HABITABLE ZONES FOR TERRESTRIAL PLANETS IN A CO_2 POLAR CONDENSATION SCENARIO.

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Introduction: Mars is in a very debatable thermal position in the Solar system. Some authors argue that it should be outside the habitable zone [e.g. 1-3] while others maintain that it must be inside the zone [e.g. 4-10]. One reason for preferring the latter is because of the apparent signs of water erosion on Mars' surface. The same authors often find different points of view with time and may "change sides" in this discussion. Some atmospheric models may have been constructed with the explicit or implicit intention of achieving liquid water at surface by introducing various exotic greenhouse species.

Recent developments in flow mechanisms for the outburst "floods" on Mars strongly suggest that CO_2 is the active volatile rather than liquid water [11], and so we no longer need to force the atmospheric models to fit this paradoxical datum.

Simple latitudinal models based on ice condensation at the poles show that the habitable zone of Sol-like stars can be described to first-order by a simple CO_2-based atmospheric model with two bounding curves. One is the CO_2-cycle curve for stability of a thick and warm CO_2 atmosphere against water-mediated carbonate formation [1]. The other is a simple surface ice formation model of atmospheric pressure maintenance by cold-trapping at the poles (Figure 1). The crossover of the two curves is an estimate of the outer bound of the habitable zone, and evolves with time (Figure 2) in parallel with the solar constant.

Atmospheric Models for Mars:

1-dimensional: At its simplest, we can take modern Mars as a calibration point and treat Mars as a globally averaged surface over time and space. Diurnal, seasonal, and latitudinal variations are all harmonised and the planet treated as a simple object. Different greenhouse atmospheres, cloud and dust scattering, and insolation patterns due to the evolving Sun, or to orbital variations can all be fed in and the average result inferred. Models like this are normally too simplistic to give reliable answers.

2-dimensional: To give more reliable results, the main effort in modelling Mars atmosphere has been to introduce more realistic vertical structure to account for the complex scattering, absorption and re-radiation properties of a real structured atmosphere [e.g. 4-10]. The surface of Mars remains an average, but the complex vertical properties of a real atmosphere are specifically modelled. Specific greenhouse cocktails can be fed into this type of model and the question of stability of the atmosphere against condensation can be addressed. Typically condensation first occurs at altitude in these classes of model.

However, it should be an obvious fact that modern-day Mars cannot be adequately treated in this manner. We know that the annual cycle of CO_2 ice condensation at the poles is responsible for maintaining Mars' atmospheric pressure, yet if we look at the output of one of these so-called 2D models, they have neglected the latitudinal (and seasonal) components. These models would all predict that the modern atmosphere of Mars was stable against condensation and that polecaps should not exist, whereas clearly they do.

Condensation of the modern Mars atmosphere does not occur at altitude in mid latitudes, but near or on the surface at the poles. Unless the models explicitly include a polar cold trap, they cannot be considered valid for modern Mars, and therefore are of no practical use for studying ancient Mars either.

True 2-D models: A better class of model includes as its second dimension not the vertical structure (which can be reasonably well parameterised, anyway) but the latitudinal structure. By studying the atmosphere at a suitable time (e.g. midwinter at one pole) we can reasonably reliably predict the atmospheric pressure in equilibrium with the polar temperature.

Of course, there are problems. The heat transport of the atmosphere to the poles is a vital and poorly known detail. Indeed many authors have claimed that it is adequate to prevent polar condensation at all in some scenarios, but this is an unproven assertation in the majority of cases.

3-D models and GCM's: Clearly, to properly resolve the issue a full 3-D surface model, with vertically structured atmosphere, orbital dynamics, and solar input needs to be run. Such climate models exist for modern Mars and do a reasonable job of predicting modern weather and the overall averages such as polar temperatures and annual atmospheric pressure cycles.

If the modern-day GCM for Mars is run with reduced insolation appropriate to a billion or more years in the past, it not surprisingly will predict a lower mean atmospheric pressure and lower polar and mean planetary temperatures.

One example of such a run with full 3D surface detail [1] addressed terrestrial planets in general and found a condensation limit for a CO_2/H_2O atmosphere at 1.47 AU at modern insolation rates. 1 Billion years ago when the supposed Boreal ocean and the outburst floods are used to indicate a warmer and wetter planet, that limit would be closer to the Sun– some 1.425 AU, since the solar constant would then have been some 94% of its present value [11]. The further back in time we go, the closer to the Sun we find the condensation limit, and in the early days of the Solar system, when the solar constant was only 70% of the present value [12], it would have been around 1.23 AU. So the further back in time that we go on Mars, the more difficult it is to avoid atmospheric condensation.

Early Mars as an iceworld: We use a model based on simple atmospheric greenhouse feedback [13] with the addition of an explicit latitudinal component. We calculate that in the absence of any additional non-solar heat sources, early Mars would have had equilibrium atmospheric pressure of less than 1 millibar of CO_2, and a mean temperature about 20K cooler than its present frigid state. This iceworld – "White" Mars – leads to a very different understanding of the planet's evolution.

Using this simple model that properly allows for polar condensation, it is hard to avoid the conclusion that Mars has never had an Earth-like climate, and has always been acutely cold and dry. Models of Mars' surface, atmosphere, and geochemical evolution need to take this into account.

Recent work [11] has shown that all of Mars' observed surface features are entirely compatible with the activity of CO_2 under this cryogenic climatic regime and liquid water is never required at surface.

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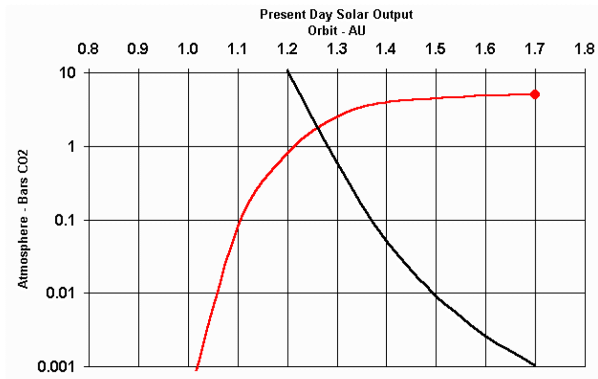

Figure 1: Equilibrium curves for a CO_2 atmosphere with modern insolation. The red curve is the equilibrium for CO_2 transformation to carbonate in aqueous environments. The black curve is the polar equilibrium with CO_2 ice. Beyond 1.26 AU, ice forms more readily than carbonate and an iceworld results. The red dot at the end of the curve represents the point where the carbonate equilibrium requires an atmosphere of greater than 5.1 bars – enabling liquid CO_2 in cold regions of the planet.

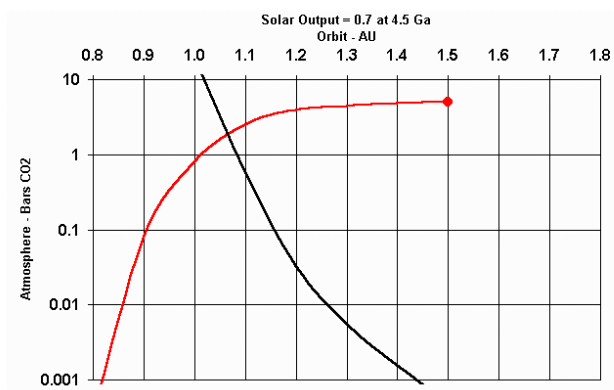

Figure 2 As for figure 1 but for a Faint Young Sun emitting 70% of its present energy at 4.5 Ga. The atmospheric crossover is at 1.07 AU. Mars at 1.53 AU is at such a distance that even if the iceworld scenario were somehow avoided, the CO_2 atmosphere would exceed 5.1 bars and spontaneously condense as liquid rain and collapse again.