmospheric greenhouse and that of internal regolith temperature in producing the morphological differences between early and later martian terrains. While our arguments here are based on $CO_2$ as the dominant atmospheric gas, similar arguments can undoubtedly be made for the supply of other gases to the atmosphere.

For any set of martian orbital parameters and level of solar activity, the atmospheric $CO_2$ pressure controls the surface temperature. For a chosen total $CO_2$ inventory (atmosphere plus regolith), and specified atmospheric mean residence time for $CO_2$, the $CO_2$ atmospheric pressure is controlled by the mean residence time of $CO_2$ in the regolith as carbonate. It has been shown [7] that the atmospheric $P_{CO_2}$ can be expressed as a function of heat flow. In addition, for any given regolith conductivity, the heat flow equation also allows temperature at any depth (and thus the depth to the 273 K isotherm) to be expressed as a function of surface temperature and heat flow. Therefore, for any assumed atmospheric mean residence time, regolith conductivity, and total available $CO_2$ inventory, the depth to the 273 K isotherm can be expressed as a function of surface temperature. The relationship between surface temperature and depth to the 273 K isotherm has been derived using relationships already in the literature [7,8]. Figure 1 illustrates that, for a given set of assumptions, the relative roles of internal regolith temperature and atmospheric greenhouse effect are inextricably interlocked. In all cases, the atmospheric mean residence time of $CO_2$ is taken to be $10^7$ yr, and regolith conductivity is $0.5 \times 10^3$ mW $m^{-1}$ $K^{-1}$. The numbers in parentheses correspond to heat flow, in units of mW $m^{-2}$. In Fig. 1a the total available $CO_2$ inventory is 1 bar, while in Fig. 1b the total $CO_2$ inventory is 5 bar. It is clear from these figures that if the total available $CO_2$ was on the order of 1 bar, then the atmospheric greenhouse effect plays a very minor role in raising the depth at which liquid water may be found, particularly in areas outside the equatorial region. If the total available $CO_2$ was at the upper end of the expected value range (4 bar or more), then the atmospheric greenhouse effect dominates almost completely in the equatorial region. However, on a global basis the suppression of

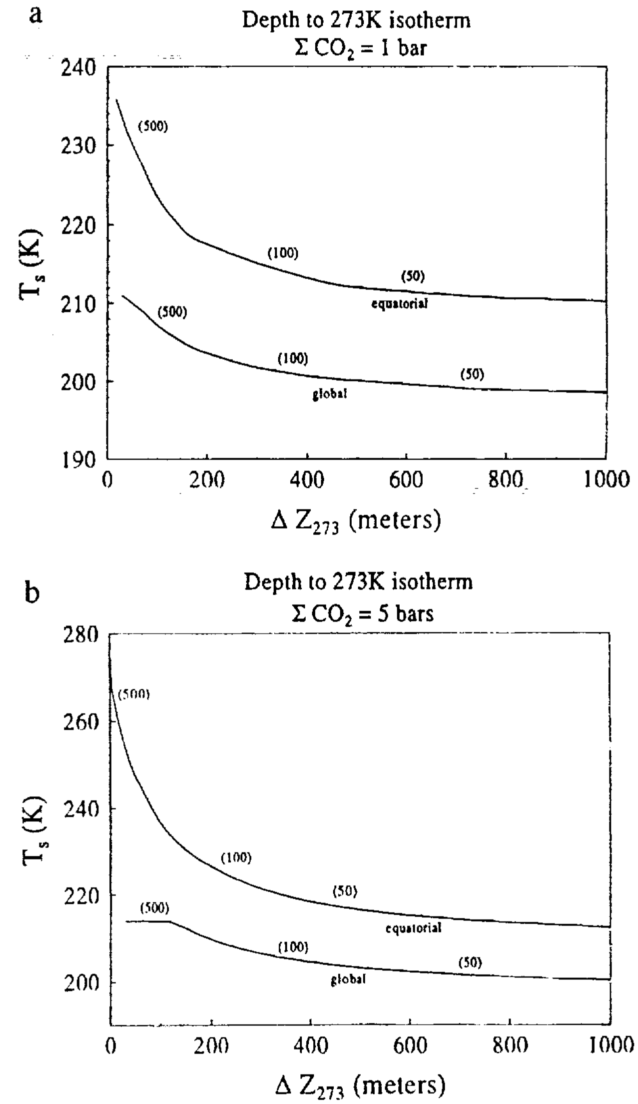


**Fig. 1.**

surface warming by condensation of atmospheric $CO_2$ [8] means that even when relatively large amounts of $CO_2$ are available the atmospheric greenhouse effect is minimal. Nevertheless, even in these cases, a change in internal gradient accompanying a higher early heat flow can still easily decrease the depth to liquid water from well over a kilometer to less than 350 m.

Many uncertainties still exist in assessing the absolute importance of an atmospheric greenhouse effect vs. higher internal regolith temperatures on early Mars. These include the question of regolith conductivity and the magnitude and timing of changes in solar luminosity, as well as the depth at which liquid water must exist in order to be able to form the valley networks. In addition, although we have examined the effectiveness of atmospheric greenhouse warming due to $CO_2$, as was previously noted it is possible that other greenhouse gases were present in the early martian atmosphere. Any calculations of the greenhouse contribution of these gases, some of which may have had relatively short atmospheric lifetimes, will need to take into account the rate at which they may have been supplied to the atmosphere. Schemes analogous to that presented for $CO_2$ will have to be explored in order to assess the absolute contribution of any potential greenhouse gas on early Mars.

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## THE MARTIAN VALLEY NETWORKS: ORIGIN BY NIVEO-FLUVIAL PROCESSES.

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The valley networks may hold the key to unlocking the paleoclimatic history of Mars. These enigmatic landforms may be regarded as the martian equivalent of the Rosetta Stone. Therefore, a more thorough understanding of their origin and evolution is required. However, there is still no consensus among investigators regarding the formation (runoff vs. sapping) of these features.

Recent climatic modeling [1] precludes warm (0°C) globally averaged surface temperatures prior to 2 b.y. when solar luminosity was 25–30% less than present levels. This paper advocates snowmelt as the dominant process responsible for the formation of the dendritic valley networks. Evidence for martian snowfall and subsequent melt has been discussed in previous studies. It has been suggested [2] that Mars has undergone periods of very high obliquities, up to 45°, thus allowing snow accumulations, several tens of meters thick, at low latitudes as a result of sublimation from the poles. Clow investigated the conditions under which snow could have melted by solar radiation by using an optical-thermal model developed for dusty snowpacks [3]. It was found that the low thermal conductivity of snow and its partial transparency to solar radiation can result in subsurface melting despite surface temperatures well below freezing. Melting and subsequent runoff can occur at atmospheric pressures as low as 30–100 mbar [3]. Carr showed that if streams 2 m deep or larger can be initiated and sustained, then flows up to a few hundred kilometers long can be established, even under present-day climatic conditions [4]. Therefore, based on the above-mentioned work, it seems logical to the author that snowfall and subsequent snowmelt has many advantages to other explanations for the formation of the valley networks.

It has been argued that the valley networks were formed primarily by groundwater seepage. This is based on the measurement of junction angles between intersecting tributaries and on morphologic characteristics that appear to suggest headward extension through basal sapping [5]. The evidence for sapping is in some cases convincing (i.e., Nirgal Vallis), but it does not explain many of the dendritic valley systems, e.g., those located in the Margaritifer Sinus region.

Some problems with the sapping model will be discussed below. First, the measurement of junction angles between individual intersecting tributaries of the valley networks does not provide evidence to refute the view that the networks were formed by rainfall/snowmelt-fed erosion. Stream junction angles are controlled by slope, structure, lithology, and basin development stage, not precipitation [6]. Sapping requires that zones of low hydraulic head somehow be established to support the gradients needed to allow groundwater flow, and that zones of high hydraulic head be recharged, presumably by precipitation. Additionally, some of the valley networks whose channels originate on crater-rim crests indicate that the local water table must have intersected the surface high on the crater wall if sapping was involved [3]. This would mean that the crater was once filled with water, but there is no evidence, such as inflowing channels, to support this condition. It should also be noted that all the valley networks have been modified by mass wasting processes such as gelifluction and thermal erosion.

In order to more fully understand niveo-fluvial systems on Mars one should study terrestrial periglacial regions such as the Northwest Territories in the Canadian High Arctic. It is proposed that the following geomorphic processes and resulting landforms of snowmelt-fed rivers be used to explain the dendritic valley networks on Mars.

The Mecham River near Resolute, Northwest Territories, provides an excellent example of stream action and valley development in the periglacial realm. The area is underlain by continuous permafrost and mean monthly air temperatures are below zero for 9–10 months a year. The Mecham River has 80–90% of its annual flow concentrated in a 10-day period. This is typical for periglacial rivers in the High Arctic. During this brief period of concentrated flow extensive movement of bedload occurs, sometimes with peak velocities up to 4 m/s, causing the whole bed to be in motion [7]. This pattern of intense activity has far greater erosive and transporting potential than a regime in which river flow is evenly distributed throughout the year. The dominance of bedload movement in Arctic streams helps explain the distinctive flat-bottomed form of many periglacial stream valleys [8]. Thermal erosion and the subsequent collapse of river banks provides material for bedload transport and deposition downstream. This process also aids in the development of the broad flat-floored valleys. The permafrost also favors the flat-floored valley profiles because it provides a near-surface limit to downward percolation of water, thereby promoting runoff [9]. Another interesting feature of these periglacial rivers is that they lack a pronounced channel on their floors. This holds true for valleys eroded into either bedrock or unconsolidated debris.

Other work [10] indicates that fluvial processes have often been underestimated in periglacial regions. Budel illustrates this point in Spitsbergen, where he pointed out that ground ice breaks apart the rocks and prepares them for fluvial action. Periglacial rivers do not need to carry out new erosive action but need only melt the eisrinde and transport the shattered debris. The eisrinde is composed of the upper frozen and highly shattered layer of the permafrost. Rivers operating under this regime can deepen their beds rapidly; down-cutting rates on the order of 1–3 m/1000 yr over the last 10,000 yr have been estimated for Spitsbergen [10].

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