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Greenhouse Effect by CO2 Ice Clouds and Dust Layer on Early Mars

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Martian fluvial landforms suggest that past Martian climate would have been warm enough for liquid water to flow on the surface. However, the solar luminosity would be about 0.7 times as large as the present value at that time (3.8 Ga). The past warm climate under the faint young sun is paradoxical and still remains a controversial problem.

Kasting (1991) shows that even if CO2 atmosphere is very thick (about 5 bar), the greenhouse effect of cloud-free atmosphere is not strong enough to allow liquid water on the surface under 70 % of present solar luminosity. Pierrehumbert and Erlick (1998), on the other hands, argue that the greenhouse effect is strengthened by CO2 ice clouds and the surface temperature is possibly kept above 273 K. However, They only consider the scattering but neglect the absorption of infrared and solar radiations by CO2 ice cloud. The scattering and transmission of solar and infrared radiations will be changed by the absorption process. Moreover, if air-borne dust existed also in the past atmosphere, it might have an effect to modify the greenhouse effect.

In this study, we examine the greenhouse effect associated with scattering and absorption of CO2 ice cloud and air-borne dust on early Mars by using a one-dimensional radiation model. The cloud (or dust) layer is assumed to exist independently above the surface atmospheric layer. We estimate the strength of greenhouse effect by using `the warming factor', which is defined as a ratio of the effective transmissivity of the solar radiation to that of infrared radiation through the cloud (or dust) layer. When the warming factor is larger than unity, the cloud (or dust) layer contributes to warming the planet. The warming factor is calculated by adopting the delta-Eddington approximation method for the infrared (wavelength = 10 micron) and the solar (0.75 micron) radiations. The optical thicknesses and particle radii of cloud and dust layers are varied as model parameters. The single scattering albedos and asymmetry factors of ice and dust particles are calculated from the optical constants of pure CO2 ice and air-borne dust in the current martian atmosphere by using the Mie theory.

Results of our model calculations are summarized as follows. Here the critical value of the warming factor is the minimum value required to keep the surface temperature above 273 K under the solar luminosity of 0.7 times the present value and the CO2 atmosphere of 5 bar.

1) CO2 Ice Cloud

The warming factor of the CO2 ice cloud layer exceeds the critical value when realistic path length and particle size (the particle radius is about 10 -- 100 micron and path length is about 10 kg/m^2) are given. This result suggests that liquid water would have existed due to the greenhouse effect of CO2 ice cloud. The warming by CO2 ice clouds is due to the infrared backward scattering which is more efficient than the backward scattering of solar radiation. Here the absorption of the solar and infrared radiations has little effect. The warming factor increases as the path length increases. As the path length exceeds 10 kg/m^2, the warming factor becomes constant. When the radius is less than 20 micron, the warming factor has maximum around the path length about 1 kg/m^2 owing to the absorption of solar radiation.

2) Air-Borne Dust

Given the particle size and path length comparable to those in the present atmosphere (the particle radius is 1.85 micron and path length is 0.1 -- 20 * 10^-2 kg/m^2), the calculated warming factor of dust layer is near the critical value. The warming factor has the maximum which exceeds the critical value at the path length about 0.5 * 10^-2 kg/m^2. So the dust layer would also have strengthened the greenhouse effect in the past Mars. The warming is due to the infrared backward scattering and absorption which is more efficient than the backward scattering and absorption of solar radiation. Here, the absorption and scattering have comparable effect.