SNOWBALL MARS: WHAT THE CURRENT STATE OF THE MARTIAN CO_2 CYCLE TELLS US ABOUT MARS' PAST CLIMATE HISTORY. D. A. Paige[1], [1]Dept. of Earth, Planetary, and Space Sciences, UCLA, Los Angeles, CA 90095 dap@mars.ucla.edu

Introduction: Mars today is a frozen planet. With the exception of the warmest near-surface regions during the warmest times of day/year, Mars is in a completely frozen state at all latitudes to kilometer depths. The cold state of the current Martian climate is fundamentally due to Mars' average distance from the sun, and the absence of sufficient atmospheric greenhouse gasses to warm the surface. Here I examine the current partitioning of carbon dioxide between the Martian polar caps and atmosphere and suggest that this current state is not coincidental, but the predictable consequence of a nearly perpetually frozen planet.

Snowball Earth: The current state of the Martian climate resembles the hypothesized state of the Earth's climate system 500-800 million years ago, when the surface of the Earth repeatedly became entirely or nearly entirely frozen [1]. "Snowball Earth" episodes are believed to have been initiated when cooling events resulted in runaway ice-albedo-temperature feedback processes that cooled the Earth from the poles to the equator. It has been proposed that Earth was able to escape from snowball states because of the accumulation of carbon-dioxide gas in the atmosphere. Earth maintains an approximate balance of greenhouse gasses over million-year timescales via feedbacks involving the aqueous weathering reaction silicate rocks, which remove CO_2 from the atmosphere, and volcanic activity, which add CO_2 to the atmosphere [2]. The cold dry climate that existed during Snowball Earth episodes drastically reduced the rates of aqueous weathering, while the emission of reconstituted carbon-dioxide from volcanos driven by plate tectonics continued unabated. The resulting spikes in CO_2 concentrations were apparently sufficient to warm the atmosphere to melt of the global surface ice layer, and to also deposit widespread "cap carbonates" which are observed to overly Snowball Earth glacial deposits [3]. Earth's geologic record includes evidence multiple earlier extreme glacial periods extending back >2.4 billion years [4]. The fact that the young sun's luminosity was only 80% of its current value during this period probably contributed to Earth's protozoic snowball tendencies.

Kahn's Hypothesis: Mars today is not covered with high albedo ice, but it's generally cold temperatures and 6 mbar CO_2-dominated atmosphere is very close to the triple point of water, and thus permits the ephemeral stability of pure liquid water only in low altitude regions during the warmest daytime periods [5]. This potential coincidence between Mars' atmospheric pressure and the triple point was noted by Kahn in 1985, and this led him to propose (which at the time was) an extremely bold hypothesis, which is that the Martian atmosphere had evolved to this state by draw-down of atmospheric CO_2 by aqueous weathering of igneous rocks [6]. In Kahn's model, if CO_2 concentrations in the Martian atmosphere were to increase and become more favorable for the widespread stability of near-surface liquid water, then aqueous weathering reactions such as the formation of carbonates would draw down the CO_2 concentration in the atmosphere to the point where surface liquid water would no longer be stable. In the intervening 35 years, a variety of new observational data has emerged that appears to support the general scenario outlined in Kahn's original paper.

Carbonates and Organics: Martian carbonates have now been definitively detected in a range of contexts, including: orbital remote sensing observations of sedimentary rock outcrops and Martian dust, landed compositional measurements in Martian soil and rocks, as well as alteration products in Martian meteorites [7]. It has also been proposed that a CO_2 can be drawn out of the Martian atmosphere to form organic carbon phases and perchlorates through the corrosion of igneous minerals in the presence of brines [8] .The products of these reactions are observed in Martian meteorites, and similar chemistry may be mirrored in the sedimentary rocks analyzed by the MSL SAM instrument at Gale Crater [8]. The quantities of carbonates and organics that have been acquired to date do not support the weathering of a dense CO_2-dominated Noachian atmosphere [7], but instead suggest low levels of carbonate formation in transient aqueous environments with limited water availability. The presence of abundant un-weathered olivine on Mars today also supports this conclusion [7].

Mars' Small South Residual Polar Cap is No Coincidence: Through orbital and infrared and radar observations, we now know that Mars' south residual polar cap contains remnant surface CO_2 deposits that are in approximate solid-vapor equilibrium with the Martian atmosphere [9], as well as a thick buried CO_2 ice deposit that contains the equivalent of 6 mbar of gaseous CO_2 [10].

The small masses of Mars' present surface and subsurface remnant CO_2 reservoirs could also be interpreted as coincidental. In Leighton and Murray's original model, if there is enough CO_2 in Mars' cap-atmosphere reservoir to support a permanent frozen CO_2 deposit at one of the Martian poles, then the partial pressure of CO_2 in the Martian atmosphere would be determined by the vapor pressure of the permanent CO_2 deposit, which is in turn determined by its annual heat balance [11]. In their 1973 paper, Murry and Malin [12] postulated that a large permanent reservoir of excess solid CO_2 must exist today on Mars, and proposed (erroneously) that it is located within larger north residual polar cap. The perennial CO_2 deposit at Mars' south residual polar cap would appear to satisfy the need for a permanent excess CO_2 reservoir, but such a small reservoir would appear be sufficient to survive warming episodes due to decreases in its surface albedo or increases in insolation during periods of higher obliquity.

It is easy to envision how long-term draw-down of atmospheric CO_2 by weathering will inevitably diminish the mass of a residual polar CO_2 deposit. In a scenario in which the heat balance of the residual CO_2 polar cap is forced by periodic obliquity variations, or any other climate forcing parameter, CO_2 added to the atmosphere will inevitably be lost to the cap-atmosphere system due to draw-down by weathering. The end result of the process is an atmospheric pressure "ceiling" that just barely permits the formation of aqueous weathering products (i.e. Kahn's original hypotheses), but also the near complete loss of residual polar CO_2. The existence of only a small CO_2 deposit at the south residual cap today suggests that present-day global aqueous weathering rates are sufficiently small as to have negligible long-term effects. Near-surface aqueous weathering environments will only become widespread on Mars when atmospheric pressures are roughly double their present-day values. One data point that confirms that the present state of the Martian climate may be "typical" comes from analyses of gas trapped in impact glass from the 180-million-year-old Mars meteorite EETA79001. The chemical and isotopic composition of the gas in EETA79001 is a perfect match for the Mars atmosphere as measured by Viking, and show CO_2 concentrations that are between one and two times the present Martian value [13].

Implications for Long-Term Climate: It has long been recognized that the draw-down of atmospheric CO_2 by weathering has important potential climatic implications [14]. While the rates at which weathering processes take place are highly uncertain, we can expect that they would accelerate with increasing temperature, CO_2 concentration, and liquid water availability. Given that weathering processes appear to be active in Mars' current climatic state, it seems reasonable to conclude that they would become even more active earlier in Mars' history when a considerable body of geologic evidence has been interpreted to suggest that Mars had a warmer and wetter climate [15]. Previous authors have suggested that past weathering sinks for atmospheric CO_2 on Mars could have been balanced by the release CO_2 via the thermal decomposition of weathering products by volcanism [14] or impacts [16]. However, even if Mars' past inventory of CO_2 was sufficient to somehow maintain long-term or ephemeral warm wet greenhouse conditions, the inability of Mars to reconstitute weathered CO_2 products appears to have sealed its ultimate snowball fate.

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