WHEN DID MARS BECOME BIPOLAR? OUTSTANDING ISSUES IN A CONCEPTUAL MODEL OF A NOACHIAN-AMAZONIAN CLIMATE TRANSITION FROM AN ALTITUDE-DOMINANT TEMPERATURE ENVIRONMENT (ADD) TO A LATITUDE-DOMINANT TEMPERATURE ENVIRONMENT (LDD). 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 nature of the evolution of the Mars atmosphere and climate from its early history to that of today (Fig. 1) is one of the most fundamental questions in planetary science [1-2]. What were the initial conditions? What were the characteristics of the Noachian atmosphere and climate ('warm and wet', rainfall and runoff, P_{atm} 1 bar or more, MAT >273K supported by greenhouse gases [3-4]; or 'cold and icy', P_{atm} 1 bar (?), MAT ~226K, icy highlands) [5-7]? What were the factors that led from the Noachian ambient climate to the currently observed ambient late Amazonian climate conditions (extremely low 6 mbar P_{atm}, hyperarid, hypothermal MAT ~213K) [8]?

Key related questions include: What was the nature of the hydrological system (horizontally stratified or vertically integrated) [9] and how did it change with time? What was the budget of surface/near-surface water [10] 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., 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 [12] and how did they vary with time?

The Question: As a step in addressing these many fundamental issues, we recently posed the question: *What is the most parsimonious set of conditions that might explain a transition from a Noachian Mars atmosphere and climate to the current benchmark Amazonian conditions?* Key elements that require explanation include: 1) a P_{atm} change from potentially >1 bar to 6 mbar, 2) a MAT change from potentially >273K to ~213K, 3) a significant decrease in the surface-near surface global water budget from as much as ~5000 m GEL [13] to <50 m GEL [10], 4) a change in the location of the major water reservoirs (from Noachian oceans or icy highlands to the polar ice caps observed today [10]) and 5) a change in the Global Temperature Distribution (GTD) from a dominantly altitude dependent temperature distribution (ADD) to dominantly latitude dependent temperature distribution (LDD) (Fig. 2).

The Conceptual Model: We presented what we believe might be the most parsimonious, yet potentially plausible, Noachian climate scenario and its transition to today as follows [14]: The Middle-Late Noachian atmosphere was characterized by P_{atm} of less than several hundred millibars, sufficient to cause an adiabatic cooling effect (ADD) in both 'cold and icy' and 'warm and wet' climate scenarios [5-7,15], and preferentially sequestering snow and ice in the southern uplands, Tharsis, and the south polar cap. A modest decrease of P_{atm} (several tens of mbar?) beginning in the Late Noachian caused the altitude-dependent dominance (ADD) GTD to decay and the LDD GDT to dominate (as observed today), significantly changing the global thermal environment with geological process consequences. During this transitional period, the equilibrium line altitude (ELA; contour separating net snow and ice accumulation, above, from net ablation, below) rose in altitude in the equatorial and mid-latitude regions and appeared in the North Polar region and migrated southward (compare Fig. 2b, a). A significant part of the water budget began to accumulate to form the North Polar Cap, and Mars became "bipolar". As the ELA rose in altitude in the equatorial/mid-latitude regions, peak daily and seasonal temperatures (PDT, PST; [16]) began to exceed 273K (as observed today) and snow and ice in the equatorial/mid-latitude uplands was subjected to periodic top-down melting [17] of sufficient duration to produce large volumes of meltwater [18], potentially forming the observed, circumhighlands fluvial and lacustrine features. This ADD to LDD transitional climate period (compare Fig. 1b and a) continued until the North Polar Cap reached its current volume configuration and the equatorial surface water budget was depleted. This transitional period appears to have been complete by the Early Amazonian (Fig 1); between then and today, variations in obliquity [19] dominated the Amazonian climate history, with polar ice being mobilized at higher obliquity and transported to lower latitude cold-traps to form regional mid-latitude glaciation/tropical mountain glaciers [20-21], returning to polar cold traps as obliquity decreased toward that of today [22].

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, 4) requires no major and persistent influx of warming greenhouse gases, 5) calls on a plausible global water budget throughout, 6) requires modest atmospheric loss to space, 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 [23].

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 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. 2b,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 [23]) 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 [24-25], outflow channel formation) consistent with this scenario?
6. Are the major periods of mineralogical alteration (Fig. 1) (phyllosilicates, sulfates, anhydrous oxidation) 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 [12]?
9. Are the observed characteristics, distribution and duration of fluvial and lacustrine environments (valley networks and lakes) [26] and crater degradation history consistent with this scenario?
10. Are the South polar/circumpolar deposits (Dorsa Argentea Formation [27]) 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 [24-25]) and climate modeling (the nature of the change from ADD to LDD; Fig. 2).

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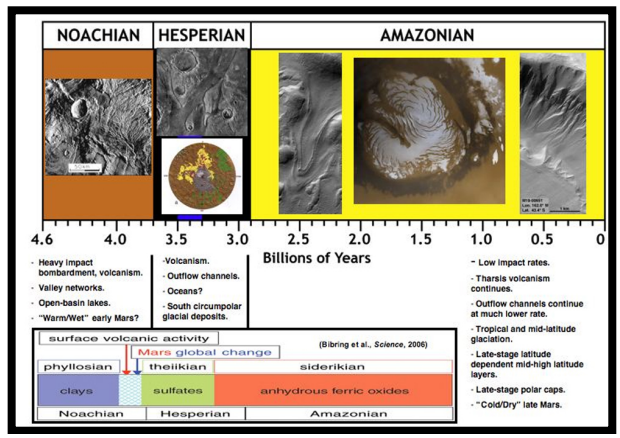

Fig. 1. Diagrammatic representation of the main themes in the geologic [1] and alteration history [28] of Mars.

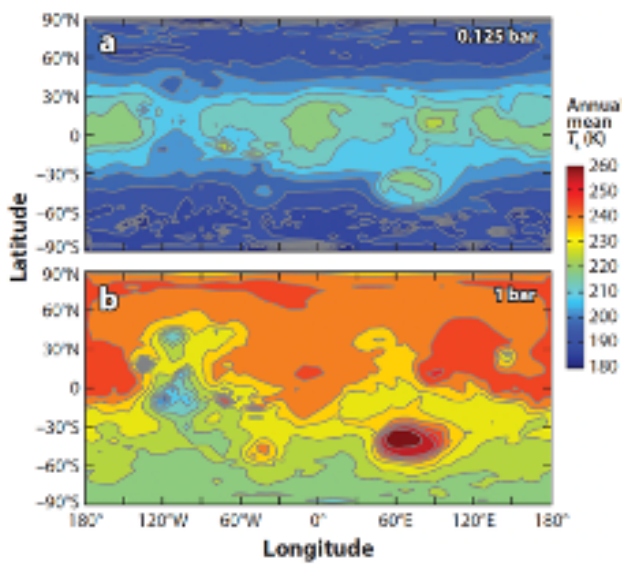

Fig. 2. The modern LDE compared to the early Mars ADE: a) MAT from 3D GCM at 125 mbar P_{atm} (Amazonian). b) MAT from 3D GCM at 1 bar P_{atm} (Noachian?) [6-7].