Reports

Mars: Influence of Topography on Formation of Temporary Bright Patches

Abstract. *The Mountains of Mitchel and other temporary bright patches observed on the Martian disk may be carbon-dioxide condensations in depressions rather than a water-ice mixture on mountains as previously thought. This interpretation supports the hypothesis that the Martian deserts, that is, the light areas, are lower than their surroundings.*

The best examples of seasonal bright spots on Mars—other than the polar caps themselves—are the Mountains of Mitchel located south of Promethei Sinus in a light area at latitude 73°S (*1–3*). They have been observed for over a century at intervals of about 15 years (*2, 3*). They appear as patches isolated from the receding southern polar cap on practically the same seasonal date at each opportunity (*3*), and thus milestones for the systematic annual retreat of the polar cap are provided. In general they vanish after only a few days (*2, 4, 5*), and only rarely last as long as 2 weeks (*5*). During the 1956 opposition they survived for 5° of heliocentric longitude, or about 7 days (*4*). Unfortunately the reverse process (condensation on these areas in the fall before the arrival of the advancing southern polar cap) cannot be tested observationally because of obscuration by the fall-winter haze over the Martian polar regions. However, a patch of temporary mist or cloud of the same size and shape has been occasionally observed about 90 days after the Mountains of Mitchel have disappeared (*3*). Some observers have concluded (*3, 6, 7*) that the Mountains of Mitchel are H_2O-ice deposits on elevated areas, an obvious application of the terrestrial analogy of snow-capped mountains.

Leighton and Murray (*8*) and Leovy (*9*) have independently concluded that the Martian polar caps are primarily solid CO_2. Their arguments were based on calculations of the radiation budget of the Martian surface and on newer measurements of the partial pressure of CO_2, $p_s(CO_2) \sim 4$ mb, at the surface. This is a higher value than previously thought, and it is now believed that CO_2 is the major constituent of the Martian atmosphere.

Leighton and Murray (*8*) made the following assumptions in their calculations: (i) There is no radiative exchange between the surface and atmosphere except insofar as the atmosphere may affect the surface emissivity by blocking certain wavelengths emitted by the surface; (ii) there is no horizontal heat transport by wind; (iii) there is no heat transfer by conduction between the surface and atmosphere; and (iv) the rates of condensation and sublimation of CO_2 are unaffected by the presence of gases other than CO_2 in the atmosphere. Taking these assumptions into consideration, we see that the temperature of the Martian surface is dependent only on insolation, heat exchange with the underlying soil by conduction, and the latent heat of any condensed volatile. In support of this treatment is the impressive agreement between the calculated and observed dimensions of the polar caps as a function of the seasons. We have adopted the same assumptions as those of Leighton and Murray (*8*), so our discussion follows from the important premise that thermal interaction between the Martian surface and atmosphere is very slight.

Since the temperature, T_{eq}, for the solid-vapor equilibrium of CO_2 increases with $p_s(CO_2)$, CO_2 condensation should occur sooner in areas of higher $p_s(CO_2)$, that is, areas depressed with respect to the surroundings. Utilizing this observation, we have carried out a calculation to determine what elevation differences are necessary to produce the observed properties of the Mountains of Mitchel.

First, the average daily insolation was computed as a function of Martian latitude ϕ and seasonal date (denoted as δ_s, the solar declination) on Mars by the formula

$$S = S_0\,(1 - A)\frac{r_0^2}{r^2}\frac{1}{2\pi} \times \int_{\text{day}} (\sin\phi \sin\delta_s + \cos\phi\cos\delta_s\cos\tau - \beta)d\tau \tag{1}$$

where S_0 is the solar constant at Mars, 0.06 watt cm^{-2}, corresponding to the distance $r_0 = 1.52$ AU (astronomical unit) from Sun (*8*), r the distance of Mars from Sun, A the surface albedo, and τ the hour angle. The quantity β, the fraction of the solar radiation attenuated by the Martian atmosphere in the zenith, was assumed to be 0.005 (*9*). The integrand is zero whenever the zenith angle is greater than 90°. Increments of 0.1 radian in τ were used for the Simpson integration on the computer. The integration was performed for intervals of 20° in heliocentric longitude, starting from summer solstice in the southern hemisphere.

The rate of gain of the solid CO_2 deposit (g cm^{-2} day^{-1}) may be written as

$$\frac{dM}{dt} = \frac{n(E\sigma T_{eq}^4 - S)}{L} \tag{2}$$

where $E = 0.85$ is the estimated effective emissivity of solid CO_2 at the Martian surface (*8*), σ ($= 5.67 \times 10^{-12}$ watt cm^{-2}(°K)$^{-4}$) is the Stefan-Boltzmann constant, T_{eq} is the temperature for the solid-vapor equilibrium of CO_2 from vapor pressure data taken from the *Handbook of Chemistry and Physics*, L (450 joule g^{-1}) is the latent heat of vaporization of CO_2 at $T_{eq} = 145$°K (*8*), and n the number of seconds in a Martian day.

In early Martian fall, solid CO_2 begins to form at night, when the temperature drops to T_{eq}. For the first few days, these deposits disappear during the day due to solar irradiation, but eventually a day arrives when the deposit is sufficiently thick to survive the insolation. On that day, a permanent CO_2 deposit starts to build up. The day is the time at which dM/dt becomes positive, and the appropriate value of the albedo for calculating dM/dt is 0.65. Thus, the daily insolation in Eq. 1 varies only with season and latitude on Mars. But T_{eq} varies with $p_s(CO_2)$, and thus with local elevation. Figure 1 illustrates the value of dM/dt at the Mountains of Mitchel as a function of Martian season for various elevations.

Column 3 of Table 1 shows the date of the beginning of CO_2 deposition as a function of elevation. This defines the lower limit of integration of the curves in Fig. 1 for calculating M, the amount of CO_2 ice at any time.

The pressures for each elevation indicated in Table 1 are based on an assumption of a scale height of 7.7 km, corresponding to an isothermal CO_2 atmosphere at a temperature of 145°K.

Column 4 of the table shows the time of the disappearance of the deposit, that is, the time for $M = 0$. The important point is that a 5-km depression would produce CO_2 deposits which would be detached from their surroundings for 17 days. In order to estimate the exact observed duration, Δt, of the Mountains of Mitchel as depositions distinct from their surroundings, we must consider the entire interval between the time the receding southern polar cap reaches $\phi = 73°S$ and the time the patches disappear. Slipher's regression curve (*3, 8*) shows the cap at 73° at $t = -53$ days, and the patches are observed as detached from the cap at $t = -35$ days. Combining this with estimates of the duration of the patches themselves (~ 7 days), we find $\Delta t \approx 25$ days. Dollfus' regression curve of the southern polar cap (*10*) showed the cap reaching $\phi = 73°S$ at $t = -49$ days. The patches become detached from the cap at $t = -29$ and survive until $t = -22$ (*4*), or $\Delta t \approx 27$ days. Photographs show the

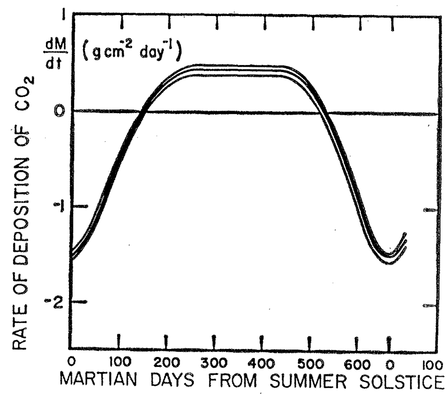

Fig. 1. The rate of deposition of CO_2 versus Martian season at the latitude of the Mountains of Mitchel ($\phi = 73°$) and for an albedo of 0.65. The top, middle, and bottom curves refer to elevations of −5 km, 0 km, and +5 km, respectively, each corresponding to values of $p_s(CO_2)$ shown in Table 1.

Mountains of Mitchel extending ~ 4° in latitude when they are barely detached from the polar cap (*3*). If we take half that value as representative of the interval of latitude between the cap reaching 73°S and the detachment of the patches, then $\Delta t \approx 17$ days.

A comparison of these values with calculations (Table 1) suggests that the Mountains of Mitchel are valleys or large craters 5 to 8 km deep. We therefore prefer the name "Depressions of Mitchel" for these seasonal bright patches.

Our predicted dates of disappearance of the solid CO_2 at $\phi = 73°S$ are later than the observed disappearance and the disappearance predicted by Leighton and Murray (*8*). Our disagreement with the latter is probably due to our assumption that the heat content of the soil does not vary from day to day. The additional discrepancy with the observed disappearance may be due to slightly incorrect values of the various parameters, such as the CO_2 albedo, CO_2 emissivity, $p_s(CO_2)$ at 0 km, and β, or to the effect of other gases. In spite of this, our dates differ from the observed date by only about 60 days, which is a small quantity compared to the 450 days in which the deposition is present. Most importantly, we are convinced that the duration of the Depressions of Mitchel is not sensitive to variations in these parameters. However, two features of the Martian atmosphere, its blanketing and conductive interaction with the surface, should be discussed in order to see if they affect this duration.

Atmospheric blanketing by the 15-μ CO_2 band was taken into consideration for the value of the CO_2 emissivity. Leighton and Murray (*8*) give ~ 12 percent as the blanketing effect at the Martian surface, as calculated from the data of Stull, Wyatt, and Plass (*11*). Our examination of their data (*12*) indicates that this blanketing would amount to 11.4 percent for 100 meter-atm of CO_2 and 9.8 percent for 50 meter-atm of CO_2, both for an effective total pressure of 10 mb and temperature of 200°K. These blanketing values are not exactly applicable to the problem. The lower pressures and temperatures expected in the Martian atmosphere would decrease the blanketing, but the large slant paths away from the zenith would increase it. Regardless of the choice of values for CO_2 path, temperature, and pressure, the maximum expected difference in CO_2 emissivities corresponding to an elevation differential of 5.5 km would be only 2 percent. This amount would "deepen" the Depressions of Mitchel by 1 km at most.

We assumed earlier that the heat budget of the Martian surface is dominated by radiative interaction with Sun and space, and that the effects of conductive interaction with the atmosphere are negligible. We believe this a good assumption for the following reasons. When condensed CO_2 is present on the Martian surface, the temperature of the atmosphere in contact with the surface must be just equal to that of the condensed CO_2. The maximum lapse rate in a pure CO_2 atmosphere above the deposits is then set by the vapor pressure equilibrium of CO_2, or 0.8°K/km. If this value is exceeded, then there would be CO_2 condensation in the atmosphere. If there are no winds, there will be no conductive exchange of heat between the CO_2 surface and the atmos-

Table 1. Predicted and observed properties of a solid CO_2 deposit at the latitude of the Mountains of Mitchel ($\phi = 73°S$). Times are in Martian days after southern summer solstice. The partial pressures of CO_2, $p_s(CO_2)$, are based on an assumed exponential atmosphere with a scale height of 7.7 km and $p_s(CO_2) =$ 4 mb for an elevation of 0 km.

Elevation (km)	$p_s(CO_2)$ (mb)	Solid CO_2: Time of beginning of deposition (days)	Solid CO_2: Time of disappearance (days)	Solid CO_2: Maximum accumulation (g cm^{-2})
		Predicted		
−5	7.7	140	29	151
0	4.0	147	12	133
+5	2.1	154	−7	115
		Observed (mean values) polar cap at $\phi = 73°S$		
		?	−51	?
		Observed (mean values) polar cap at $\phi = 73°S$		
		?	−27	?

phere in contact with it, since the temperatures are the same. In the spring, winds may be more prevalent and stronger than in the winter. If the wind regime is symmetric and the air flow at the surface is from south to north, the cold air at the polar cap displaces the warmer air over the adjacent clear ground. The CO_2 gas produced in the sublimation will reinforce this effect. Thus the temperature of the air moving over the CO_2 deposit will be essentially that of the deposit, so that conductive effects will be absent. If the winds are not symmetric, then some warmer air may flow over the cap. Its effect in conductively heating the CO_2 deposit will be diminished by the boundary layer at the temperature of the surface, which hinders conductive heat transport to the surface (*9*). We realize the qualitative nature of this discussion, but we believe that it is reasonable, particularly in view of the low density of the Martian atmosphere.

Various other temporary bright patches have been observed on Mars. Slipher (*3*) discussed morning frost patches of "islands in the south" over Martian light areas during the summer and early fall between $\phi = 60°$ and 70°S. This is precisely what is expected if these areas were valleys. The minimum nighttime temperature for those latitudes in that season might be just low enough for CO_2 condensation to occur (*8*, fig. 2) in regions of higher $p_s(CO_2)$. The CO_2 frost would then vaporize daily as the surface warms up on exposure to Sun. The same reasoning might apply to the light area Hellas which is "often snow-covered, and in winter forms a vast extension of the polar cap down to latitude 30°" (*13*).

Bright patches have been occasionally observed on the light area Nix Olympica at $\phi = 20°$N in summer (*7, 14*). Although it is clear that CO_2 cannot condense under these conditions, H_2O ice might form either in the atmosphere or on the surface of Nix Olympica. We suggest that this area is also depressed, since the partial pressure of the atmospheric H_2O would be higher in the lower areas. The conditions for condensation of H_2O in the Martian atmosphere will be somewhat different from those in our own atmosphere. For example, the negligible heating effect of the Martian atmosphere on its surface will have the following implications: The severe nightly cooling of the surface will form a pronounced inversion with a very cold boundary layer. This occurrence, together with the higher H_2O partial pressure in the depressions, will form fog or frost. Whether or not this analysis is applicable to all of the observations of bright patches is not clear—it requires a detailed study of the circumstances of each observation.

It has been frequently suggested that the deserts are elevated (*3, 6, 7*). Rea (*15*) favored the idea that the light areas are lower because dust storms, which sometimes obscure even the dark areas but consist of material from the light areas, settle back into the light areas. It would be difficult to imagine dust settling preferentially in areas of higher elevation. Wells (*16*) argued that the dark areas are elevated because of the tendency for white clouds to remain over light areas bordering dark areas, which he interpreted as being a result of lee waves formed by mountainous Martian maria. The results of our study support this thesis that the light areas are depressed.

B. T. O'Leary
D. G. Rea
Space Sciences Laboratory,
University of California, Berkeley

References and Notes

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Frost Phenomena on Mars

Abstract. *The hypothesis that the Martian wave of darkening might be a frost-heaving phenomenon has been examined. Consideration of the water-vapor sorption characteristics of a silicate mineral surface at temperatures below freezing leads to the conclusion that, without strongly deliquescent salts to attract and retain liquid water in the Martian soil, frost-heaving phenomena are not to be expected on Mars. On the other hand frost-heaving phenomena involving the freezing and thawing of ammonia may be common in the soils of Jupiter.*

Otterman and Bronner have suggested (*1*) that the dark regions on Mars may be caused by small-scale surface roughening associated with frost phenomena in the Martian soil. Frost phenomena common on earth are frost heaving (including needle-ice formation as a special case), the formation of hoar frost at or below the surface, the formation of massive ice bodies exemplified by ice wedges, ice lenses, and pingos found in the terrestrial arctic, and finally, the simple freezing *in situ* of soil water. Of these phenomena only frost heaving produces changes in the texture of the soil surface of the type required by the hypothesis of Otterman and Bronner.

The principal requirements for frost heaving in the terrestrial environment are (i) a temperature gradient with temperatures below freezing at the soil surface but above freezing at depth; (ii) soil water in the liquid state available at depth for transfer to the freezing zone; (iii) soil containing a significant proportion (5 to 20 percent or more) of fine particles (50-μ diameter or less). Frost heaving occurs when soil water is drawn upward from unfrozen regions to the freezing zone where it then accumulates as ice. During crystallization the tendency to exclude solutes and particles at the interface between ice and water results in the growth of segregated ice lenses. This disturbance often is expressed in changes in the configuration of the soil surface, and in various ways it can lead to roughening. The rate and extent of frost heaving depend critically on a favorable balance between the movement of soil water to the growing ice lenses and removal of the latent heat of freezing. This balance is governed by the initial