Warming Early Mars with Carbon Dioxide Clouds that Scatter Infrared Radiation

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Geomorphic evidence that Mars was warm enough to support flowing water about 3.8 billion years ago presents a continuing enigma that cannot be explain by the conventional greenhouse warming mechanisms. Model calculations show that the surface of early Mars could have been warmed through a scattering variant of the greenhouse effect resulting from the ability of the CO_2 ice clouds to reflect the outgoing thermal radiation back to the surface. This process could also explain how Earth avoided an early irreversible glaciation and could extend the size of the habitable zone for extrasolar planets around stars.

The most likely composition for the martian atmosphere 3.8 billion years ago is primarily CO_2, with a surface pressure ranging from a few hundreds up to several thousands of millibars, and some H_2O (*1*). At that time, the solar luminosity was about 25% lower than that at present. In such conditions, calculations performed with a one-dimensional climate model by Kasting (*2*) showed that the atmospheric CO_2 should condense overall the planet for surface pressures larger than a few tens of millibars. Kasting found that the condensation of CO_2 decreases the atmospheric temperature lapse rate and reduces the magnitude of the greenhouse effect, making it impossible to warm the surface of Mars enough to allow fluid water with a CO_2-H_2O gaseous atmosphere. Several alternative mechanisms such as geothermal heating (*3*), an early more massive sun (*4*), or the greenhouse effect of methane (CH_4) (*5*) and ammonia (NH_3) (*6*), have been considered, but none has provided a likely solution to the early Mars climate enigma (*5*).

Another consequence of the condensation of CO_2 is the formation of CO_2 ice clouds. Because they are perfect scatterers at solar radiation wavelengths, the CO_2 ice particles should raise the planetary albedo. In the thermal infrared (IR), CO_2 ice is at least 500-times more transparent than water ice, except near 15 μm where the ν_2 absorption band is located and above 90 μm where two broad lattice vibration bands were measured (*7*). Thus, CO_2 ice clouds should not be able to contribute to an absorption/emission greenhouse effect as cirrus clouds on Earth do. On this basis, Kasting

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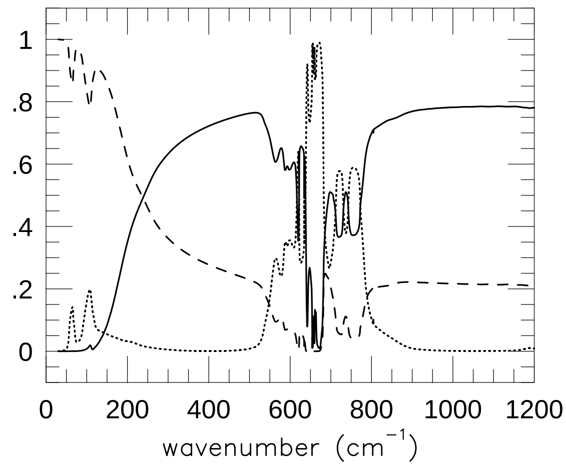

Figure 1: *The reflectivity α (solid curve), transmissivity β (dashed curve) and emissivity ε (dotted curve) of a pure CO_2 ice cloud (particle radius $r = 10\mu m$) of visible optical depth $\tau = 10$, corresponding to a mass of CO_2 ice about 100 g m^{-2}. Except in the far infrared where the cloud particles are too small to scatter the radiation, and near the 15-μm CO_2 absorption band, the main effect of the cloud is a reflection of the infrared radiation*

(*2*) estimated CO_2 ice clouds should cool the planet through reflection of sunlight uncompensated by infrared trapping.

We have studied the IR properties of the CO_2 ice clouds using a two-stream, hemispheric mean, source function code that allows for multiple scattering, absorption and emission by atmospheric particles (*8*). The CO_2 ice particle single scattering properties were obtained from the refractive index measured by Hansen (*7*) using Mie theory with a modified gamma size distribution of effective variance 0.1 (*9*). As expected by Kasting, a cloud composed of CO_2 ice particles smaller than a few micrometers should be almost transparent in the IR, except near 15 μm. However, larger particles can be expected in CO_2 ice clouds. Crystal size is determined by the time required for crystal growth versus the time it takes for the particles to fall out of a supersaturated layer (sedimentation). On Earth, despite the fact that the growth of water ice particle is limited by the diffusion of water vapor through air, particles 80 μm or larger are often observed in cirrus ice clouds, and the observed radiative properties of Earth's cirrus clouds can be fit by assuming equivalent spheres with a radius of 16 μm (*10*), with optical depth up to 30. On early Mars, because it is the primary atmospheric constituent that is condensing, the CO_2 cloud particles should grow faster, for a comparable sedimentation rate (*11*). Although not much is known about the exact microphysical processes involved, particle radii between 10 μm to about 100 μm can be expected (*12*). Such particles can more readily scatter the infrared radiation (Fig.1). A cloud composed of such particles would be able to scatter the IR radiation back to the ground and thus contribute to surface warming. IR scattering by clouds or aerosols is not important on Earth, but its warming effect has been considered for other planets (*13*). It has been studied as a means of accounting for the observed IR spectrum of Mars (*14*), Venus

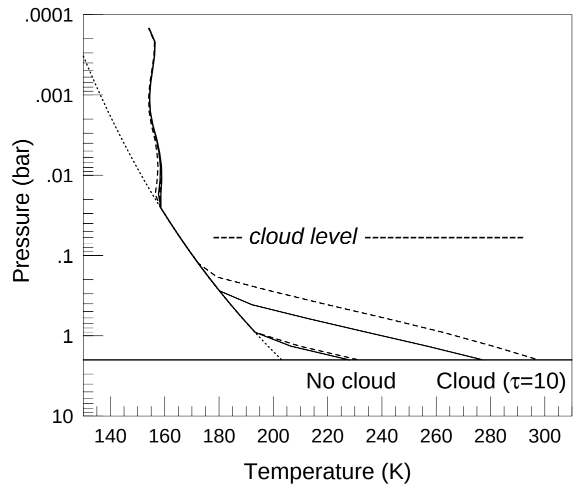

Figure 2: *Calculated mean temperature profiles for a 2 bar CO_2 atmosphere assuming a 25% reduced solar luminosity corresponding to the early Mars conditions. The effect of the cloud from Fig.1 ($\tau = 10$, $r = 10\mu m$) is shown in the cases of a wet (fully saturated troposphere, dashed curves) and a dry atmosphere (solid curves). Dotted curve shows the CO_2 condensation temperature profile.*

(*15*) and even Titan (*16*). In particular, CO_2 ice clouds that scatter IR radiation are thought to have an impact on the radiative budget of the polar regions of Mars at the present time (*17*).

We included the effect of the CO_2 ice clouds in the one-dimensional radiative-convective model designed for early Mars by Kasting (*2*). In the IR wavelength, this model is based on a traditional radiative transfer band model. To account for scattering by CO_2 ice clouds, we used the multiple scattering code and assumed that the effect of a given cloud could be mimiced in the band model by a single layer cloud with the same transmissivity, reflectivity and emissivity (*18*). At solar wavelengths, we used a δ-Eddington code to compute multiple scattering by the CO_2 ice particles consistently with Rayleigh scattering by the CO_2 gas molecules, and the system was integrated to radiative-convective equilibrium using a straightforward time-stepping method (*19*). Overall, this climate model gives results similar to the model of Kasting (*2*) when the cloud optical depth is set to zero. When a cloud composed of particles with radii larger than 6-8 μm is included, the model predicts a warming of the troposphere and the surface (Figs. 2 and 3). Such a warming may seem surprising because one would expect the infrared scattering induced warming to be balanced by a strong cooling due to scattering of sunlight. In fact, the two effects are not compensating. At solar radiation wavelengths, the importance of the clouds is limited by the fact that the planetary albedo without clouds is already quite high because of Rayleigh scattering in the clear atmosphere (the Rayleigh scattering coefficient for CO_2 is 2.5 times that for air on Earth), whereas in the IR the CO_2 clouds tend to block the outgoing thermal radiation at wavelengths where it would freely escape otherwise. For instance, the planetary albedo of Mars with a 2 bar cloud-free CO_2 atmosphere would be $A_{\rm clear} = 0.38$. By increasing the planetary albedo up to $A_{\rm cloudy} = 0.65$, the cloud of Fig. 1 only reduces the absorbed solar energy by about 40% while trapping more than 60% of the

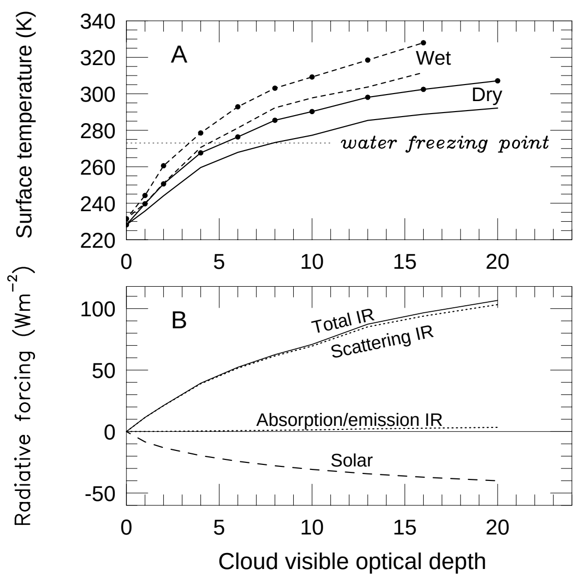

Figure 3: **(A)** *Calculated surface temperature as a function of the cloud visible optical depth for cloud particles radii $r = 50\mu m$ (with dots) and $r = 10\mu m$ (no dot) in the cases of a wet (dashed curves) or a dry (solid curves) 2 bar CO_2 atmosphere on Mars. A 25% reduced luminosity is assumed.* **(B)** *The corresponding cloud radiative forcings with particle radii $r = 10$ μm cloud. The surface warming results from the excess of radiative forcing in the IR compared to the negative solar forcing. The radiative forcings were defined as $\Delta F_{\rm Sol} = S(A_{\rm clear} - A_{\rm cloudy})$ and $\Delta F_{\rm IR} = F_{\rm clear} - F_{\rm cloudy}$, with S the mean incoming solar flux, A the planetary albedo and F the outgoing thermal fluxes computed in the clear-sky and in the cloudy atmosphere cases. The scattering component of $\Delta F_{\rm IR}$ was computed assuming that it was proportional to $\alpha I_{\rm subcloud}$ at every wavelength, with α the cloud infrared reflectivity (Fig. 1) and $I_{\rm subcloud}$ the upward radiance from the subcloud atmosphere. Similarly, the absorption-emission component was assumed to be proportional to $\varepsilon[I_{\rm subcloud} - B(T_{\rm cloud})]$, with ε the cloud emissivity (Fig. 1) and $B(T_{\rm cloud})$ the Planck function at the cloud temperature.*

outgoing thermal radiation (Fig. 3B). The cloud reduces the outgoing thermal radiation by reflecting the infrared flux from below on the one hand, and by absorbing it and reemitting at a colder temperature on the other hand. This last effect corresponds to the "conventional" cloud greenhouse effect which is observed for terrestrial clouds. However, because the cloud can only emit where the atmosphere is opaque, the absorption/emission radiative forcing of CO_2 clouds is almost negligible (Fig. 3B), except for a few W m^{-2} in the 15-μm band wings. Consequently the cloud-induced warming does not depend upon the cloud temperature. Thus, it is almost insensitive to the cloud altitude, except when the cloud is artificially put near the surface. In the lower troposphere, the vertical heat transport due to convection and turbulence is larger than the radiative heat flux and the model predicts a reduced cloud induced warming. In reality however, CO_2 clouds should be higher, where condensation temperatures are reached (Fig. 2).

If the early martian atmosphere was in contact with water on the surface, the atmo-

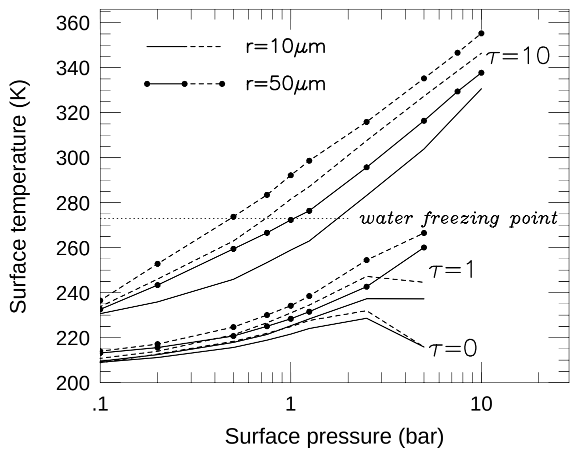

Figure 4: *Mean surface temperature as a function of surface pressure for several values of the mean visible cloud optical depth τ, in the cases of a wet (dashed curves) or dry (solid curves) CO_2 atmosphere on Mars. A 25% reduced luminosity is assumed.*

sphere probably contained enough water to increase the IR opacity of the atmosphere (*20*). Assuming a fully saturated troposphere, the greenhouse effect is strongly increased, especially for high surface temperatures (Figs. 2 and 3A). Water clouds, or maybe CO_2-H_2O clathrate hydrate clouds probably formed below and within the CO_2 ice cloud layer. With CO_2 ice clouds above, their impact on the planetary albedo was probably small. However, they may have contributed to the greenhouse effect by their IR absorption. Calculations performed with water ice particles mixed with the CO_2 ice particles in the modeled cloud reveal a possible warming due to an increase of the absorption-emission cloud radiative forcing uncompensated by the decrease of the IR scattering forcing (*21*).

Overall, even in the absence of other greenhouse gases except CO_2 and H_2O, the magnitude of the total greenhouse effect of the early Mars atmosphere should have been relatively strong, depending on the assumed humidity, CO_2 and H_2O clouds properties, and fractional cloud cover. This last parameter was probably below 100% because cloud formation may have been inhibited in regions of atmospheric subsidence. Surface temperatures calculated assuming a 75% fractional cloud cover with $\tau = 10$ were found to be 20 to 30 K colder than for a 100% cloud cover. It might be expected that clear sky regions were harder to maintain on early Mars than on modern Earth, as the clouds in the former case arise from condensation of the atmosphere's primary constituent, whence subsidence must maintain anomalously warm conditions in a deep layer to inhibit condensation. The issue of fractional cloud cover is an important one, which is inextricably tied up with dynamics and can only be treated in the context of a full three dimensional climate model.

Eventually, without taking into account the additional effect of water clouds, we have found that a surface pressure lower than one bar may have been sufficient to raise the global mean temperature of early Mars to the melting point of water (Fig. 4). In fact, it has been suggested that the geomorphic observations on Mars can be explained with mean temperatures a few tens of degrees below freezing (*3*, *22*). According to Fig. 4, this would allow a surface pressure as low as 0.3 bar or a mean cloud optical depth of only 1. In any cases, conditions suitable for life could have been easily reached. The requirement for life is liquid water directly, regardless of mean temperature and pressure. As seen in Earth's polar regions, major liquid water habitats for life can be maintained by the insulating properties of an ice cover or by geothermal activity even when temperatures are well below freezing (*22*).

The high surface temperatures (Fig. 4) indicate that the greenhouse effect of a thick, wet, condensing CO_2 atmosphere can be extremely powerful. This general mechanism should be taken into account in the estimation of the "habitable zone" (suitable for life on extrasolar planets) around stars. For instance, a wet 10 bar CO_2 atmosphere filled with $\tau = 10$ CO_2 ice clouds would allow a mean surface temperature above the freezing point of water at more than 2.4 AU from a sun-like star, beyond the outer edge of the habitable zone found by (*23*) at 1.37 AU. Similarly, CO_2 ice clouds may have played a role in warming Earth when the sun was fainter than today (*24*), assuming that enough CO_2 was available on early Earth (*5*). As for Mars, given our current knowledge of the environmental conditions 3.8 Gyr ago, our conclusions must remain speculative. Nevertheless, it must be emphasized that our CO_2 ice clouds scenario is simple. It does not require any ad hoc combination of physical processes : Assuming that the atmosphere was composed of more than a few 0.1 bar of CO_2, it is likely that CO_2 clouds formed, and that they contributed to warm the planet enough for liquid water to flow on the surface.

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18. The original radiative transfer model is described in detail in (*2*) and J.F. Kasting, J. B. Pollack and T. P Ackerman, *Icarus* **57**, 335 (1984). Infrared absorption is calculated in 55 spectral intervals ranging from 0.54 to 500 μm, using 25 vertical layers. The original code was only designed for pure absorption. For instance, the upward component of the spectral intensity I_0 in a given band at level z was

$$I_0(z,\mu) \;=\; B(z_s)e^{-\tau(z\ldots z_s,\mu)} + \int_z^{z_s} B(z')e^{-\tau(z\ldots z',\mu)}\frac{d\tau}{dz'}dz'$$

where μ is the cosine of the zenith angle, $B(z)$ is the Planck function at level z (z_t at the top of the atmosphere, z_s at the surface), and $\tau(z...z',\mu)$ the slant opacity between level z and z'. Clouds were introduced in the model by modifying the upward and downward infrared fluxes respectively above and below the cloud. The contribution from accross the cloud was reduced by the cloud band transmissivity β and increase by the the reflection and emission of the cloud of reflectivity α and emissivity ε. For instance, the upward intensity above the clouds level z_c became

$$\begin{aligned} I(z,\mu) \;=\; & \beta I_0(z,\mu) + (1-\beta)\int_z^{z_c} B(z')e^{-\tau(z\ldots z',\mu)}\frac{d\tau}{dz'}dz' \\ & -\alpha\int_{z_t}^{z_c} B(z')e^{-\tau(z'\ldots z_c\ldots z,\mu)}\frac{d\tau}{dz'}dz' + \varepsilon B(z_c)e^{-\tau(z\ldots z_c,\mu)} \end{aligned}$$

Doing so, we neglected the enhanced gaseous absorption which can occur in multiple scattering clouds. However, because IR radiation scattering by CO_2 ice is important at wavelengths where the CO_2 gas is relatively transparent (especially at the expected cloud pressure levels on Mars) we believe that this simplification did not affect our calculations, except maybe in the 15-μm band wings. In any case, the omission is acceptable because by neglecting this additional CO_2 gas opacity we tend to underestimate the gas greenhouse effect and thus the surface temperature increase due to CO_2 clouds.

19. The δ-Eddington solar scattering calculation was based on (*8*), using 5619 spectral intervals covering the solar range and 100 layers in the vertical. Cloud scattering parameters were computed using Mie theory with optical data from (*7*), and near-IR absorption and Rayleigh scattering representations were the same used in (*2*). The Newton's method iteration referred to in (*2*) was found to converge unreliably in the presence of CO_2 condensation. Rather than adopting the isothermal-stratosphere aproach used in (*2*), we employed a time-stepping scheme similar to that in S. Manabe and R. T. Wetherald, *J.*

Atmos. Sci. **24**, 241 (1967), in which the model is integrated as an initial value problem until it reaches equilibrium. Convergence to equilibrium was reliable, but required typically several hundred time steps even using adaptively adjusted time-stepping to accelerate convergence. In contrast, the Newton's method iteration, when it works, converges in a dozen or fewer iterations.

20. Moisture affects both IR opacity and lapse rate. In our "dry" calculation, we zeroed out the radiative effects of water vapor, but still used the moist adiabat for the tropospheric temperature profile. This corresponds to the typical practice in radiative- convective modeling of using the moist adiabat even in highly subsaturated conditions, as in (*2*). On Earth, it is known that a moist adiabat can be maintained even if the relative humidity is low almost everywhere in the atmosphere (K. A. Emanuel, J. D. Neelin, C.S. Bretherton *Quart. J. Roy. Meteor. Soc.* **120**, 1111 (1994) ; K. M. Xu and K. A. Emanuel *Mon. Wea. Rev.* **117**, 1471 (1989). Our use of the moist adiabat is a conservative choice from the standpoint of surface warming. A totally dry planet would likely adjust to the dry adiabat, which is steeper and would yield slightly greater surface temperatures than in the "dry" case we show.

21. Adding 10% in mass of 10 μm water ice particles to the cloud of Fig 2 ($r = 10\mu$m, $\tau = 10$) reduces the absorbed solar energy by 2 Wm^{-2} and the scattering radiative forcing by 1.5 Wm^{-2}, but increases the absorption-emission forcing by 8.5 Wm^{-2}, resulting in a 1.5 K surface warming. However, the effect of the water ice particles depends on their temperature. A lower, thicker water cloud would slightly cool the surface.

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