

The great climate paradox of ancient Mars

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Understanding Mars' past climate and the availability of surface water through time is paramount to assessing the Red Planet's astrobiological potential. While cold and dry today, with an average surface pressure of 6 mbar, there is intriguing geomorphic evidence that ancient conditions were drastically different (Fig. 1). The so-called "valley networks" are found across the old cratered terrains and remain the best evidence that Mars had a long-lived, integrated hydrosphere covering much of the planet (e.g., Craddock and Howard, 2002; Hynek et al., 2010). Additionally, hundreds of paleolake basins have been identified (Fassett and Head, 2008a; Goudge et al., 2016) and over 50 fan deltas supporting subaqueous deposition are present (di Achille and Hynek, 2010a). Controversial evidence exists for a vast ancient ocean including shoreline features (Parker et al., 1989; 1993), deltas along an equipotential (di Achille and Hynek, 2010b), and evidence of tsunamis (Rodriguez et al., 2016).

Despite the wealth of geologic observations of past surface waters, the vast majority of climate models produced for ancient Mars stubbornly do not produce temperatures above freezing. A recent climate hypothesis offered a possible solution to this conundrum. In this "cold-icy highlands" model (Fig. 1), snow accumulation and subsequent melting could have provided the surface water necessary to carve the fluvial valleys, even under globally cold and dry conditions (Forget et al., 2013; Wordsworth et al., 2013). Support for this hypothesis has come from Wordsworth et al. (2015), who showed cold-icy paleoclimate simulations had a positive spatial correlation between drainage density and maximum snow accumulation, while their warm-wet models did not match. These workers argued that regions of the highlands without valley networks, most notably the Arabia Terra region, should have received high amounts of precipitation in warm-wet scenarios. Yet very few valley networks have been recognized in previous studies.

Davis and colleagues (2016, p. 847 in this issue of *Geology*) throw a wrench into the cold-icy hypothesis by documenting extensive fluvial activity throughout Arabia Terra, thus supporting warm-wet conditions. While valleys are rare in the Arabia region, Davis et al. have identified extensive networks of sinuous ridges that are interpreted as inverted fluvial channels. These features have been reported for other areas of Mars (e.g., Pain et al., 2007; Williams et al., 2009; Burr et al., 2010) and are convincingly of fluvial origin given that the sinuous ridges conform to regional topography, do not cross divides, and often display anabranching geometries and tributary junctions (see examples in Davis et al.'s figure 2). The ancient inverted channels, like many of the global valley networks, are sourced in and traverse across regional terrains. These observations are inconsistent with discrete and localized sources of water expected for meltwater from highland snowpack. Additionally, here and elsewhere, valleys tend to grow in size downstream and be sourced from dispersed areas, which would be unexpected from a melting snowpack in otherwise cold conditions with a low atmospheric pressure.

The largest martian valley networks are dendritic in form and similar in length and drainage area to Earth's largest river systems and individual trunk-segment valleys can be 20 km wide and >1 km deep. Few of the larger valley systems have sedimentary deposits at their termini; however, many of the lower reaches of the large ancient valley networks have been

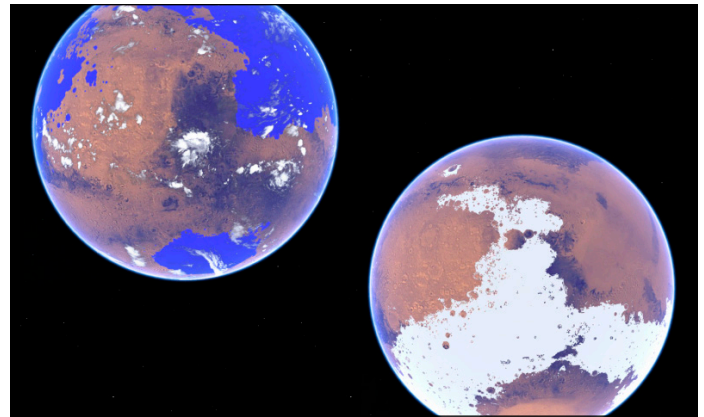


Figure 1. Contrasting scenarios for early Mars. On the left is an ocean world with an active hydrologic cycle that is supported by ancient geological evidence. On the right is a cold-icy highlands representation, more consistent with climate models. Credit: Robin Wordsworth.

obscured by younger resurfacing. Analytical methods have been used to assess the formation timescales of larger networks by applying sediment transport models to Mars. Results indicate that it took 10^5 – 10^7 yr to transport enough sediment out of the valley network to match the observed volumes (Hoke et al., 2011). Considering the large uncertainty in these calculations and the combination of parameters that produced minimum timescales, it is possible that the formation timescales approach durations similar to their span in ages of $\sim 10^8$ yr. Cross-cutting relations with ancient cratered highlands (e.g., Hynek et al., 2010) and network crater-age dates (Fassett and Head, 2008b; Hoke and Hynek, 2009) indicated that a majority ($\sim 90\%$) of these systems seem to have formed in the Late Noachian up through the Noachian Hesperian boundary (ca. 3.7 Ga).

Meanwhile, climate modelers continue to point out the hardships of making early Mars (or even Earth) warm enough to support liquid water. This is in part due to the faint young sun paradox; the idea that our nascent sun provided only $\sim 75\%$ of the energy output as today. Mars is especially hard to warm up, given its greater distance from the sun. Recent modeling has provided possible solutions that permit a warm early Mars and these rely on punctuated volcanism or better inclusion of radiative effects of clouds in the models (Halevy and Head [2014] and Urata and Toon [2013], respectively). While more work needs to be completed, these directions may be the key to explaining the geological evidence of persistent water on early Mars. On the other side, geologists need to provide the climate modelers with hard constraints on the magnitude and duration of warm-wet conditions through time. This is challenging, given that we cannot determine ages of the fluvial episodes by traditional methods but the timing and length scales of valley and delta formation are now at least somewhat constrained (e.g., Hoke et al., 2011). Only then will we be able to reconcile the observations with the theoretical work and provide an accurate picture of the potential habitability of early Mars.

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