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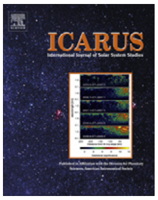

An impact-induced, stable, runaway climate on Mars

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ABSTRACT

Large asteroid and comet impacts on Mars, such as the one that formed the Argyre basin, delivered considerable amounts of kinetic energy to the planet and raised the surface temperature hundreds of degrees. The impact that formed the Argyre basin occurred 3.8–3.9 byr ago (Werner, S.C. [2008]. Icarus 195, 45–60; Fassett, C.I., Head, J.W. [2011]. Icarus 211, 1204–1214), during the time of formation of fluvial features on the early martian surface, and was capable of causing global-scale precipitation and warming of the surface. Dual solutions to the climate of early Mars, one cold like present Mars and the other in a hot runaway state, exist for the pressure range of 0.006–1 bar of CO_2, and for water inventories 6.5 bars or greater. A large impact event may have pushed Mars to a long-lasting hot runaway state. The runaway state would persist until escape processes reduced water vapor and forced the planet to return to a cold climate.

1. Introduction

The largest craters that are still visible on Mars formed about 3.7–4.1 byr ago, corresponding to the same time frame during which many of the fluvial martian Valley Networks formed (Carr and Head, 2010). For example, the Argyre basin is thought to be 3.8–3.9 byr old (Werner, 2008; Fassett and Head, 2011, respectively) and could have been formed by a 100–200 km diameter object, based upon the crater's 1140 km diameter and using equations and varying assumptions found in Melosh (1989). The kinetic energy in this object would have been on order of 10^{26} J. The delivery of this energy to the martian system would have heated the surface and atmosphere significantly (Segura et al., 2002, 2008). Here we consider whether this change in temperature would lead to a transient alteration of the climate (as described in Segura et al. (2008)) or could have pushed Mars into a long-term stable warm state reminiscent of the "runaway" state.

Ingersoll (1969) and Kobayashi (1967) showed that as the temperature increased at the base of a purely radiative atmosphere with a constant relative humidity of water vapor, a point would be reached where the flux leaving the top of the atmosphere would decline with increasing basal (base of the atmosphere) temperature. They identified this as the point beyond which a runaway greenhouse would occur. Nakajima et al. (1992) further investigated the runaway greenhouse and showed that it also applies to a radiative–convective atmosphere over a surface. We illustrate this effect in a simplified way with a gray model of a purely radiative atmosphere. Fig. 1 shows computations of FIR_{top} for a given basal temperature given the following equations:

$$\sigma T_b^4 = FIR_{top}[1/2(2 + 3/2\tau)] \tag{1}$$

where FIR_{top} is outgoing infrared radiative flux at the top of the atmosphere, τ is the total gray (wavelength-independent) opacity of all absorbing species in the atmosphere, σ is the Stefan–Boltzmann constant, and T_b is the basal temperature. If we assume that water vapor is uniformly mixed, that the optical depth is dominated by water vapor, and that τ_{H2O} varies with vapor pressure following a simple power law, then:

$$\tau_{H_2O} = kP^n_{H_2O} \tag{2}$$

where P_{H_2O}, is the vapor pressure of water, computed from the Clausius–Clapeyron relation: $P_{H2O} = P_0e^{-B/Tb}$, where $B = L/R$ (the latent heat of vaporization over the universal gas constant), T_b is the basal temperature, and P_0 is the reference vapor pressure computed at the triple point for water. When $k = 0.1$ and $n = 1$, Fig. 1 (when rotated clockwise 90°) reproduces Fig. 2 in Nakajima et al. (1992). The figure shows that given unlimited availability of water, for solar fluxes below the computed runaway flux of 385 W/m^2, two temperature solutions exist for one given planetary flux: one at cool temperature and one at a warm temperature. The warm temperature solution is a non-stable equilibrium state and the temperature will rise until the supply of water on the surface is exhausted by evaporation into the steam atmosphere, hence the term "runaway". Thus, when the amount of water available is finite there are three

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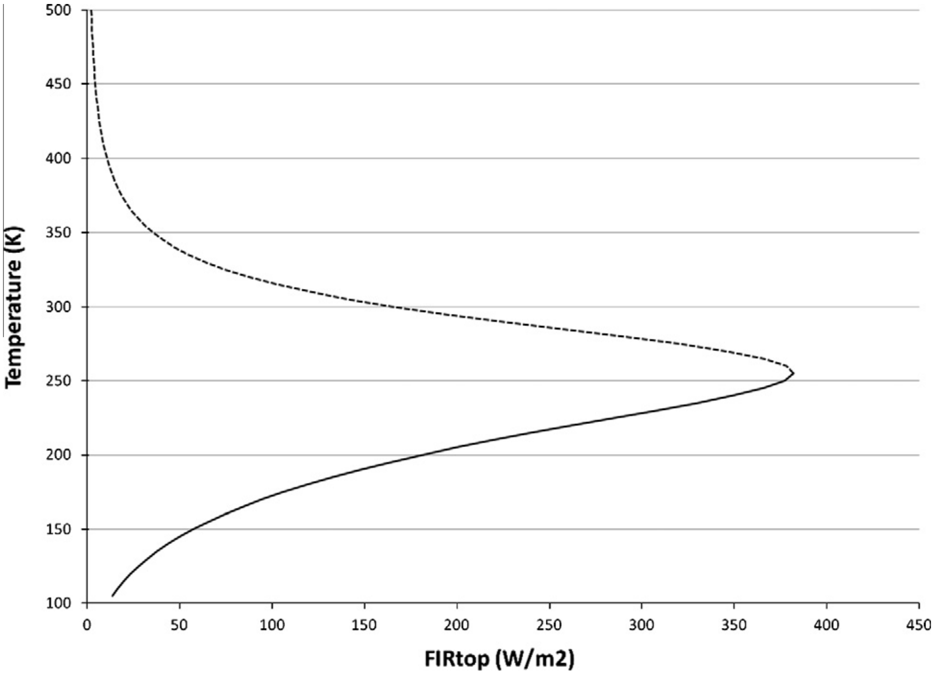

Fig. 1. Temperature at the base of a purely radiative atmosphere as a function of the outgoing IR flux at the top of the atmosphere. The solution of Eqs. (1) and (2) shows that for fluxes below the Runaway point (marked RA at the turnover point in the curve), two solutions for temperature may exist. However, the upper branch (indicated by the dotted line) is typically considered to be physically unrealistic (Nakajima et al., 1992).

solutions: a cool stable state with water as liquid on the surface (low temperature solutions in Fig. 1), a warm unstable solution (high temperature solutions in Fig. 1), and a hot stable ("runaway") state with all the water as vapor in the atmosphere. This hot stable state is not shown in Fig. 1, but will be illustrated in later figures.

2. Numerical computations of flux–temperature space

We numerically explored the multiple solutions of the flux–temperature phase space, suggested by the gray model equations above, for Mars using a non-gray time-dependent radiative–convective 1-D numerical model. The mechanics of the numerical model are described in Section 3 of Segura et al. (2008) and in the Supporting Online Material of Segura et al. (2002). The non-gray radiation code is based on the correlated-*k* method, with *k* coefficients derived from line-by-line calculations done at the Ames Research Center for their General Circulation Model (see http://spacescience.arc.nasa.gov/mars-climate-modeling-group/brief.html for a brief summary) and the radiation code developed by Toon et al. (1989). Radiative heating rates using these coefficients were discussed by Haqq-Misra et al. (2008). Colaprete and Toon (2000, 2003) simplified the *k*-coefficients to treat overlap more efficiently, and we use the same approach for this study. In summary, the modeled atmosphere is divided into 50 layers of equivalent fraction of pressure between adjoining layers, and the model computes the addition (via surface evaporation) and removal (via surface precipitation) of atmospheric water at the surface at each time step. Potential temperature is computed via both radiative transfer and vertical diffusion, and used to compute the atmospheric temperature, pressure, and gas masses at every time step. Water may condense and evaporate within the atmosphere, may evaporate into the atmosphere from the surface, and may precipitate out of the atmosphere when it is saturated. When evaporation occurs, water (as vapor) is added to the atmospheric column. The surface pressure is computed for the added water mass and the pressures at the remaining atmospheric layers are computed as equal fractions of the surface pressure to preserve hydrostatic equilibrium. The radiative effects of clouds were not included in the model.

As initial conditions for this numerical exploration of the multiple solutions shown in Fig. 1, the simulated Mars was assumed to have a surface pressure of 6.1 mbar of CO_2 and a total water inventory of 500 mbar (a global equivalent layer of 13.3 m). We determined the equilibrium surface temperature on Mars for a given net incoming solar flux. The incoming solar energy is $(1 - A)S/4$, where *A* is the albedo (a function of pressure due to Rayleigh scattering) and *S* is the solar constant at the orbit of Mars (currently 600 W/m^2). The quantity $[(1 - A)S/4]$, which we call the available incoming solar flux, was varied from 60 to 280 W/m^2. The planetary albedo changed as the pressure changed, due to Rayleigh scattering and absorption in the near infrared by the water vapor (Fig. 2). Equilibrium flux–temperature points were found by systematically choosing increasing incoming solar fluxes, and next

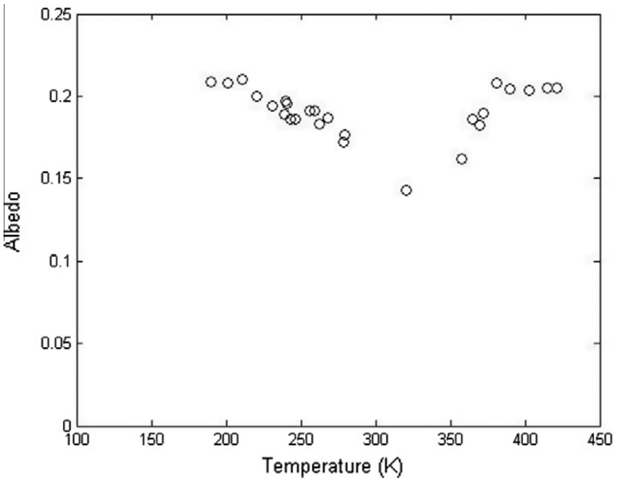

Fig. 2. Albedo as a function of temperature for model runs presented here.