WHEN DID MARS BECOME BIPOLAR? AN ANALYSIS OF THE KEY FACTORS IN THE LATE NOACHIAN-AMAZONIAN CLIMATE TRANSITION. James W. Head[1], Robin D. Wordsworth[2] and James L. Fastook[3], [1]Brown University, Providence, RI 02912 USA, [2]Harvard University, Cambridge, MA 02138 USA, [3]University of Maine, Orono, ME 04469 USA (james_head@brown.edu).

Introduction: The history of the atmosphere and climate of Mars is one of the major current outstanding question in planetary science. Mars today has a ~6 mbar CO_2-dominant atmosphere, and a hypothermal (~213K MAT), hyperarid polar desert climate, with surface water sequestered in polar ice caps. Yet in earlier history (Noachian, N), there is abundant evidence for sustained periods of flowing water (valley networks) and standing surface water (open-closed basin lakes, oceans), and correspondingly higher atmospheric pressure (P_{atm} ~1-2 bar?) and temperatures (MAT in excess of 273K) [1].

Two general classes of models have been proposed to account for these observations: 'Warm and Wet' scenarios [e.g., 2] 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., 3-4) point to the 'faint young Sun', and predict a resulting MAT of ~226K, with 273K MAT reached nowhere on Mars even with P_{atm} between 1-7 bars; thus, this ambient 'Cold and Icy' climate requires 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., 5].

Currently debated issues 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? Major obstacles to resolving these questions 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 mbar), and 3) Identification of the fate of the very large volumes of surface water required by an ambient N clement climate [6]. 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 N conditions that could have led forward to this benchmark, tracking the distribution and fate of water, and accounting for the geologic observations.

Current Mars Climate Benchmark: The extremely low current MAT (~213K) and P_{atm} (~6 mbar) result in very low atmosphere water content, poor atmosphere-surface thermal coupling, and surface temperature distributions that are dominated by latitude-dependent, not altitude-dependent, effects (Fig 1). 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; 2) Water is metastable, with ablation dominated by sublimation; 3) The North and South polar regions are cold traps that sequester the vast majority of surface water in thick ice caps [6].

Amazonian Mars Climate: Amazonian climate history is thought to be largely similar to that of today, with spin-axis/orbital variations (primarily obliquity) from time to time mobilizing polar ice and transporting it to lower latitudes to form local and regional glacial deposits [7]; evidence for associated Amazonian ice melting is minimal and linked to local conditions [8]. The global water budget remains substantially the same (within a factor of two of today) [6]. These observations suggest that any major transition from 1) N to current benchmark P_{atm}, and 2) global water inventory, must have occurred before the Amazonian.

The Nature of the N Atmosphere and Climate: A common characteristic of all models for the early Mars climate is the adiabatic cooling effect (ACE) [3,4,9-11] (Fig.1b). 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. 1a,b). This effect is one of the mainstays of all N climate models. There is little to no North polar cap, Tharsis is a second pole, analogous to the Tibetan Plateau on Earth today, and the south circum-polar region is the third locus of snow and ice accumulation.

A Parsimonious Scenario for the N Ambient Climate and its Transition to the Current Benchmark Climate: On the basis of the role of the integrated impact flux and Early Noachian basin formation (Hellas, Argyre, Isidis) in stripping a significant part of the primary atmosphere, and the relatively low contributions of middle Noachian volcanic outgassing to the secondary atmosphere [1,6], it is interesting to explore scenarios where the N P_{atm} was in the several hundred millibar range, and where the surface water budget was within a factor of two of its current value [6]. Under these conditions, the MAT is predicted to be ~226K the ACE would dominate the surface water budget distribution (Fig. 1b), and snow and ice would preferentially accumulate in three cold traps: 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. This scenario would define the ambient Noachian climate, but does not account for the abundant observed fluvial and lacustrine activity.

We propose that a modest decrease in P_{atm} of the ambient N climate could plausibly account for the observed fluvial and lacustrine activity. In this scenario, modest atmospheric loss to space during this period could initiate a transition from a global adiabatic cooling dominant atmospheric regime (altitude dominant effect; ADE; Fig. 1b) to a global latitude dominant atmospheric temperature regime effect (LDE; Fig. 1a) similar to the benchmark climate of today. 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 ADE (topography) patterns to LDE (latitude) patterns.(compare Fig. 1a,b).

2) Reorganization of water ice cold traps: Mars would become bipolar, similar to the current benchmark climate; the southern uplands and Tharsis ADE cold traps would be replaced by a robust LDE North polar ice cap, and the southern ice cap would become smaller (it is currently 2.5x less in area than in the N [12]).

3) Equatorial and mid-latitude surface temperatures begin to exceed 273K: During the transition to dominantly LDE, >273 K peak daytime/seasonal temperatures (PDT/PST) would migrate from the northern lowlands toward equatorial regions, causing transient heating and melting of snow and ice sequestered in the ADE southern uplands cold traps; such a transitional period could produce a prolonged phase of periodic melting and fluvial/lacustrine activity. Meltwater would return to cold traps between peak T phases, but 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) toward a latitude-dominant distribution. Accompanying this transition would be a rise in altitude of the position of the ELA 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 [13] 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 [14].

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 top-down melting episodes seen in the McMurdo Dry Valleys [15]. During these 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 unlikely to be less than 10^6-10^8 years, 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 ADE cold traps.

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. 1b to a). These predictions can be tested with analysis of the stratigraphy and timing of features related to the rising ELA [e.g. 16].

9) Final Desiccation of the Equatorial Region: The final stage of the transition is marked by the depletion of the ADE snow and ice reservoirs in the equatorial and mid latitude cold traps (Fig. 1a).

We describe current unknowns/uncertainties, and tests of this N->A climate transition scenario elsewhere [17].

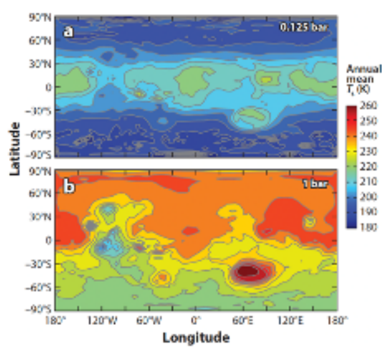

Fig. 1. The modern LDE compared to the early Mars ADE: a) MAT from 3D GCM at 125 mbar P_{atm} (Amazonian). b) MAT from 3D GCM at 1 bar P_{atm} (Noachian?) [3-4].

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