LATE BURSTS OF HABITABILITY ON MARS-LIKE PLANETS

The roles of obliquity, carbonate formation and atmospheric escape

1. INTRODUCTION

Small amounts of snowmelt can wet the Mars soil during the Late Hesperian and Amazonian and this would create a ‘cool little pond’ environment suitable for forming the carbonates in Mars’ shallow subsurface. Fresh shallow valleys show that surface runoff did sometimes occur; runoff was not spatially correlated with impact events, suggesting climate-driven habitability. Obliquity variations are critical to post-Noachian climate (e.g., [1-10]). We are building on existing models (e.g. [8-11]) by combining orbitally-resolved full atmospheric pressure of carbon dioxide (PCO2) < 1 bar.

Itay Halevy, Melinda Kahre and Mike Wolff made valuable contributions to the energy balance model.


2. MULTI-GYR ORBITAL FORCINGS:

Mars’ obliquity varies chaotically, so we generated 18 orbital histories for Mars (4-7) using the mercury N-body code [12] to integrate the solar system for 3.5 Gyr. We then applied an obliquity code [13]. The results show a remarkably widespread spread of equally possible orbital forcings (Fig. 2). This raises the question – did Mars’ small size seal its fate, or are there orbitally based tracks that would have allowed habitable conditions at the present day?

Fig. 2. Disparate obliquities for equally likely orbital evolution tracks suggest a role for obliquity in intermittent Mars habitability on multiple timescales. Left: Myr-mean obliquity for three 3.5-Gyr orbital trajectories. Right: Showing that individual 3.5 Gyr histories can differ in their cumulative years spent at high obliquity (≥40°) by a factor of 10. In addition, peak obliquity at the time when those obliquities are sampled (colors; °/m/°m) can differ by up to 200 °/m/°m due to increasing solar luminosity. Black curve shows average.

3. CLIMATE EVOLUTION MODEL.

We used the spin-out orbit to drive a simple snowpack energy balance model [10], which was in turn coupled to an atmospheric evolution model. The energy balance model assumes that warm-season snow was only present in cold traps (locations that minimize annual-average sublimation rate), which is reasonable [10, 14]. The atmospheric evolution model assumes that the initial atmospheric pressure (P) was 100 mbar. CO2 is currently escaping from Mars at >1 mbar/Gyr. Our escape-to-space parameterization follows [15], scaled to the higher UV flux of the young Sun.

Fig. 3. Example of our melt model calculations showing surface liquid water areas (green) for (a) ≤0.14 Arc, (b) 40, P = 49 mbar, AT = 3 K) using our simple energy balance model [10]. Blue-shaded areas correspond to cold traps – likely locations of warm season snow. Red-shaded areas are hot enough for melting at some point during the year, if snow were present. Where the blue and red zones intersect, melt occurs (solid green shading). Thick black line corresponds to the boundary of recently-resurfaced terrain, which is masked out. Ga = Gall, Gu = Gusev, MP = Mendisani Planum. Background contours are topography: interval 1.5 km, minimum −5 km, maximum +10 km.

4. CARBONATE FORMATION.

Self-consistently calculating P loss also requires considering carbonate formation (e.g., [16-17]). Because low melt rates are sufficient to form carbonate but insufficient for runoff, evidence for climate-driven runoff (e.g., [18-20]) implies physical conditions suitable for carbonate formation over a much wider range of locations and times. Carbonate formation must have occurred on Mars to explain the carbonate dispersed in the soil and in Amazonian alteration veins (e.g., [21-22]); carbonate isotopes indicate “derivation” from atmospheric interaction with only transient water” [23], while (5-5) wt % abundances reported equate to ~1 mbar CO2 drawdown per 10° km/dust/silt/sand. Because >10° km dust/silt/sand was cycled through the weathering-proximal diurnal skin depth since 3.5 Ga (e.g., [24]), there is a potential for liquid water availability to feed back on P (as on Earth) [18, 11, 25]. Although a potentially significant feedback on climate, the relatively modest amounts of carbonate formed in our models are consistent with the paucity of bedrock carbonate. We assumed MgCO3 formation within parts of the planet experiencing seasonal melting was limited by the supply of weatherable sand, silt and clay.

Fig. 4. Intermittency of liquid water (peak day-integral melt, blue) predicted by using our obliquity tracks (red) to drive a simple energy balance model of snowmelt. Three different, equally likely tracks are shown. Black line shows atmospheric pressure. Bottom right: Intermittency of surface liquid water (blue) is much greater than intermittency of high obliquity (gray). Though the specifics of the exact tracks differ greatly, the results show common intermittency-spectrum characteristics. A subset of tracks (e.g. Orbital Integration #6) match geologic-history constraints for the real Mars.

The results show a wide range of possible histories. Size is not fate: Among the modeled ensemble of Mars-like planets, some are habitable at the present day. For this to happen, obliquity has to stay low for most of the 3.5 Gyr-long simulation (so that carbonate formation does not occur), with a “jump” to high obliquity in the recent past. This is an uncommon, but not impossible, circumstance. Although obviously not representative of the Mars in our own solar system, this shows a pathway by which Mars-sized exoplanets (28) could be habitable late in their histories. Relatively late wet “spikes” define bursts of habitability: Late Hesperian / Amazonian crater-retention ages obtained for alluvial fans can be understood in terms of higher solar luminosity at later times favoring surface liquid water. Intriguingly, the expectation of >100 comparably-wet intervals (given 10° quasiperiodic forcing) is flatly contradicted by the results, which instead show a few very wet “spikes” due to rectification at the melting-point and buffering of P by carbonate formation (Fig. 1). Intermittency of liquid water at all timescales: Although the details of the orbital histories vary greatly, a common trend is that surface liquid water availability is more intermittent at all timescales than are high-obliquity conditions (Fig. 1). Biological isolation of late bursts of habitability: >10° global desert conditions are common, due to long periods of low q. Long global desert intervals define a challenge for the persistence of life on the Mars surface. The longest continuous run of wet years (each wet year has a dry season) is ~60 Kyr. Work in progress consists of refinement and extension to our forward modeling framework to investigate obliquity’s role in the greater detail allowed by the LMD GCM (e.g., [29]).