WHAT IS THE TIME SCALE FOR ORBITAL FORCING OF THE MARTIAN WATER CYCLE?

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Introduction: Calculation of the periodic variations in the martian orbital parameters by Ward [1] and subsequent refinements to the theory [2,3] have inspired numerous models of variation of the martian water cycle. Most of these models have focused on variations in planetary obliquity on a both a short-term (110 kyr) time scale as well as larger oscillations occuring over millions of years. To a lesser extent, variations in planetary eccentricity have also been considered. The third and fastest mode of variation, the precession of the longitude of perihelion, has generally been deemphasized because, among the three parameters, it is the only one that does not change the integrated annual insolation. But as a result of this precession, the asymmetry in peak summer insolation between the poles exceeds 50%, with the maximum cycling between poles every 25.5 kyrs.

The relative contribution of these different elements to orbital forcing of climate takes on particular importance in the context of apparently recent water-related features such as gullies or polar layered deposits (PLD). Christensen, for example, recently indentified mantling of heavily gullied crater walls as residual dust-covered snow deposits that were responsible for the formation of the gullies in a previous epoch[4]. Christensen assumed that the snow was originally deposited at a period of high obliquity which was stabilized against sublimation by a lag deposit of dust.

It is suggested here that not obliquity, but the short-term oscillations associated with precession of the perihelion may play the dominant role in the formation of gullies, major strata in the polar layered deposits (PLD), and other water-related features.

Importance of a hydrological cycle: Though Mars is a cold, dry planet, with respect to the thermal stability of liquid water at low altitudes it is not terribly different from comparably cold places on Earth [5]. In dry air such water would evaporate faster on Mars, at a rate comparable to a 60°C hot spring on Earth, but the heat loss associated with that evaporation would be mitigated by the poor thermal convection in the thin Martian air. Even at higher altitudes where the atmospheric pressure does not reach the triple point of water, liquid water might theoretically exist in a low-vapor pressure form such as wet soil, in a briny solution, or simply under a layer of dust or snow [6,7].

The theoretical stability of liquid water does not suggest its occurrence, however, either on Mars or in Antarctica. In general, locations warm enough for ice to melt will eventually become dessicated because the average temperature exceeds the frostpoint Global models of mars have suggested supported the premise that locations capable of providing sufficient heat for melting are, precisely for that reason, too dry for water to be present [8-10]. To form gullies or other water-related features, the water supply must be periodically recharged. Moreover, it can be convincingly argued that seasonal recharging is necessary – otherwise the boundary of the cryosphere will tend to adiabatically adjust to the changing heat balance. Recent observations from the Odyssey spacecraft of permafrost buried deeper in the southern hemisphere than in the northern hemisphere is likely an example of this phenomenon.

Consistent with the Christensen observation, a premise of this work is that the atmospheric cycling of water, through sublimation and subsequent condensation and precipitation, is the most likely source of recharging. The physical conditions necessary for melting to occur in seasonal deposits has been described elsewhere [5]. Currently, tens of precipitable microns of water are available in the atmospheric reservoir for seasonal condensation. Though this amount can be multiplied by factors of 10-100 by local coldtrapping [11], on present-day Mars we still expect less than 0.1 g/cm^2 seasonal accumulation of frost or snow in a particular location such as a gully. To explain formation of geological features, these numbers would need to be multiplied by additional factors of 50-100. Orbital forcing provides a ready means to do that.

Modeling of orbital forcing: Studies of the relative role of the orbital elements in providing water to the atmosphere have led to discrepant conclusions. Thus Fanale [12] calculated the peak vapor pressure at the North Pole by assuming a surface of pure water ice or CO_2 ice with distinct optical properties, incorporating only radiative balance and latent heat of CO_2 deposition. It was further assumed that the zonal humidity was proportional to that peak water vapor, which was in turn a simple function of the ice surface temperature. The analysis indicated the possibility of two orders of magnitude increase in humidity with the 51,500 year precessional cycle, with additional gains under more favorable obliquity. While Jakosky et al. [13], in a more rigorous model, concluded that the effects of precession were more modest, the models of Mellon et al. [14] indicated a larger temperature excursion at high latitudes from extremes of precession than from obliquity.

To further understand these discrepancies, a protocol similar to Fanale's was employed, but with the critical addition of the tracking latent heat of water condensation and sublimation. A formula proposed by Ingersoll [15] was used to convert temperature to sublimation rate, assuming constant total atmospheric pressure. A typical result of that model is shown in figure 1. All three curves represent an extrapolation back only 150 kyrs. Rather than extrapolating back far enough to reflect large changes in obliquity, the obliquity was forced to specific values. Thus one curve represents the calculated obliquity, a second holds the obliquity at the current value of 25°, and the third holds the obliquity at 40°. The data is expressed in terms of the amount of heat from insolation that is converted to sublimation under these circumstances. It can be seen that, at constant obliquity, the sublimation rate can increase by a factor of 100 with the passage of only 20 kyrs. Changing the obliquity from 25° to 40° adds another factor of only approximately 5.

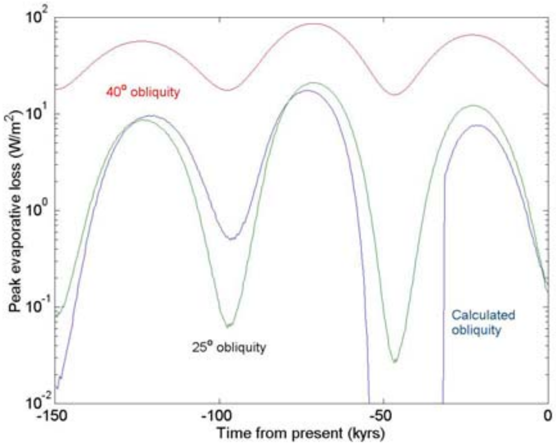

Figure 1: Calculated peak evaporative loss at the North Pole of Mars, expressed as an evaporative heat measure over 150,000 years. The calculation balances radiation, latent heat of CO_2 and H_2O, and insolation using orbital parameters from Ward [1], albedo and emissivity values suggested by Fanale et al [12]. To show the relative effect of precession and obliquity, the three curves represent calculated obliquity and obliquity fixed at 25° or 40°.

The result of figure 1 is surprising in that the relative influence of the orbital variations is highly nonlinear with the actual change in insolation. Figure 2 provides a qualitative guide to the source of that nonlinearity, showing how much heat is partitioned into evaporation of ice (in equilibrium) as a function of the total absorbed heat. In radiative balance, the surface temperature will scale as the ¼ power of insolation, but the evaporation rate will increase as a much higher power of temperature. Thus, at low temperatures, the evaporation rate rises steeply with increasing temperature. At higher temperatures, however, sublimation consumes most of the available power, and the relationship trends towards linear, governed by the available heat rather than the temperature. With Mars currently experiencing a dessicated atmosphere, t follows that the largest changes in humidity follow from the initial, modest gains in insolation.

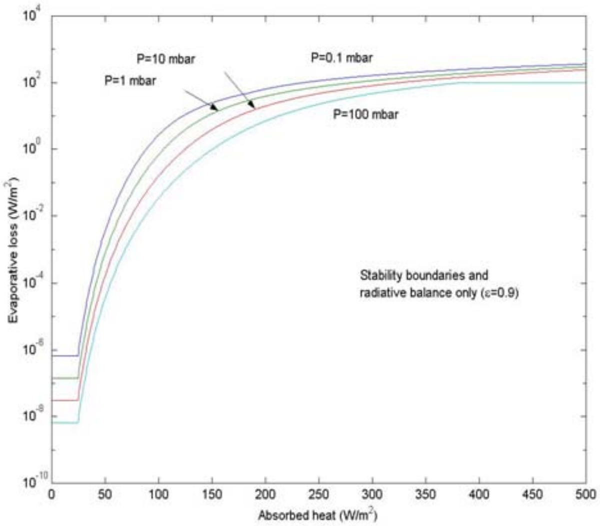

Figure 2: Evaporative loss, calculated as in figure 1 as a function of absorbed heat and total pressure. Flat regions at the high and low end reflect contributions of solid CO_2 (left) and liquid H_2O (right).

The limitations of models such as this can not be overstated. Albedo, for example, has a much greater influence on temperature than orbital forcing, and seems to be linked to insolation, possibly via its influence on dust transport [16]. Lateral and vertical transport of both heat and water will profoundly effect the actual influence of orbital forcing on climate. These factors in turn depend on total pressure, which can not be established without an understanding of the depth of the CO_2 reservoir. Of particular relevance to this work, the discrepancy between the results of Jakosky, and the present results (or those of Fanale) follow primarily from the use of peak seasonal temperature rather than integrated temperature. With respect to sublimation, the most singular difference between high and low obliquity epochs follows from the length of the summer season rather than the peak temperature.

An additional factor that has not been incorporated into published models may be of critical importance in interpreting models such as this one. It has been assumed to this point that the supply of water is limited by the delivery of heat alone. In practice, a limited amount of water can probably be desorbed from the polar cap as a result of orbital forcing before a lag deposit of dust shuts off the process. At the present time, for example, very little exposed water appears to be available for sublimation in the southern hemisphere. Qualitatively, this phenomenon would tend to punctuate the delivery of water vapor to the atmosphere, resulting in bursts of high humidity, possibly from each pole, every 51,000 years. While quantitative modeling of this phenomenon is outside the scope of this abstract, qualitatively it can be concluded that such an effect would further erode the advantage of obliquity over procession in its capacity to inject water vapor into the atmosphere.

Conclusions: Models of peak seasonal sublimation from the north polar cap suggest that the important cycle of water injection is 25.5 or 51 kyrs, depending on whether one or two poles are involved. If the process is limited by hemispheric depletion of available dust-free water, the result may be periodic pulses of water injection. Such a finding is consistent with the recent conclusions of Laskar et al. [3], derived from analysis of PLD stratigraphy. The proposed timescale is shorter by perhaps two orders of magnitude than current thinking about water-related events on Mars. The implications of this shift for geology as well as astrobiology are significant.

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