METHANE-BURST CLIMATE SCENARIOS FOR EARLY MARS RIVERS AND LAKES.

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Motivation: Early Mars climate models using CO$_2(g)$ + H$_2$O$_2(g)$ greenhouse forcing yield temperature too cold to match geologic data [1,2]. A promising candidate for the extra warming is CH$_4(\pm$H$_2$) [3,4]. Reducing gases are expected products of water-rock reactions early in Mars history [5,6]. However, CH$_4$ is rapidly lost from the atmosphere due to photolysis. Therefore, in order to outgas CH$_4$ late enough to match geology data and swiftly enough to overwhelm the loss processes, we need a trap-and-release mechanism. A plausible trap is CH$_4$-clathrate formation. A possible release mechanism for the Late Hesperian - Amazonian lake-forming climate(s) [7] is chaotic transitions in mean obliquity. Results are for a single ensemble of integrations of Mars’ obliquity history [9], grids of GCMs [2], recent CH$_4$-CO$_2$ Collision-Induced Absorption (CIA) results [4], and full photochemistry codes. Strengths of these scenarios are: climate optima of duration 10$^5$-10$^6$ yr, consistent with data; intermittent lakes permitting olivine preservation; and potent self-sustaining feedbacks (Fig. 1). The key requirement of our models is that the CH$_4$ clathrate stability zone (CSZ) on past Mars had an occupancy fraction >(1-10)$\%$. If these high past CSZ occupancy fractions actually occurred, then this would imply nonzero present-day CSZ degassing. This prediction can be tested by tracking the source of (putative) CH$_4(\pm$H$_2$) on modern Mars.

Late Hesperian - Amazonian lake-forming climates triggered by transitions in mean obliquity [10]: Build-up of relatively young (<3.6 Ga) deltas and alluvial fans on Mars required lakes to persist for >3 Kyr (assuming dilute flow), and the watersheds’ little-weathered soils indicate a climate history that was >99% dry. However, the post-Noachian lake-forming climates’ trigger mechanism remains unknown. In our CH$_4$-burst scenario, chaotic transitions in mean obliquity drive latitudinal shifts in temperature and ice loading that destabilize CH$_4$ clathrate. Outgassed CH$_4$ builds up to levels whose radiative forcing is sufficient to modulate lake-forming climates for past clathrate hydrate stability zone occupancy fractions >0.04. Such occupancy fractions are consistent with CH$_4$ production by >3 Ga water-rock reactions. Individual lake-forming climates are curtailed to <10$^5$ yr duration (matching data) by UV-limited CH$_4$ photolysis.

Collapse-and-reinflation trigger for the Late Noachian – Early Hesperian fluvial optimum [11]: The progressive drying-out of Mars’ surface was punctuated by a dramatic transient increase in fluvial erosion around the Noachian-Hesperian boundary [8]. Standard explanations of this climate optimum appeal to volcanic- or impact-triggered climates and imply that individual runoff episodes were brief, apparently inconsistent with evidence for persistent runoff. We have examined a scenario in which the duration, intensity and uniqueness of the Noachian-Hesperian climate optimum result from degassing of CH$_4$-clathrate consequent to Mars’ first prolonged atmospheric collapse (Fig. 2). Atmospheric collapse causes low-latitude surface H$_2$O-ice to sublimate, depressurizing and destabilizing CH$_4$ clathrate in subglacial pore space. Subsequent atmospheric re-inflation leads to further warming and further destabilizes CH$_4$ clathrate. CH$_4$-induced warming is efficient, permitting strong positive feedbacks, and possibly raising Mars into a climate optimum. The optimum is brought to a close by photolysis of CH$_4$, and drawdown of the clathrate reservoir prevents recurrence. This scenario predicts a 10$^5$-10$^6$ yr climate optimum, transient connections between the deep hydrosphere and the surface, and strong surface weathering, all of which are consistent with recent observations. Crustal hydrothermal circulation very early in Mars history could yield CH$_4$ that would be incorporated into clathrate on approach to the cold surface. The scenario explains why regional watershed integration on Mars occurred relatively late and only once, and suggests that the contrasts between Noachian versus Hesperian climate-sensitive deposits on Mars correspond to a transition from a never-collapsed atmosphere to a collapse-prone climate, ultimately driven by slow loss of CO$_2$ to space.

Fig. 1. Gain due to CH$_4$-warming-induced CH$_4$-release (colors). Gain = 1 implies no net feedback. White corresponds to runaway (= gain). Results are for a single regolith column at initial (pre-burst) surface temperature of 240K. Results for 3D simulations with realistic topography and surface temperature variations are qualitatively similar.
Figure 2. Overview of proposed scenario for the Late Noachian / Early Hesperian climate optimum. (a) Left: schematic of the long-term evolution of a column of the Mars highlands. Right: obliquity diffusion and slow CO$_2$ loss lead to polar temperatures dropping below a pressure-dependent critical value for atmospheric collapse initiation, $\phi_c$. (b) Below $\phi_c$, >90% of the atmosphere will condense in 1-10 Kyr (step 1). This unloads high ground (step 2), releasing CH$_4$ from sub-ice clathrate. (GCM simulations indicate that ice unloading can take >10$^6$ yr, but conclusions are unaffected.) Reinflation of the atmosphere leads to climate optimum (steps 3-4).

**Discussion:** The methane burst hypothesis is an attractive explanation for lake-forming climate optimum in Early Mars history. Formation of CH$_4$-clathrate at relatively shallow (<300 m) depths in the Mars subsurface requires that temperatures were warm at these shallow depths at the time of clathrate formation. This might occur due to insulation from a Late Noachian Icy Highlands ice sheet, or due to a very early (pre-Noachian?) warm climate. The CH$_4$-burst hypothesis cannot explain all aspects of the Early Mars sedimentary record. For example, thick packages of light-toned, layered sedimentary rock required many Myr to form, too long to be explained by methane bursts. Modest amounts of snowmelt may be sufficient to form these features [12].

**Tests:** The collapse-and-reinflation CH$_4$-burst scenario for the climate optimum makes novel, testable predictions. Perchlorates and <50m-diameter craters should be absent before the climate optimum, because both require a thin atmosphere to form. The CH$_4$/CO$_2$ ratio during the climate optimum can be high, permitting abiotic soots to be incorporated into the geologic record. Present-day CH$_4$ degassing should occur and may be detectable with NOMAD.
