EARLY MARS CLIMATE MODELING AND THE FAINT YOUNG SUN PARADOX. 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 precipitation falls as snowfall. Yet early in its history during the Noachian epoch, there is geological and mineralogical evidence that liquid water from rainfall flowed on its surface creating drainage systems, lakes, and – possibly - seas and oceans [1]. More recent observations by Curiosity in Gale crater hint that such conditions may have persited into the Hesperian [2]. The implication is that early Mars had a wamer climate than it does today as a result of a thicker atmosphere with a more powerful greenhouse effect 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 [3]. 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.

Greenhouse Models: If the early mantle was not too reducing, CO_2 and H_2O would have been the likely outgassing products of volcanic activity. 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 [4]. However, more detailed follow on work showed that Rayleigh scattering [5], CO_2 condensation [6], and more realistic treatment of collision-induced absorptions [7], 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 [8]. 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? Sulfur dioxide (SO_2), methane (CH_4), hydrogen sulfide (H_2S), ammonia (NH_3), and hydrogen (H_2), are candidate greenhouse gases that have been suggested in the literature [e.g., 9, 10]. They provide additional greenhouse opacity and can raise tempeatures to near freezing if they exist at the right concentrations. Unfortunately, these gases have sustainability issues that have yet to be resolved. Ammonia is photochemically unstable, for example, and SO_2 will convert to sulfate in an oxidizing environment. Thus, while they offer an attractive solution to the faint young sun problem, it is not clear if they were ever present at the right concentrations for a long enough period to explain the geological evidence.

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 [11]. 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.

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 [8]. 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 [12]. However, these scenarios still require an energy source to melt the ice.

Towards a Solution: The problem of early Mars remains unsolved. Continuously warm and wet ideas have not demonstrated that the required greenhouse gas concentrations can be sustained; episodically warm and wet ideas do not appear to generate enough erosion, and the cold early mars scenarios need strong external forcings to melt enough snow. 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 is 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.

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