EPISODIC VS. STEADY STATE WARMING ON EARLY MARS: A STOCHASTIC MODEL APPROACH

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Introduction. Extensive geologic evidence indicates that 3-4 Ga, surface conditions on Mars were dramatically different from today, with multiple episodes of fluvial erosion, aqueous alteration and sediment deposition [1]. The most plausible explanation for the aqueous alteration of Mars' surface is greenhouse warming from a thicker early atmosphere, although the details of the warming mechanism continue to be debated [2,3]. Geomorphic and geochemical analyses suggest that in total, between 10^4 and 10^7 years of warm conditions were required to erode observed valley networks, deposit sediment in craters and form Al-/Fe- phyllosilicate weathering sequences [4-7]. In addition, the relative absence of surface carbonates on Mars, including in excavated northern terrain and in dust, suggests that large bodies of surface liquid water and a thicker CO_2 atmosphere could not have been present simultaneously over periods much longer than a few million years [8,9].

The chemical state of the martian surface has also varied significantly over time. While martian meteorite data suggests that much of Mars' mantle is more reducing than Earth's, Mars' surface today is highly oxidized, with abundant ferric iron lending the planet its reddish appearance and species such as hydrogen peroxide present in the atmosphere and likely also in the regolith. Orbital and rover observations of surface mineralogy indicate spatial and temporal variation of redox environments on Mars [9], with some indications of a slow transition from a more reducing early state to its current oxidized condition.

Stochastic atmospheric evolution model. To investigate how these diverse strands of geologic evidence can be understood in a single framework, we have developed an integrated atmospheric evolution and climate model (Fig. 1). A key feature of our model is that it is stochastically forced in a way that captures the episodic nature of the key processes that altered Mars' atmosphere in its early history. We represent the release of reducing gases to the atmosphere due to meteorite impacts [10], volcanism [11] and crustal alteration [12,13] in a generalized way by randomly sampling from a power law distribution. We allow the mean input flux to decrease slowly with time to represent the secular decay in all of the injection processes over martian history. Escape of hydrogen and oxygen to space via diffusion-limited and non-thermal escape processes is also included, as is oxidative weathering of the crust. Changes in surface temperature over time due to greenhouse warming by CO_2 and reducing gases are also taken into account.

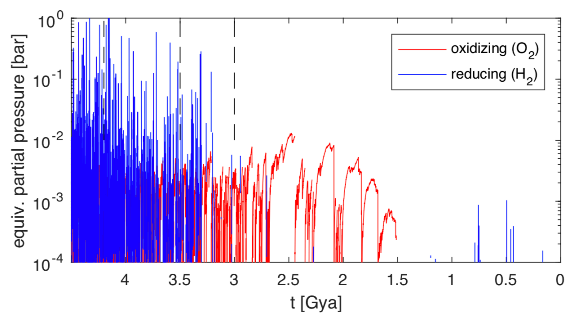

Figure 1: Example output of the stochastic atmospheric evolution model. Changes in the net redox state of the atmosphere vs. time due to the competing effects of episodic release of reducing gases, atmospheric escape and surface weathering are shown.

Climate parametrization. We use the PCM_LBL line-by-line radiative-convective code [12] to calculate equilibrium surface temperature as a function of reducing gas concentration in the model. We assume that CO_2 and H_2 are the primary warming agents, although other gases such as CH_4 may also have contributed. Surface temperatures are calculated as a function of solar flux, total surface pressure and atmospheric composition. We test the effects of using both theoretical [12] and recent experimental [14] CO_2-H_2 collision-induced absorption data.

Oxidation constrained by D/H through time. Net oxidation occurs when H_2O is photolyzed at high enough altitude to allow non-stoichiometric loss of H to space [15,16]. Limited oxygen (O_2) buildup in the atmosphere can occur under cold conditions when reducing gas input and surface weathering rates are both low. Here we assume a long-term transport rate of H_2O to the high atmosphere that constrains the evolution model to match D/H values through time (Fig. 2).

Results and Observational Implications. After describing our model setup in detail and presenting example model output for standard external parameters (Figs. 1 and 3), we discuss the model behavior when a variety of uncertain factors such as the forcing distribution and evolving solar output are varied. We demonstrate how the model can be used to determine the likelihood of an episodically warm or steady-state warm early Mars as a function of the total forcing. Implications of the model results for the evolution of Mars' surface mineralogy will also be presented. Finally, we will discuss implications of the results for the Mars 2020 mission and eventual sample return.

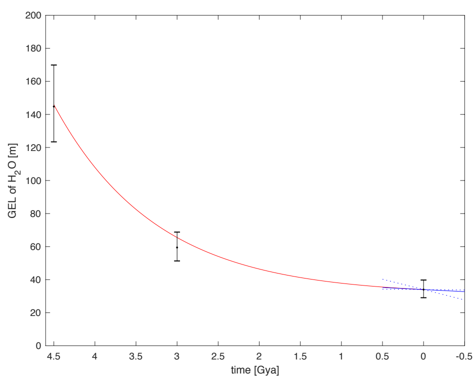

Figure 2: Observed martian D/H ratios (black error bars) vs. time displayed alongside our empirical water loss fit (red line) in terms of global equivalent layer depth (GEL) of H_2O in m.

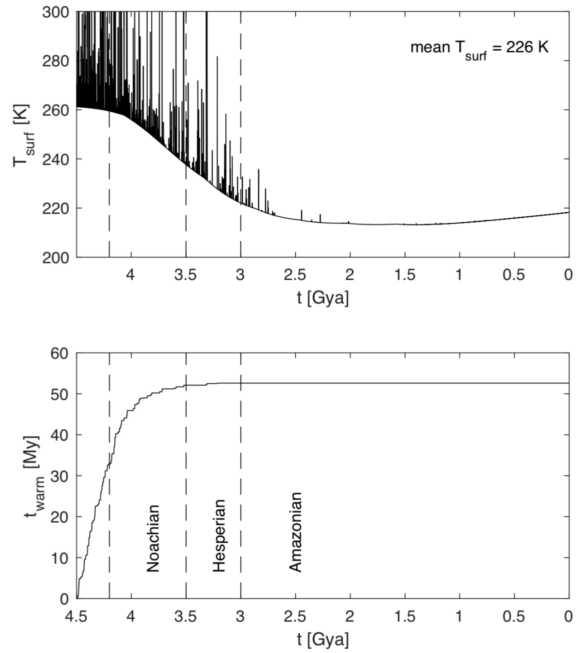

Figure 3: Surface temperature evolution and cumulative integral of time spent with surface temperature >273 K. In this run, the time-mean surface temperature was 226 K, and the total duration of warm conditions during the Noachian period was around 20 My.

References: [1] Carr., M. H. (2007), vol. 6. Cambridge University Press. [2] Wordsworth, R. (2016), *Ann Rev Earth and Plan Sci*, 44(1). [3] Haberle, R. M. et al. (2017), Cambridge University Press. [4] Hoke, M. R. T. et al. (2011), *Earth Plan Sci Lett*, 312(1):1–12. [5] Bishop , J. L. et al. (2018), *Nat Astro*, 2(3):206. [6] Fukushi, K. et al. (2019), *Nat Comm*, 10(1):1–11. [7] Kite, E. S. (2019), *Space Sci Rev*, *215*(1), p. 10. [8] Niles, P. B. et al. (2013), *Space Sci Rev*, 174(1-4):301–328. [9] Ehlmann, B. L. and Edwards, C. S. (2014), *Ann Rev Earth Plan Sci*, 42:291–31. [10] Haberle, R. M. et al. (2020), *Geophys Res Lett*, in press. [11] Ramirez, R. M. et al. (2014), *Nat Geosci*, 7(1):59–63. [12] Wordsworth, R. et al. (2017), *Geophys Res Lett*. [13] Chassefière, E. et al. (2016), *Meteorit Plan Sci*, 51(11):2234–2245. [14] Turbet, M., (2019). *arXiv:1912.05630*. [15] Chaffin, M. S. et al. (2017), *Nat Geosci*, 10(3):174–178. [16] Heavens, N. et al. (2018), *Nat Astro*, 2(2):126.