TOWARD AN UNDERSTANDING OF EARLY MARS CLIMATE HISTORY: NEW THEMES, DIRECTIONS AND TESTS. James W. Head, Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 20912 USA (james_head@brown.edu).

Introduction: Discussion and debate continue concerning the nature and evolution of the atmosphere and climate in the Noachian and Hesperian periods of the history of Mars, centering on two end-member hypotheses (Fig. 1): 1) "warm and wet/arid" (WW/A), with fluctuations in the amount and intensity of rainfall (infiltration versus overland flow), and a Late Noachian climate optimum causing overland flow [1], valley network (VN) formation, open and closed basin lakes (CBL/OBL) and a northern lowlands ocean; and 2) "cold and icy" (CI), with mean annual temperatures (MAT) ~225 K, an adiabatic cooling effect forming a Noachian Icy Highlands (NIH), and transient perturbations to the ambient CI climate to cause melting of the NIH to form VN, OBL/CBL [2,3]. Here we outline a series of concepts and themes that are currently emerging from this discussion and identify several drections for the path forward.

(1) <u>Time Period Involved</u>: The Noachian begins with the formation of the Hellas basin, and continues with Isidis and Argyre (Fig. 2); therefore the Middle and Late Noachian (M-LN) are characterized by significant *inheritance* from the influence of these large basins on the atmosphere, hydrosphere, surface temperatures, regional to global resurfacing, geomorphology, exposure of deep primary and secondary rock types and anomalous alteration mineralogy. It is also a period of relatively higher impact flux, with temporally decreasing flux offset by decreasing atmospheric pressure. This is all built on top of *Pre-Noachian inheritance* (Fig. 2).

(2) <u>Nature of the Ambient Background Atmosphere and its Evolution</u>: What is the nature of the ambient atmosphere, the long-term background atmosphere that exists throughout the 250 Ma Middle-Late Noachian (M-LN)? Critical to this question is how the atmosphere responds to and recovers from impact basin formation, the fate of the magnetic field, and the timing and rates of early loss-to-space mechanisms. These effects are largely poorly known/unknown, but are likely to have occurred and been in place by the M-LN. Atmospheric pressure is unlikely to have exceeded 1 bar, CO_2 is the dominant component, and other greenhouse gases appear to have been minimal. These conditions and Mars' distance from a faint young Sun favor MAT ~225 K. Long-term loss-to-space rates decreased atmospheric pressure with time, but it is unlikely that a M-LN *ambient atmosphere* could have been characterized by sustained MAT >273 K; sustained *evolutionary* warming mechanisms to >273 K appear difficult.

(3) <u>Nature of M-LN Background Climate</u>: Barring major changes in our understanding (which are certainly possible!), the characteristics of the ambient background atmosphere predict that the background M-LN climate (Fig. 1) is characterized by MAT ~225 K, an adiabatic cooling effect, highlands which act as a cold-trap for water, and accumulation and storage of the water as snow and glacial ice there (the 'icy highlands'). This strongly suggests that the abundant geological evidence of surface liquid water may be due to *perturbations* to this background climate, not to a sustained >273 K climate itself. In searching for such perturbations, peak annual and seasonal (PAT, PST) temperatures are likely to be important, as well as intermittent (occur for time to time) and heterogeneous (occur in some places but not others) melting conditions.

(4) <u>Nature of Precipitation (rainfall, snowmelt)</u>: Most contributions use the term *precipitation* and parenthetically add (*rainfall, snow; or snowmelt*). It is important to distinguish between rainfall and snowmelt in proposed hypotheses for M-LN climate conditions. It is extremely difficult to produce sustained or widespread rainfall in a climate with MAT <273 K, but such a climate can undergo intermittent or heterogeneous melting of snow and ice under a variety of conditions, producing significant volumes of glacial meltwater.

(5) <u>Hydrological System and Cycle</u>: End-member climate models predict very different water cycle scenarios. In the WW/A model, the hydrological system is vertically integrated, rainfall is common, groundwater plays an important role, and northern lowland oceans are an important part of the cycle. In the CI model, there is a thick global cryosphere, the hydrological system is horizontally stratified, there is no sustained ocean or connection to the groundwater system, and the majority of the water is located as snow and glacial ice in the uplands above an ELA of ~+1 km. Any ocean formed from the release of groundwater is very short-term, rapidly freezing and returning to upland cold-traps.

(6) <u>Water Budget</u>: The M-LN surface-near surface estimated water budget is uncertain but may only have been within a factor of 2-3 of the current 34 m GEL [4]. Furthermore, *water recycling* needs to be considered in all estimates of total water volumes required to erode VN and fill CBL/OBL, and thus estimating the total water budget. Water recycling readily occurs in both WW/A and CI scenarios. Increased total water budget in the CI scenario means more ice in the uplands available to melt during climate perturbations.

(7) <u>Polar Deposits</u>: The presence of significantly larger (~2.5 x > area) LN-EH south polar-circumpolar deposits (the Dorsa Argentea Formation; DAF) are consistent with CI climate models in which the ACE causes ice to reside in the southern uplands and not in the relatively "warmer" northern lowlands.

(8) ML-N Geological Processes: Impact basin aftermath hot rains may be a critical erosional and alteration process in EN basins [5,6] but ML-N impact craters have little effect on the climate except for hot ejecta melting surface snow and ice [6]. CI upland glaciation is cold-based except under extreme water budgets, and thus is likely to leave little evidence of its presence except when top-down melting occurs (fluvial) [7]. Flood volcanism is a very significant ML-N-H process, resurfacing >30% of Mars; although gas release may locally contribute to raising PAT/PST toward melting [8], the most important effect may be lava/ice contact/deferred melting, which can produce very significant amounts of meltwater [9].

(9) Mineralogical Perspectives and Constraints: The surface phyllosilicate and related mineralogical record is an important constraint on climate history but uncertainty as to the provenance and environment of origin of these has precluded definitive application to the climate discussion. Advances are needed in terms of understanding necessary water/rock ratios, temperatures, time-scales and micro-environments; also necessary is a better understanding of the climate implications of preserved salts and olivine.

(10) Lander/Rover Perspectives: Surface exploration of a variety of local environments will help resolve many of these issues by providing evidence to distinguish between local microenvironments and global climate effects. At the same time, global climate models provide paradigms to test with surface exploration data (e.g., are Meridiani deposits due to fluctuating groundwater table flooding levels or could they be doe to intermittent overland flooding and evaporation? Similarly, improved understanding of *sediment protoliths* and the role of *impact preprocessing* in influencing sediment grainsize/shape is important [10].

(11) Candidates and Timescales of Climate Perturbations: A sustained WW/A MAT >>273 K climate needs only minor perturbations to produce sustained liquid water and runoff; in contrast, a nominal CI MAT ~225K climate needs significant perturbations to produce the same effects. Among the types of variability and Intermittencies are: 1) Episodic/Periodic: Two scales: *Normal atmospheric system variability*: This *episodic* intermittency operates on <1-10^3 years timescales; *Spin axis/orbital variation-forced climate cycles*: This *periodic* intermittency operates on 10^3-10^6 year timescales. 2) Punctuated: Two types: *Variability in effusive/explosive volcanic processes*: Volcanism is likely to be punctuated and more episodic than periodic, with uncertain intermittency; *External stochastic variability: Impact cratering*: Episodic and punctuated (but vary in magnitude); durations of atmospheric effects estimated at 10^2-10^3 years [5,6]. Introduction of additional greenhouse gases can also cause significant perturbations of uncertain duration. Examination of the durations of fluvial activity (Fig. 3) suggest that the required duration of individual perturbations may not be long and their total number may not be large.

(12) The Early Mars Climate Aftermath: All Noachian climate models must account for LH and Amazonian events [11] in an evolutionary manner.

References: [1] Ramirez and Craddock (2018) NG 11, 230; [2] Wordsworth et al. (2015) JGR 120, 1201; [3] Head and Marchant (2015) AS 26, 774; [4] Carr and Head (2015) GRL 42, 1; [5] Palumbo and Head (2017) MAPS 53, 687; [6] Turbet et al. (2019) LPSC 50; [7] Fastook and Head (2015) PSS 86, 102; [8] Palumbo et al. (2019) LPSC 50; [9] Cassanelli and Head (2016) Icarus 271, 237; [10] Arp et al. (2019) Icarus 321, 531; [11] Carr and Head (2010) EPSL 294, 185; [12] Head et al. (2017) 4th Early Mars; [13] Fassett and Head (2011) Icarus 211, 1204; [14] Buhler et al. (2014) Icarus 241, 130.

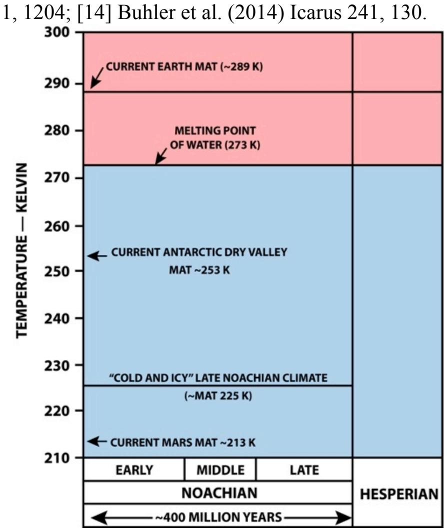

Fig. 1. Temperature-time framework [12].

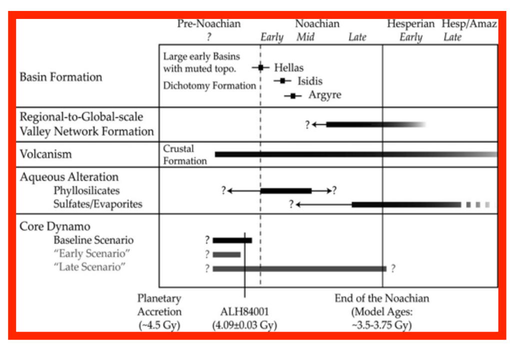

Fig. 2. Major factors in early Mars history [13].

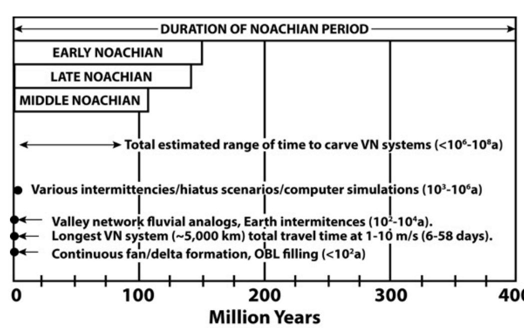

Fig. 3. Process duration estimates [12-14].