WHEN DID MARS BECOME BIPOLAR?: AN ANALYSIS OF THE KEY FACTORS IN THE LATE NOACHIAN-AMAZONIAN CLIMATE TRANSITION FROM AN ALTITUDE-DOMINANT TEMPERATURE DISTRIBUTION (ADD) TO A LATITUDE-DOMINANT DISTRIBUTION (LDD).

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Introduction: The history of the atmosphere and climate of Mars (Fig. 1) is one of the major current outstanding question in planetary science [1-2]. Mars today has an ~6.5 mbar CO_2-dominant atmosphere, and a hypothermal (~210K MAT), hyperarid polar desert climate (10-20 precipitable microns of H_2O in the atmosphere) [3], with surface water sequestered in the polar caps [4]. Yet in earlier history (Noachian, N), there is strong evidence for sustained periods of abundant surface liquid water, both flowing (valley networks) and standing (open-closed basin lakes, oceans) (Fig. 1), correspondingly higher atmospheric pressure (P_{atm} ~1-2 bar?) [5], and surface temperatures (MAT in excess of 273K) [6-7] (Fig. 2).

Two general classes of models have been proposed to account for these observations (Fig 2): 'Warm and Wet' scenarios [e.g., 6-7] propose N clement conditions (MAT >273K), with rainfall, runoff, fluvial, lacustrine activity, transitioning to the type of climate observed today. 'Cold and Icy' scenarios (e.g., 8-9) point to the 'faint young Sun', and predict a resulting MAT of 225K (Fig. 2), with 273K MAT reached nowhere on Mars even with P_{atm} between 1-7 bars; thus, this ambient 'Cold and Icy' climate requires significant transient input of greenhouse gases to elevate temperatures to cause melting of snow and ice to produce the observed fluvial and lacustrine features [e.g., 10-11

Currently debated issues: These include: What was the nature of the ambient (background) N climate? How long did it last and was it sustained or were changes episodic? What caused its transition to the climate of today and when and how did this occur? What was the nature of the hydrological system (horizontally stratified or vertically integrated) [12] and how did it change with time? What was the budget of surface/near-surface water [4] and how was it distributed? What were the conditions that led to observed fluvial, lacustrine and possibly oceanic environments (duration, periodicity, episodicity)? What were the warming greenhouse gases, their sources [e.g., 10-11], and the mechanisms for sustaining them in the atmosphere? What was the mean annual temperature (MAT) as a function of time and did global temperature distribution (GTD) change? What are the atmospheric loss rates to space [13] and how did they vary with time?

Major obstacles to resolving these questions: These include: 1) Identification of sufficiently robust greenhouse gas sources to produce and sustain a clement N ambient climate, or a prolonged transient heating event in the 'Cold and Icy' scenario, 2) Mechanisms to account for the decrease in P_{atm} from N-H conditions (>1 bar?) to today (P_{atm} 6.5 mbar)(Fig. 3), and 3) Identification of the fate of the very large volumes of surface water required by an ambient N clement climate [4].

Here we propose a scenario that addresses several of these obstacles and makes a number of testable predictions for future research and exploration. We start with the currently observed climate as a *known benchmark* and then assess the most parsimonious Noachian conditions that could have led forward to this benchmark (Figs. 2,3), tracking the distribution and fate of water, and accounting for the geologic observations (Fig. 1).

Current Mars Climate Benchmark: The extremely low current MAT (~213K) and P_{atm} (~6.5 mbar) (Figs. 2-3) result in very low atmosphere water content [14], poor atmosphere-surface thermal coupling, and surface temperature distributions [3] that are dominated by latitude-dependent (Fig 4a), not altitude-dependent (Fig 4b), effects. This has three effects: 1) The equator-to-polar temperature gradient is significant; despite 213K MAT, equatorial peak daytime and seasonal surface temperatures can exceed 273K [15]; 2) Water is metastable, with ice ablation dominated by sublimation [16]; 3) The North and South polar regions are cold traps that sequester the vast majority of surface water in thick ice caps [3-4].

Amazonian Mars Climate: Amazonian climate history is thought to be largely similar to that of today [17], with spin-axis/orbital variations (primarily obliquity [18]) from time to time mobilizing polar ice and transporting it to lower latitudes to form local and regional glacial deposits [19-21]; evidence for associated Amazonian ice melting is minimal and linked to local conditions [22-23]. The global water budget remains substantially the same (within a factor of two of today) [4]. These observations suggest that any major transition from 1) N to current benchmark P_{atm} (Figs. 2-3) and 2) N to current global water inventory [4], must have occurred before the Amazonian.

The Nature of the Noachian Atmosphere and Climate: A common characteristic of all models for the early Mars climate is the adiabatic cooling effect (ACE) [8-9, 24-26] (Fig. 4b). If the atmospheric pressure exceeds a few tens of millibars, atmosphere-surface thermal coupling becomes effective and altitude-dependent atmospheric temperatures begin to dominate over the latitude-dependent temperatures that characterize the Amazonian benchmark atmosphere (compare Fig. 4a-LDD; b-ADD). This effect is one of the mainstays of all N climate models. Under ADD conditions, there is little to no North polar cap, Tharsis is a second pole, analogous to the Tibetan Plateau on Earth today, and the south polar region is the third locus of snow and ice accumulation (Fig. 4b).

A Parsimonious Scenario for the Noachian Ambient Climate and its Transition to the Current Benchmark Climate: On the basis of the roles of XUV-driven loss, the integrated impact flux and Early Noachian basin formation (Hellas, Argyre, Isidis) in stripping a significant part of the primary atmosphere [27], and the relatively low contributions of middle Noachian volcanic outgassing to the secondary atmosphere [1,4,28], it is interesting to explore scenarios where 1) the Middle to Late Noachian P_{atm} was in the several hundred millibar range [5, 29], and 2) where the surface water budget was within a factor of two of its current value [4]. Under these conditions, the MAT is predicted to be ~225K the ADD would dominate the surface water budget distribution (Fig. 4b), and snow and ice would preferentially accumulate in three cold traps (Fig. 2, right): 1) the south circumpolar region, 2) the southern uplands, and 3) the Tharsis rise. The north polar region, situated deep in the relatively warmer northern lowlands, would not be the site of significant snow and ice accumulation and there would be no significant north polar ice cap [8-9, 30-31]. This scenario would define the ambient Noachian climate (Fig. 4b), but does not account for the abundant observed fluvial and lacustrine activity.

Nature of the Middle-Late Noachian to Hesperian-Amazonian Transition Period: We propose that a modest decrease in P_{atm} of the ambient Noachian climate could plausibly account for the observed Late Noachian fluvial and lacustrine activity. In this scenario, modest atmospheric loss during this period could initiate a transition from a global adiabatic cooling dominant atmospheric regime (altitude dominant temperature distribution; ADD; Fig. 4b) to a global latitude dominant atmospheric temperature regime effect (LDD; Fig. 4a) similar to today's benchmark climate. Climate models suggest that this *transition period* would have the following elements:

1) *Mean Annual Temperature*: MAT would not vary significantly, but *global temperature distribution* would transition from ADD (topography) patterns to LDD (latitude) patterns.

2) *Reorganization of water ice cold traps*: Mars would become bipolar, similar to the current benchmark climate; the southern uplands and Tharsis ADD cold traps would be replaced by a robust LDD North polar ice cap, and the southern ice cap would become smaller (it is currently 2.5x less in area than in the N [32]).

3) *Equatorial and mid-latitude surface temperatures begin to rise*: During the transition to dominantly LDD, warmer temperatures (including any >273 K peak summer daytime/seasonal (PDT/PST) temperatures [33] would migrate from the northern lowlands toward equatorial regions, causing regional MAT to increase. Under peak seasonal conditions, transient heating and melting of snow and ice sequestered in the ADD southern uplands cold traps could occur (Fig. 2, right), such as is observed in the Antarctic Dry Valleys [34]. Such a transitional period could produce a prolonged phase of periodic melting and fluvial/lacustrine activity, easily capable of producing sufficient meltwater to fill the observed lakes [35]. Meltwater would return to cold traps between peak T phases; recycling reduces the total amount of water required from 5000 m GEL [36] to a more plausible 640 m [37]. Over time, water would be preferentially lost from the uplands to the newly growing North Polar Cap.

4) *Migration of the Equilibrium Line Altitude (ELA) to Higher Altitudes*: During the ADE-LDE transition, the global distribution of warmer MAT isotherms would migrate from the lowest regions (Northern Lowlands, Hellas; Fig. 4b) toward a latitude dominant distribution (Fig. 4a). Accompanying this transition would be a rise in altitude of the ELA position into the snow-and-ice-dominated mid-latitude-equatorial highlands cold traps.

5) *Formation of Observed Fluvial and Lacustrine Features*: Rise of the ELA into the icy highlands is predicted to cause ablation of snow and ice and ultimate demise of the icy highlands, as water migrated to the newly growing North Polar Cap. Gradual sublimation of high-altitude snow and ice and its migration to new cold traps (primarily the North Pole) is accompanied by snow and ice melting during periods when PAT and PST exceed 273K. Such PAT/PST phases [33] of heating and melting of snow and ice would be sufficient to provide volumes of meltwater comparable to those required to form the observed fluvial and lacustrine features [35, 37].

6) *Predicted Stratigraphy and Timing of Fluvial and Lacustrine Deposits*: In this transition period, melting episodes are predicted to be largely seasonal (PDT, PST) with periodic annual and decadal warming variations extending the duration, analogous to the types of seasonal top-down melting episodes seen in the McMurdo Dry Valleys [34]. Following these peak warm episodes, meltwater is predicted to return to the cold traps until ablation has depleted the reservoirs at the end of the transition to a bipolar Mars. Stratigraphy of lacustrine deposits should exhibit multiple layers related to this activity. Currently unknown is the duration of this transition, but it is likely to be less than 10^7-10^8 years [38], during which

time spin axis/orbital changes (obliquity/eccentricity) may also influence the duration of melting phases.

7) *Growth of the North Polar Cap*: During this climate transition, Mars becomes bipolar, with the North Polar Cap growing towards its current large volume at the expense of the previous ADD cold traps. Due to known Amazonian obliquity variations, the original deposits from the pre-Amazonian North Polar Cap have been recycled back and forth to mid-latitude ice-deposits numerous times [19-21].

8) *Predicted Temporal Changes During the Transition*: The hypothesis presented here predicts that ablation and melting of 'icy highlands' cold traps should proceed from lower to higher elevations as the ELA migrates vertically, governed by the transition toward global latitude-dependent distribution (from Fig. 4b to 4a). These predictions can be tested with analysis of the stratigraphy and timing of features related to the rising ELA [39-42].

9) *Final Desiccation of the Equatorial Region*: The final stage of the transition is marked by the depletion of the ADD snow and ice reservoirs in the equatorial and mid latitude cold traps (Figs. 2-right; 4a), and progressive dehydration of the upper part of the cryosphere to produce the global distribution of surface and near-surface water seen today [43-44].

We describe this scenario as '*parsimonious*' because it: 1) involves a plausible Noachian P_{atm}, 2) utilizes known global atmospheric effects (P_{atm}-dependent ADD-LDD conditions), 3) requires minimal changes in global MAT (Figs. 2-3), 4) may require no major and persistent influx of warming greenhouse gases, 5) calls on a plausible global water budget throughout [4], 6) requires modest atmospheric loss to space [13], 7) provides a more plausible D/H ratio history, and 8) requires no Tharsis-induced true polar wander (TPW) to account for valley network distribution patterns [45].

Tests of the Model: Here we describe the significant questions that this scenario raises and how the hypothesis might be further tested, refined, or rejected: 1. Is a Noachian P_{atm} of several hundred mbar [5, 29] plausible and what is the geologic evidence for this? 2. What is the P_{atm} tipping point at which the ADD dominant scenario begins to decay to the LDD dominant scenario (compare Fig. 4b,a), how long does this transition take, and does it change global atmospheric circulation patterns significantly? 3. What are the effects of variations in obliquity during the transition, including potential very low obliquity-induced atmospheric collapse? 4. When did the Tharsis Rise form (including possible TPW [45]) and what effect did it have on the atmosphere and climate? 5. Are documented geologic events in the Hesperian transitional period (Fig. 1) (e.g., volcanic resurfacing, sulfate deposits [46-47], outflow channel formation) consistent with this scenario? 6. Are the major periods of mineralogical alteration (Fig. 1) (phyllosilicates, sulfates, anhydrous oxidation [2]) consistent with this scenario? 7. Are the major findings of the robotic surface exploration missions MER, MSL (Gale CBL and Jezero OBL), and Zhurong (southern Utopia Planitia) consistent with this scenario? 8. Are the predicted rates of volatile loss to space envisioned by this scenario consistent with MAVEN results [13]? 9. Are the observed characteristics, distribution and duration of fluvial and lacustrine environments (valley networks and lakes) [27,38] and crater degradation history [48] consistent with this scenario? 10. Are the South polar/circumpolar deposits (Dorsa Argentea Formation [32]) and their timing consistent with this scenario?

Current Work: We are currently exploring several of these questions using geologic observations and mapping (the Hesperian sulfate transition period [46-47]) and climate modeling (the nature of the change from ADD to LDD; Fig. 2).

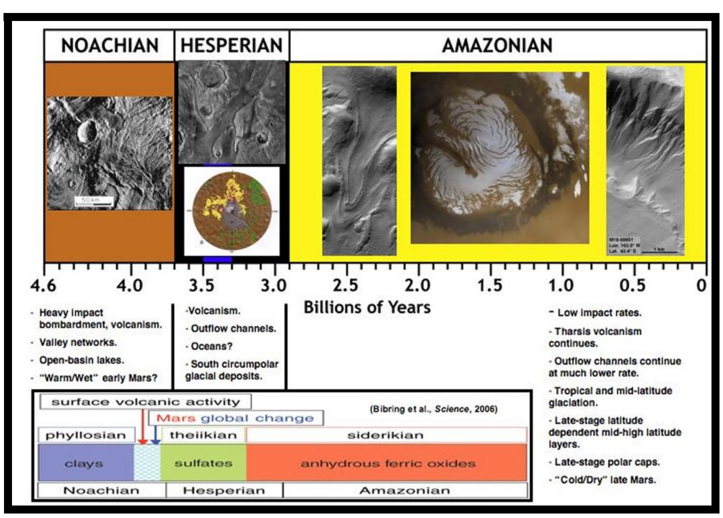

Fig. 1. Diagrammatic representation of the main themes in the geologic [1] and alteration history [2] of Mars.

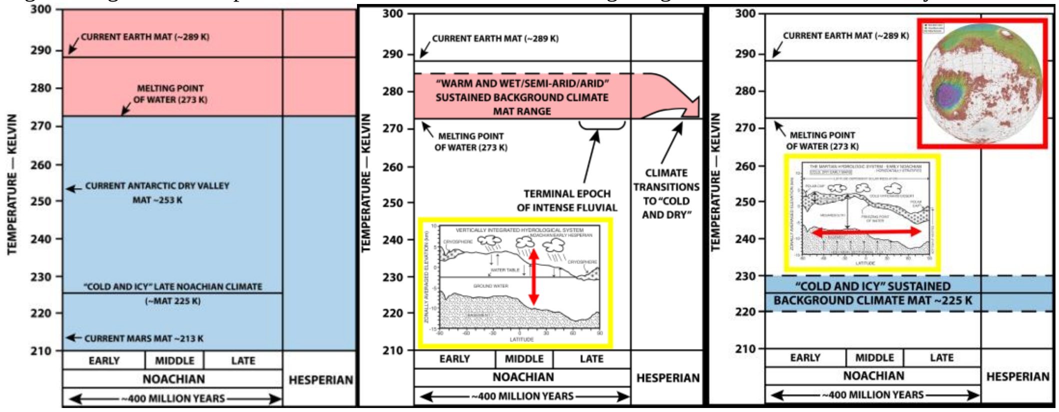

Fig. 2. Mean Annual Temperature (MAT)-Time (Noachhian-Early Hesperian) relationships: Left: Baseline examples. Middle: "Warm and Wet" Ambient Climate Scenario [6-7] with vertically integrated hydrological system (inset) [19]. Right: "Cold and Icy " Ambient Climate Scenario [9], with horizontally stratified hydrological system (inset) [19] and the distributi of snow and ice above an Equilibrium Line Altitude (ELA) of +1 km [34].

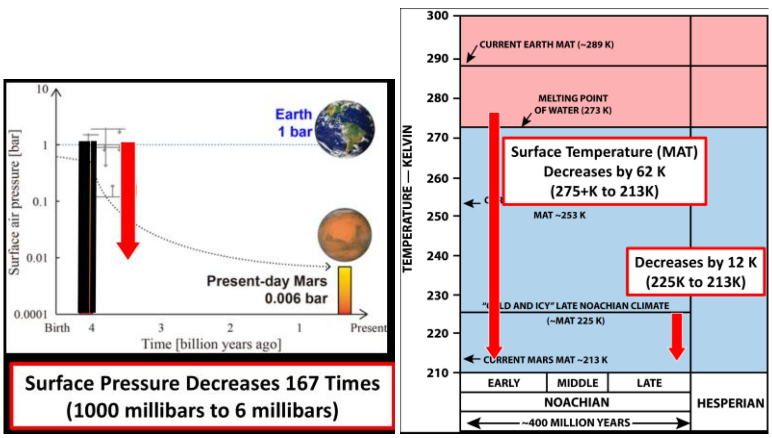

Fig. 3. Requirements for changes from a Noachian Ambient Climate to that of todayin atmospheric pressure (left) and temperature (right) for the two models.

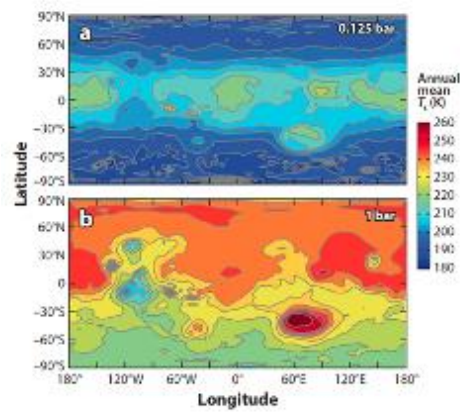

Fig. 4. The modern LDE compared to the early Mars ADE: a) MAT from 3D GCM at 125 mbar P_{atm} (Amazonian). b) MAT from 3D GCM at 1 bar P_{atm} (Noachian?) [8-9].

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