MARS: THE FIRST BILLION YEARS – WARM AND WET VS COLD AND ICY? Robert M. Haberle, Space Science and Astrobiology Division, NASA/Ames Research Center, Moffett Field, CA 94035, Robert.M.Haberle@nasa.gov.

Introduction: Today Mars is a cold, dry, desert planet. Liquid water is not stable on its surface. There are no lakes, seas, or oceans, and rain falls nowhere at no time during the year. Yet early in its history during the Noachian epoch, there is geological and mineralogical evidence that liquid water did indeed flow on its surface creating drainage systems, lakes, and – possibly - seas and oceans [1]. The implication is that early Mars had a different climate than it does today, one that was based on a thicker atmosphere with a more powerful greenhouse effect that was capable of producing an active hydrological cycle with rainfall, runoff, and evaporation. Since Mariner 9 began accumulating such evidence, researchers have been trying to understand what kind of a climate system could have created greenhouse conditions favorable for liquid water. Unfortunately, the problem is not yet solved.

Faint Young Sun: The principle issue is coping with the faint young sun. Stellar evolution models and observations suggest that stars like our Sun increase in luminosity with time [2]. During the Noachian epoch the sun was approximately 25% less luminous than it is today. All things being equal, this means that the planet's effective temperature would have been 196 K, about 15 Kelvins less than it is today. Thus, if a stronger greenhouse effect from a different early atmosphere is the solution, as is thought to be the case for Earth, then for Mars it must produce 77 K of warming to bring mean annual surface temperatures up to the melting point of water. Furthermore, any greenhouse theory must (a) produce the warming and rainfall needed, (b) have a plausible source for the gases required, (c) be sustainable, and (d) explain how the atmosphere evolved to its present state. These are challenging requirements and judging from the literature they have yet to be met.

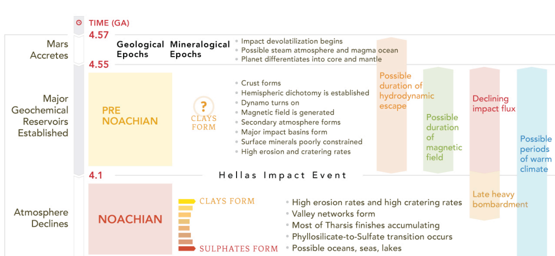

Fig 1. Timeline of early Mars.

Origin and Evolution of the Atmosphere: To assess the feasibility of an early greenhouse atmosphere on Mars we need to consider its organ and evolution. Fig. 1 summarizes our present thinking. Mars formed quickly with accretion and core formation largely complete within the first 10 Ma. Impact devolatization created a steam atmosphere and possibly a magma ocean. Much of this water was probably lost during a brief episode of hydrodynamic escape. A secondary atmosphere subsequently developed from volcanic outgassing. Since rapid core formation probably left the mantle in a mildly oxidizing state, the composition of this secondary atmosphere was likely dominated by CO_2 and H_2O. Estimates of their initial abundances range from 6-15 bars of CO_2 and 10's to 1000's of meters of water, though their outgassing history and subsequent fate is of course highly uncertain. Although water can escape, enough must have been present during the Noachian to form the observed fluvial features. And while there are a variety of loss mechanisms that can limit the buildup of CO_2, outgassing associated with Tharsis volcanism likely produced a Noachian atmosphere that was thicker than it is at the present time. How much thicker is difficult to determine, but factors of 10-100 times thicker do not seem unreasonable. On the other hand, atmospheres too much thicker than this are not consistent with outgassing models [3], impact/sputtering removal estimates [4], loss to the carbonate reservoir [5], and small-crater statistics [6]. Thus, the Noachian atmosphere was likely predominantly CO_2 with a rough upper limit of ~ 1 bar.

Greenhouse Models: An early CO_2/H_2O atmosphere would have produced a greenhouse effect whose magnitude depends on their abundances. The first studies of such atmospheres showed that 5-10 bars of CO_2, less than the estimated inventory, could have raised surface temperatures to the melting point. However, more detailed follow on work showed that Rayleigh scattering [7], CO_2 condensation [8], and more realistic treatment of collision-induced absorptions [9], limited the ability of these atmospheres to produce warm and wet conditions regardless of how much CO_2 was available. And though reflecting CO_2 clouds once showed some promise, their contribution was ultimately shown to be inadequate as well [7]. Thus, state-of-the-art models of pure CO_2/H_2O atmospheres do not appear capable of raising mean annual surface temperatures much above ~235 K during the Noachian epoch for surface pressures near the upper limit of ~1 bar.

Could additional greenhouse gases solve the problem? As mentioned above, it is likely that the early atmosphere was composed mainly of CO_2 and water. But there are a variety of gases that even in trace amounts in such an atmosphere could help reduce the outgoing long wave radiation needed to boost the greenhouse effect. Sulfur dioxide (SO_2), methane (CH_4), hydrogen sulfide (H_2S), ammonia (NH_3), and nitrous oxide (N_2O), have all been considered in the literature, but only for SO_2 has there been significant published work on this topic [10]. Fig 2. shows the wavelength dependence of the absorption cross-sections for these gases to illustrate which regions in the infrared they are most effective. More recently, hydrogen (H_2) has been suggested as a possible trace gas that could solve the early Mars dilemma [11]. While under the right circumstances these gases can produce warm and wet conditions, their sources and sinks cast doubt on their ability to achieve and maintain the needed concentrations. Thus, while supplemental greenhouse gases offer an attractive solution to the faint young sun problem, they have sustainability issues that have yet to be resolved.

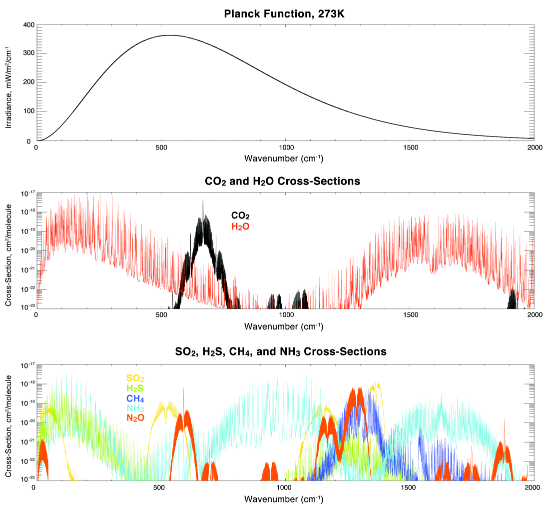

Fig. 2. Absorptions cross-sections of potential greenhouse gases.

Continuous vs. Episodic: A major question in the debate about early Mars revolves around the needed duration of warm and wet conditions. Do the observed fluvial features require a long-lived (10^6-10^8 years??) continuously warm and wet climate system with an active hydrological cycle, or could these features be produced in transient warm and wet episodes due to impacts and/or volcanism for example? If long-lived continuous conditions are required then large bodies of liquid water, i.e., seas or oceans (as opposed to lakes or ponds) must have existed on the surface. Given the theoretical difficulty of sustaining such conditions, some researchers have explored the episodic alternative [12]. Certainly volcanic activity and impact rates were much higher during the Noachian and both are capable of temporarily changing the climate. However, the main problem with these ideas is demonstrating that they can produce enough rainfall and erosion to explain the fluvial features. And for the impact hypothesis there is the additional constraint of not overwhelming the system with deluge style flooding since breached craters, which such flooding would produce, are rare [13].

Cold Early Mars: Yet another alternative is that early Mars was mostly cold and occasionally wet. In this instance the fluvial features would form from the occasional melting of surface ice deposits. General circulation model simulations of CO_2/H_2O atmospheres with surface pressure above ~ 200 mb show that such atmospheres can deliver considerable snowfall to the southern highlands [14]. As long as temperatures there can later reach the melting point, liquid water will flow and erode the surface. Under the right circumstances, glacial melting of southern ice sheets could also form a cold northern ocean that would suppress clay formation thereby explaining the paucity of clays in exposed northern plains [15]. However, these scenarios still require an energy source to melt the ice.

Towards a Solution: The problem of early Mars remains unsolved. Progress will come from a multi-disciplinary research effort. The geological community should strive to reach a consensus on the need for rainfall (vs. snowmelt or hydrothermal melting, for example). If rainfall is required, what are its intensity, timing, and duration? Better estimates of the erodibility of the surface and the volume of eroded material would also be helpful. From the geochemical community, a better understanding of the redox state of the mantle and the volume and timing of outgassed volatiles during the first billion years would provide important constraints on the mass and composition of the atmosphere and how it evolved. And from the climate community, the trend toward the use of sophisticated general circulation models should continue. These models can address several areas that have not yet received enough attention including, orbital variations, the greenhouse potential of water ice clouds, and impact-induced climate change.

References: [1] Carr, M.H. (2006) Cambridge Univ Press. [2] Gough, D.O. (1981) *Solar Physics*, 74, 21-34. [3] Grott, M. et al. (2011) *Earth and Planet. Sci. Lett.*, 308, 391-400. [4] Jakoksy et al. (1994) *Icarus*, 111, 271-288. [5] Pollack et al. (1987) *Icarus*, 71, 203-224. [6] Kite et al. (2014) *Nature Geo.* [7] Forget et al. (2013) *Icarus*, 222, 81-89. [8] Kasting, J.F. (1991) *Icarus*, 94, 1-13. [9] Wordsworth R. et al. (2010) *Icarus*, 210, 992-997. [10] Johnson et al. (2008) *J. Geophys. Res*., 11. [11] Ramirez et al. (2013) *Nature*. [12] Segura et al. (2008) *J. Geophys. Res*. 113. [13] Barnhart, C.J. et al. (2009) *J. Geophys. Res*., 114. [14] Wordsworth R. et al. (2013) *Icarus*, 222, 1-19. [15] Fairén et al. (2011) *Nature*, 4, 667-670.