Why and When an early Wet Mars

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Abstract

When and why Mars sustained liquid water has been a continuing question. A model is proposed that quantitatively addresses this question.

The model is based on the stability of the solar system which is determined by solar radiative and non-radiative (solar wind) mass loss since the formation of the solar system, the associated decrease of solar gravity and expansion of planetary orbits, and the stability of planetary orbits.[1] The model predicts that at the formation of the solar system five billion years ago, the orbit of Mars was 30 million km closer to the sun than at present (198 vs. presently 228 E+06 km). Higher Mars temperatures in the past are predicted from changes of solar radiation at Mars' orbit. The model predicts the transition from liquid water to ice (273K) on Mars at about 3.4-3.8 billion years before the present time, in agreement with experimental estimates from observations on Mars of 2.9 – 3.7 Byr. The presence of hothouse gases (carbon dioxide, water vapor), brine formation, and effects dependent on variations in solar volume might have extended the presence of liquid water closer to the present.

Key Words: Water to ice transition on Mars; Reaction kinetic model for solar system; solar mass loss; Planetary and Mars orbit changes; Mars temperature change

Introduction

Images from Mars satellites show lacy networks that have the appearance of riverbeds and lake systems. Evidence is overwhelming that running water eroded Mars at an earlier time (Kerr 2003, Christensen 2003).[2,3] The question of when and why Mars sustained liquid water has been a continuing question. The time of the liquid water to ice transition is indicated by a detailed study of the dentritic valleys in the Valles Marineris of Mars. This work estimates that wet climate occurred 2.9 to 3.4 billion years ago (Mangold et al., 2004).[4] The same paper mentions that at that time Mars was thought to have been too cold and could not sustain liquid water. Evaluation of erosion rates from the Gusev-crater as well as those from Viking 1 and Pathfinder limit the warmer and wetter period to the Noachian, pre-3.7 byr, and a dry and desiccating climate since (Golombek 2004)[5]. All discussions imply that Mars remained in its present orbit throughout its past (Kerr 2003). The problem of why Mars was previously wet was aptly expressed in a review article as 'mind-boggling Martian gullies raise climate conundrum'(Anon, 2004).[6] Using celestial mechanics and dynamic astronomy concepts, we were able to develop a model which provides quantitative answers to both questions as to why and when Mars sustained a wet climate.

The proposed model predicts a warmer earlier Mars based on planetary orbit changes as a function of stellar (solar) radiative and non-radiative (solar wind) mass loss (Leubner 2004).[7] The mass-to-energy conversion (reaction kinetics) of the sun leads to proportional loss of gravity. This results in planetary radial orbital expansion and to an increase of orbital periods. This was modeled for the solar system as a function of time and as a function of the solar decay constant.[1]

The decay of stellar and the solar systems is increased beyond radiative mass loss by physical mass loss, i.e., solar wind. The radiative solar mass loss is about 4.20E+12 g/s, and the solar wind was determined to average 1.38E+12 g/s (McComas 2000).[8] In the present paper, both effects are included.

The model allows calculating the separation and rate of separation of the planets from the sun. For present solar radiative and solar wind decay conditions, the separation time increases from Pluto to Mercury from about 1.34 to 137 billion years (byr). The orbital periods were calculated to increase presently for Mercury 4.21E-05 s/year and for Pluto 4.42 s/year (Leubner 2004).[1]

For earlier than the present time, the model predicts closer orbits of the planets, with implied warmer climates. This is modeled in the present paper for Mars. Combining the Mars orbit changes with experimental orbit-temperature correlations allows predicting changes of Mars' climate in the past, present, and future. The model predicts that Mars at earlier times was significantly closer to the sun and that its climate was at earlier times significantly warmer than presently.

1. Model

The exponential decay for the solar decay processes is modeled analog to first order radioactive processes. The rate of solar mass loss is given by the first order equation (1).

$$\mathbf{M(t) = M_0 e^{-kt}} \tag{1}$$

Here, M_0 is the present mass of the sun, M (t) is the mass at the time t, and k is the solar (radiative plus solar wind) decay constant (Equation (2)). The solar radiative mass decay constant, k_i, equals 21.01E-22 s^{-1}, which presently represents a solar radiative mass loss, M_r, of $4.2*10^{12}$ g/s.

The solar wind removes mass at a rate of M_{nr} (g/s) from the sun by a non-radiative process. If the mass removed by radiative processes is M_r (g/s), then the solar radiative plus non-radiative decay constant, k_s (1/s) is given by equation (2):

$$\mathbf{k = \left[\frac{M_r + M_{nr}}{M_0}\right]} \tag{2}$$

The present average value of the average solar wind is about 1.38E+12 ^{g}/s, and varies with solar activity (McComas, 2000).[8] Since the solar radiative decay and solar mass loss are a function of nuclear processes related to the solar composition, it is assumed that the mass decay constant is relatively stable over a long time.

The orbits of the planets are determined by equation (3) (Leubner 2004).[1]

$$\mathbf{R_p(t) = \frac{2GM_s(t)}{2GM_s(t)/R_s - v_p^2}} \tag{3}$$

G (equation **Error! Reference source not found.**) is the universal gravity constant, $M_s(t)$ is the solar mass at time t (equations (1) and **(2)**), and R_s is the solar radius. For the present calculation it is assumed that the solar radius R_s is constant over the calculated time.

$$\mathbf{v_p^2 = 2GM_s\left(\frac{1}{R_s} - \frac{1}{R_p}\right)} \tag{4}$$

The planetary launch speed of the planet, v_p, is calculated from the present conditions using equation (4). The solar launch speed is a (hypothetical) speed with which a mass must be ejected from the sun to reach a given orbit. This does not imply that the planets were formed by such an ejection mechanism, but it is providing a working approach to the model. For Mars, a solar launch speed of 616.302 km/s is calculated. The variation of R_p with time predicts that at earlier times the orbits of the planets were closer to the sun, and will be further from the sun in the future (Leubner 2004). [1]

2. Mars Orbit as a Function of Solar Radiative and Solar Wind Mass Loss

It is generally accepted that the planets formed between four and five billion years before present. Thus, the orbit change of Mars was modeled between five billion years before until after the present time.

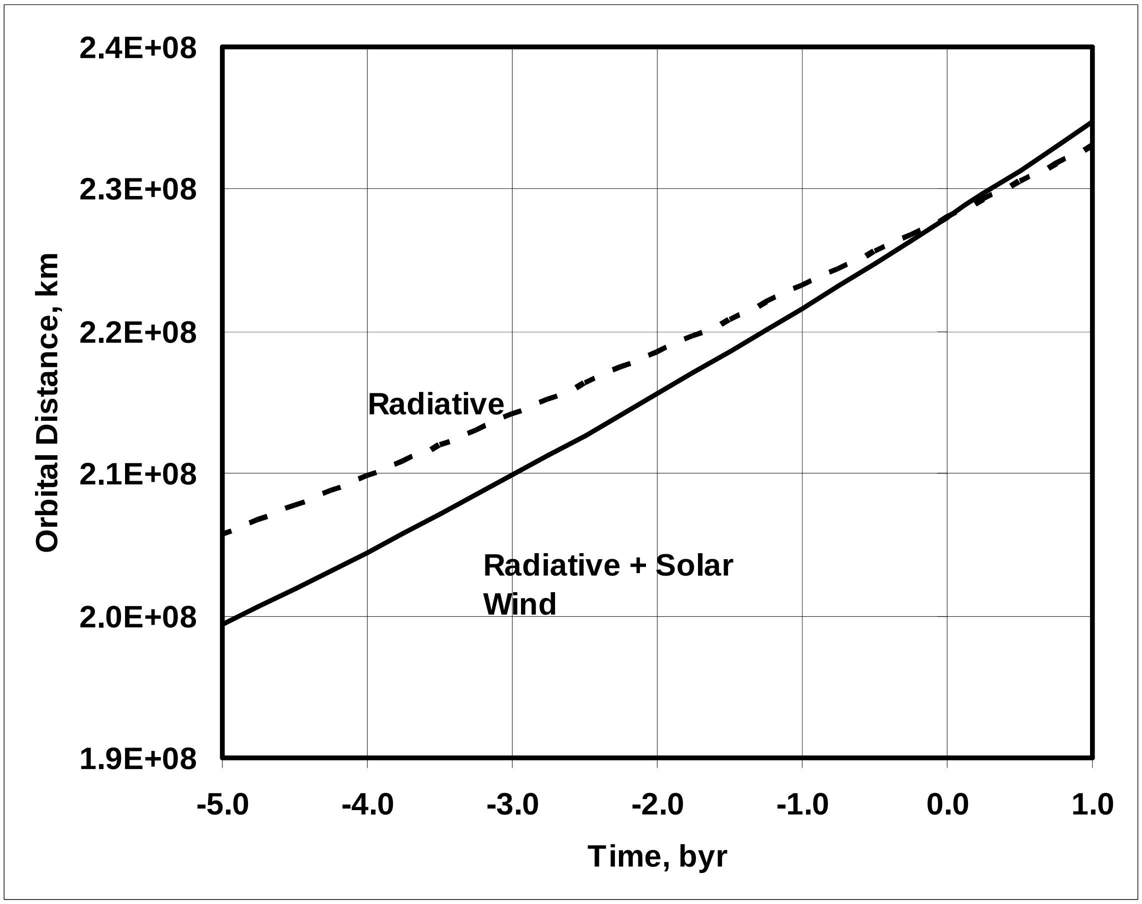

Figure 1: Mars Orbit vs. Time calculated with and without Solar Wind

The effect of solar mass loss on the Mars orbit by radiation and solar wind was modeled using equations (1) - (3).

The plots in Figure 1 show the effect of radiative mass loss and of the total mass loss (including solar wind). The curve for the total mass loss is more predictive of the actual orbital change, since solar wind is probably always associated with radiating stellar systems. The major uncertainty in the calculations is the magnitude of the solar wind during the extended times considered in the calculations. This determines an uncertainty of the change of the Mars orbit, and through this, the estimate of the temperature changes (see below). Calculations show that the orbit and the orbital period are increasing at a rate of 6.6 m/yr and 2.6E-03 s/yr, respectively.

The calculations show that under the present assumptions Mars was at its formation about five byr ago located at an orbit of 198 million km from the sun, about 30 million km closer than its present orbit (228 million km). As a reference, the present earth orbit is at about 150 million km from the sun. The results suggest that at earlier times Mars had a significantly warmer climate than during the present.

3. Mars Temperature as a Function of Time

At present, a sustained peak daytime temperature of 260K on Mars was reported (Christensen 2003).[3] This temperature is associated with a solar constant of 0.827 cal/ cm^2/min, from which an equilibrium temperature of 319 K is calculated (Lide 2004).[9] The actual surface temperature, however, is different from this temperature due to individual planetary properties, like albedo and atmosphere. It can also not be excluded that temporary higher temperatures than the reported 260K may be possible due to a confluence of circumstances.

It is assumed for the present calculation that the temperature for a given planet, e.g., Mars, is proportional to the solar equilibrium temperature at its orbit. As the orbit of a planet and solar radiance change, it is assumed that the temperature of the planet varies proportional to the solar constant. The peak temperature of Mars at its present orbit (260K) was taken as the reference, and used for normalization at changing times. At closer orbits, where the solar constant is greater, proportionally higher temperatures are calculated.

The solar constant is proportional to the radiation intensity of the sun. The radiation intensity changes with time according to equation (1). Thus, the equilibrium constant was adjusted to the solar radiative decay constant, k_r (equation (5)).

For the extrapolation of the peak Mars temperature as a function of orbit (R_p) and time (T_p), the equilibrium temperature, $T(R_p)$ was calculated. For the calculation of the equilibrium temperature, equation (5) was used, which was derived from published data (Lide 2004). I this equation, R_p, the planetary orbit, is given in units of 10^6 (km).

$$T(R_p) = 4811 * e^{-k_r t} * R_p^{-0.50} \qquad (5)$$

The calculated equilibrium temperature for Mars is about 319K and thus significantly higher than the experimentally observed highest daytime temperature of about 260K. Thus, the theoretical equilibrium temperature, T (R_p) was normalized to the present temperature of 260K to give T_c (R_p) (Equation (6). The 260K temperature is the presently best determination, and errors in its value will proportionally translate into the estimate of the ice-water transition time.

$$T_c(R_p) = \frac{260 * T(R_p)}{T(R_0)} \qquad (6)$$

Here, $T(R_0)$ is the calculated temperature (319K) for the present time and orbit. Mars temperature as a function of time and as determined by the above calculations is shown in Figure 2 for average solar radiative and solar wind conditions.

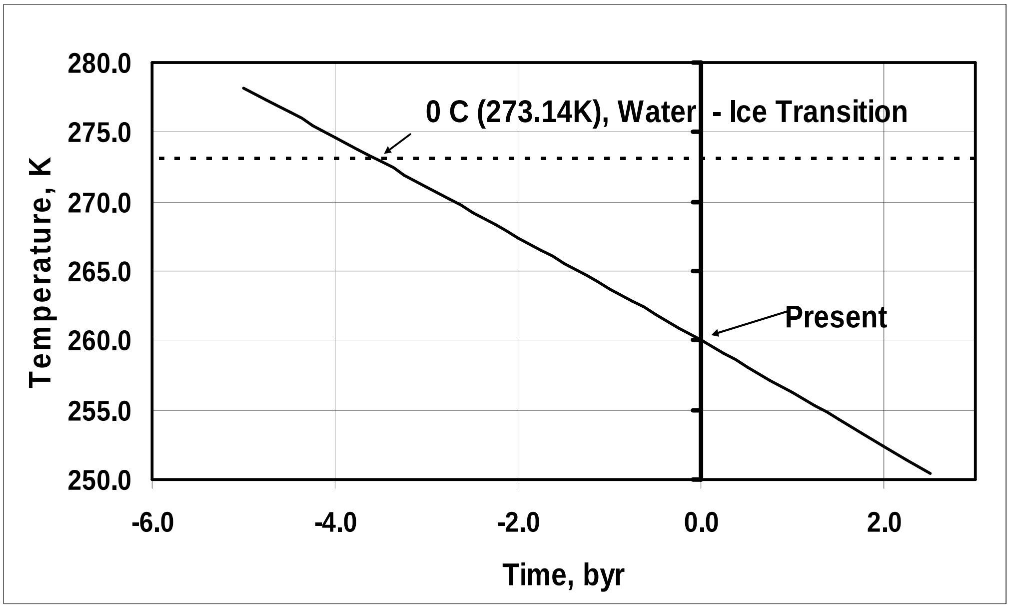

Figure 2: Mars Temperature History for radiative plus solar wind Mass Loss

In Table 1, the initial Mars orbit and the transition time from wet to ice conditions are listed for radiative decay only, and for lower, average, and higher experimental limits of solar wind.

Table 1: Initial Mars Orbit (km) and Temperature Transition Time (Byr)

Solar Mass Loss Mechanism	Solar Decay Constant [a]	Initial Orbit [b] *10^8 km	Transition Time (Byr) to 273.14K
Present		2.28	
Radiative	1.000 k_s	2.06	-4.23
+ Low Solar Wind	1.262 k_s	2.01	-3.75
+Average Solar Wind	1.329 k_s	1.99	-3.56
+High Solar Wind	1.398 k_s	1.98	-3.39
(a) k_s = 6.630E-05 byr^{-1}; (b) at – 5.0 byr			

The lower and higher limits of solar wind were predicted from six years of data collection by the Ulysses satellite (McComas 2000).[8] Present modeling predicts a range from 1.98 to 2.01E+08 km initial Mars orbit for the upper and lower solar wind values. For the transition from water to ice, the range is between 3.4 and 3.8 byr ago. Since these ranges represent upper limits of time from present, the agreement with the experimental data (2.9 to 3.8 byr) is excellent.

4. Results and Discussion

The results of the modeling show that under all discussed scenarios of solar decay, Mars was at earlier times significantly closer to the sun than its present orbit (198 vs. 228 million km, Figure 1). The condition where only the solar radiative decay is considered ($k=1.0k_s$), Mars was five billion years ago at an orbit of 2.06E+08 km. This is 22 million km closer to the sun, and 56 million km further than the present Earth orbit (150 million km). For the combined effects of radiative of solar wind mass loss, the Mars orbit for this time was calculated to 1.98 to 2.01 E+08 km.

Using the change of orbit with time, the Mars temperature was calculated as a function of time (Figure 2). The results show that when the radiative and solar wind are included in the modeling, the Mars surface temperature due to solar insolation decreased for present Mars conditions from about 278K to 260K over the past five billion years. The model predicts that the temperature change to the freezing point occurred between about 3.4 to 3.8 billion years ago, with an average of 3.6 byr.

The calculated equilibrium temperature of 278K does only consider the solar equilibrium temperature and Mars in its present state. Other effects than solar radiative and solar wind mass loss are likely to have lengthened the time of wet climate on Mars.

1. The present calculation is valid as long as the present atmospheric condition of Mars is unchanged. The actual temperature history is complicated by

the presence of the Mars atmosphere. Carbon dioxide is a known hothouse gas, which sublimes at about 194K. It probably contributes to the temperature of Mars.

2. At temperatures where water vapor enters the Mars atmosphere, the temperature will increase beyond the calculated value. The vapor pressure of ice is highly sensitive to the temperature, and increases with temperature. For the present high Mars temperature of -13C (260K) the ice vapor pressure is reported to 198 Pa, while the vapor pressure at the water triple point (273K) is 612 Pa (Lide 2004).[9] The contribution of ice evaporation will enhance the hothouse effect. Thus, it is expected that the actual Mars temperature extended the calculated time of wet climate as long as hothouse gases were present in the atmosphere to a significant degree.

3. During the water – ice transition, the water in the water/ice mixture is expected to have had high salt concentrations (=brine). This brine would freeze well below the 273K temperature and would have extended the liquid water phase.

4. At its formation, Mars was probably a hot liquid object, and its heat was dissipated over time. Depending on the cooling rate, the changeover from liquid to frozen water might have been later than predicted by the present model.

5. Radioactive processes in the body of Mars may contribute to higher surface or sub-surface temperatures. Depending on the rate of radioactivity and the mass of radioactive material, the time limit for liquid water on Mars may have been extended.

The time of water to ice transition on Mars was estimated by independent measurements at its surface and found in excellent agreement with the present experimental results. The model may be refined by improved determination of the long-term value of the solar wind, and by refinement of the temperature-orbit correlation for Mars. Other refinements are suggested by considering the cooling rate of Mars, and atmospheric temperature effects by greenhouse gases.

In conclusion, the proposed model provides both a reason a and time of the water-ice transition and a quantitative estimate of the past and future climate history of Mars. The predictions are in agreement with observed indications of liquid water on Mars at previous times, which until now could not be accounted for. The model also gives quantitative upper limit estimates of the transition time from the state of liquid water to ice on Mars, which are in agreement with experimental estimates. Other effects that may have extended the wet climate are internal heat, radioactive processes, and the presence of hothouse gases. Thus, the present model gives a rational explanation for the wet stage of Mars, and an estimate of the transition time from water to ice in agreement with experimental data. Additional information about the present temperature distribution on Mars may help to further refine the modeling and the experimental determination of the water history on Mars.

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