THE INFLUENCE OF TOPOGRAPHY ON THE FORMATION OF TEMPORARY BRIGHT PATCHES ON MARS

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ABSTRACT

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The Mountains of Mitchel and other temporary bright patches observed on the Martian disk have been previously interpreted as elevated areas where H_2O-ice has formed. However, a calculation of the radiation balance on Mars and the observed duration of the Mountains of Mitchel suggest that they are CO_2 condensations in depressions with depths of $\sim 6-9$ km. The appearance of bright spots on Hellas and other areas in the southern hemisphere can also be explained by depressions where the minimum night-time temperature is low enough for CO_2 to condense. The possibility of H_2O condensation in depressions is also discussed. These results support the hypothesis that the Martian deserts are lower than their surroundings.

Author

The best examples of seasonal bright spots on Mars, other than the polar caps themselves, are the Mountains of Mitchel at Martian latitude 73°S (Figure 1). They have been observed for over a century at intervals of about 15 years(1, 2). A remarkable fact is that they appear as patches isolated from the receding souther polar cap on practically the same seasonal date at each opportunity(2), thus providing interesting milestones for

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the systematic annual retreat of the polar cap. In general they vanish after only a few days[1, 3, 4], and only rarely last as long as two weeks[4]. During the 1956 opposition they survived for 5^{o} of heliocentric longitude, or about 7 days[3]. 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[2]. It has been concluded[2, 5, 6] that the Mountains of Mitchel are H_2O-ice deposits on elevated areas, an obvious application of the terrestrial analogy of snowcapped mountains.

Recently, Leighton and Murray[7] and Leovy[8] 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 surface partial pressure of CO_2, $p_s(CO_2) \sim 4$ mb. This is a higher value than previously thought, and it is now believed that CO_2 is the major constituent of the Martian atmosphere.

Our discussion follows from the important premise that the thermal interaction between the Martian surface and atmosphere is negligible. Referring to their own calculations, Leighton and Murray[7] stated, "Radiative thermal exchange with the atmosphere is assumed negligible except insofar as the atmosphere may affect E (the emissivity of the surface) by blocking certain wavelengths emitted by the surface. Horizontal heat transport by wind is also neglected..." They also neglected heat transfer by conduction between the surface and the atmosphere. The temperature of the Martian surface is then dependent only on insolation, heat exchange with the underlying soil by conductivity, and the latent heat of any condensed volatile.

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 $p_s\,(CO_2)$, i.e. 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

$$S = S_o\,(1 - A)\,\frac{r_o^{\,2}}{r^2}\,\frac{1}{2\pi}\int_{day}(\sin\phi\ \sin\delta_s + \cos\phi\ \cos\delta_s\ \cos\tau - \beta)\,d\tau \qquad (1)$$

where S_o is the solar constant at Mars, 0.06 watt cm^{-2}, corresponding to the distance r_o = 1.52 a.u. from the Sun[7], r the distance of Mars from the 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[8]. The integrand is zero whenever the zenith angle is greater than 90^o. Increments of 0.1 radian in τ were used for the Simpson integration on the computer. The integration was performed for intervals of 20^o in heliocentric longitude, starting from summer solstice in the southern hemisphere.

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

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

where E = 0.85 is the estimated effective emissivity of solid CO_2 at the Martian surface(7), $\sigma \left(= 5.67 \times 10^{-12} \text{ watt cm}^{-2}\ {}^{\circ}K^{-4}\right)$ the Stefan-Boltzmann constant, T_{eq} 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}, the latent heat of vaporization of CO_2 at $T_{eq} = 145^{\circ}$ K(9), and n the number of seconds in a Martian day.

In early Martian fall solid CO_2 would form at night, when the temperature drops to T_{eq}. For the first few days, these deposits would 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 equation (1) varies only with season and latitude on Mars. But T_{eq} varies with p_s (CO_2), and thus with local elevation. Figure 2 illustrates the value of dM/dt at the Mountains of Mitchel as a function of Martian season for various elevations.

Column 3 of the Table shows the date of the beginning of CO_2 deposition as a function of elevation. This defines the lower limit of integration t_o of the curves on Figure 2 for calculating M, the amount of CO_2 ice at time t:

$$M = \int_{t_o}^{t} \frac{dM}{dt}\, dt \qquad (3)$$

The pressures for each elevation indicated in the Table assume 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, i.e. the time for M = 0. The important point to note is that a 5 km depression would produce CO_2 deposits which would be detached from their surroundings for a duration of 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 $\phi = 73^{\circ}$S and the time the patches disappear. Slipher's regression curve[2, 7] shows the cap at 73° at $t = -53^{d}$, and the patches are observed as detached from the cap at $t = -35^{d}$. Combining this with estimates of the duration of the patches themselves ($\sim 7^{d}$) we find $\Delta t \approx 25^{d}$. Dollfus' regression curve of the southern polar cap[9] showed the cap reaching $\phi = 73^{\circ}$ S at $t = -49^{d}$. The patches became detached from the cap at $t = -29^{d}$ and survived until $t = -22^{d}$[3], or $\Delta t \approx 27^{d}$. Photographs show the Mountains of Mitchel extending $\sim 4^{\circ}$ in latitude when they are barely detached from the polar cap[2]. Taking half that value as being representative of the interval of latitude between the cap reaching 73° S and the detachment of the patches, then $\Delta t \approx 17^{d}$.

A comparison of these values with calculation (cf. the Table) suggests that the Mountains of Mitchel are valleys or large craters of 5 - 8 km depth. We therefore prefer the name "The Depressions of Mitchel" for these seasonal bright patches.

Our predicted dates of disappearance of the solid CO_2 at $\phi = 73^\circ$ S are later than the observed disappearance and the disappearance predicted by Leighton and Murray[7]. 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, e.g. the CO_2 albedo, CO_2 emissivity, p_s (CO_2) at 0 km, and β. 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 lapse rate, should be discussed in order to see if they affect this duration.

Atmospheric blanketing by the 15μ CO_2 band was taken into consideration for the value of the CO_2 emissivity. Leighton and Murray[7] give ~ 12% as the blanketing effect at the Martian surface as calculated from the data of Stull, Wyatt, and Plass[10]. Our examination of their data[11] indicate that this blanketing would amount to 11.4% for 100 meter-atm. CO_2 and 9.8% for 50 meter-atm. 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 CO_2 path, temperature, and pressure values, the maximum expected difference in CO_2 emissivities corresponding to an elevation differential of 5.5 km would be only 2%. This amount would "deepen" the Depressions of Mitchel by 1 km at most.

As for the effect of possible temperature decreases with elevation, we mentioned earlier that it was assumed that heat transfer to the Martian surface is dominated by radiative interaction with the Sun and with space, and not by convective interaction with a turbulent atmosphere. A lapse rate of 0 to 2.5 K^o km^{-1} [12] would make the atmospheric temperature 0 to 20 K^o warmer in the depressions. It can be expected that this small temperature differential in a tenuous Martian atmosphere would have a negligible effect on the surface temperature.

Other examples of temporary bright patches observed on the Martian light areas are Hellas[6, 13], the "islands in the south"[2], and Nix Olympica[6]. Again, each author has concluded these bright patches are H_2O frost on elevated areas, but we prefer the interpretation that they are deposits on lowlands.

Regarding Hellas (at ϕ = 40° S), McLaughlin[13] stated "it is often snow-covered, and in winter forms a vast extension of the polar cap down to latitude 30°". Our computations show that CO_2 cannot form a winter deposit at ϕ = 30° S to 40° S for any reasonable p_s (CO_2), elevation, or CO_2 albedo. However, the diurnal temperature variation is important at these latitudes. Leighton and Murray's Figure 2[7] shows that CO_2 condensation during the night is possible for several weeks near winter solstice at ϕ = 40° S and A = 0.15, p_s (CO_2) = 4 mb. But Hellas is actually one of the brightest areas, favoring preferential condensation, and p_s (CO_2) may be higher than previously thought[12, 14], especially if Hellas is a lowland. We see no reason to describe Hellas as being elevated, and believe it may in fact be depressed.

Slipher[2] discussed morning frost patches or "islands in the south" over Martian light areas during the summer and early fall between $\phi = 60^{\circ}$ 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 (see ref. 7, 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 the Sun.

Various other observations of Martian bright patches have been made. Their classification is uncertain since it is not clear whether they are clouds or surface deposits. For example, bright patches have been occasionally observed on Nix Olympica at $\phi = 20^{\circ}$N, and have been interpreted as frost or snow[6,15]. Although it is clear that CO_2 cannot condense in summer at $\phi = 20^{\circ}$ N, H_2O ice condensation might occur, either in the atmosphere or on the surface of Nix Olympica. This tendency would be greater if it were 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,and this is beyond the scope of the present work.

The bright patches definitely prefer forming on the Martian light areas, so this study obviously suggests that the deserts are depressed and not elevated as previously thought[2, 5, 6]. Rea[16, 17] has favored the idea that the light areas are lower on the basis that 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[18] argued that the dark areas are elevated because of the tendency for white clouds to remain over light areas boardering along dark areas, as a result of lee waves formed by mountainous Martian maria.

The radio occultation data from Mariner IV led Fjeldbo _et al._[12] to suggest that the dark area Mare Acidalium is lower than the light area Electris. From tracking data the Martian radius at Electris was found to be ~4 km larger than the radius at Mare Acidalium. This agrees with the tracking data reductions of Kliore _et al._[14] who suggest a 5 km ($\pm$ 7 km) difference. These studies also show the surface pressure to be ~ 8.5 mb over Mare Acidalium and ~ 4.9 mb over Electris. Fjeldbo _et al._[12] concluded, "The differences in pressure and radius both suggest that the Martian maria may be lowlands; the bright areas, highlands". However, Kliore _et al._[14] noted that the Martian dynamical flattening of 0.0052 would predict the radius at Electris to be 3 km larger than that at Mare Acidalium, in good agreement with the tracking data. If the Martian optical flattening of 0.0117 $\pm$ .0012 (ref. 9) is due to the surface, then the radius difference should be 6 km, also in good agreement with the tracking data. From these data there is therefore no evidence for any "local terrain features at the occultation points (or) greater oblateness than a gravitational equipotential surface"[12].

If the observed optical flattening of Mars is due to the Martian surface and not to its atmosphere, then any excess value of the true flattening over the dynamical flattening can be reconciled only if the equatorial bulge of the planet were greater than that of a gravitational equipotential surface. Therefore, the surface pressure, p_s, at the Martian poles would be greater than that at the equator. Since this excess equatorial bulge would amount to 22 km, Dollfus[9] estimated that p_s would be a factor of about e, or 2.7, higher at the poles than at the equator, for a scale height of 24 km. However, the presently accepted value for the Martian scale height near its surface is 8 to 13 km[14] so the pole-to-equator pressure discrepancy would be a factor of 5 to 16. If this idea is correct, the pressure over Mare Acidalium should exceed that over Electris by a factor of 1.4 to 1.7, precisely what is observed in the radio occultation data[12,14].

However Spinrad[19] has tested this prediction by examining CO_2 bands in the Martian spectrum with the spectrograph slit aligned approximately along the polar axis. He concluded that the ratio of the pressures at the poles and equator does not exceed 2. Thus, the suggestion that a difference between the pressures at Electris and Mare Acidalium is attributable to a "deviation of the mean surface from the equipotential"[14] is probably incorrect. If the pressure difference over the two areas is real, and not a result of measurement errors, it would appear that Mare Acidalium is at a lower elevation than Electris. It is accordingly premature to make any dogmatic statements about the relative elevations of the bright and dark areas, although our preference for depressed bright areas remains.

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REFERENCES

1. E. M. Antoniadi, La Planète Mars (Herman et Cie., Paris), 221 (1930).
2. E. C. Slipher, A Photographic History of Mars (Lowell Observatory Flagstaff, Arizona), Chap. 3 (1962).
3. A. Dollfus, private communication (1966).
4. J. S. Hall, private communication (1966).
5. C. W. Tombaugh, Nature, 209, 1338 (1966).
6. S. Miyamoto, Icarus, 5, 360 (1966).
7. R. B. Leighton and B. C. Murray, Science, 153, 136 (1966).
8. C. B. Leovy, Radiative-Convective Equilibrium Calculations for a Two-Layer Mars Atmosphere, Rand Corporation Memorandum RM-5017-NASA (1966).
9. A. Dollfus, Ann. d'Astrophys., 28, 722 (1965).
10. V. R. Stull, P. J. Wyatt, and G. N. Plass, Appl. Opt., 3, 243 (1964).
11. V. R. Stull, P. J. Wyatt, and G. N. Plass, Infrared Transmission Studies, Final Report, Vol. 3, The Infrared Absorption of Carbon Dioxide, SSD-TDR-62-127, Space Systems Division, Air Force Systems Command, Los Angeles, Calif. (1963).
12. G. Fjeldbo, W. C. Fjeldbo, and V. R. Eshleman, Science, 153, 1518 (1966).
13. D. B. McLaughlin, Publ. Astron. Soc. Pac., 66, 221 (1954).
14. A. J. Kliore, D. L. Cain, and G. S. Levy, "Radio Occultation Measurement of the Martian Atmosphere over Two Regions by the Mariner IV Space Probe," presented to the Seventh International Space Science Symposium, Committee on Space Research (COSPAR), Vienna, Austria, May 11-17, 1966.

REFERENCES (Cont.)

15. G. de Vaucouleurs, Physics of the Planet Mars (Faber and Faber, London), 29 (1954).

16. D. G. Rea, Nature, 200, 114 (1963); ibid, 201, 1014 (1964).

17. D. G. Rea, Proc. Cal. Tech.–JPL Lunar and Planetary Conf., JPL Technical Memorandum No. 33-266 (1966).

18. R. A. Wells, Nature, 207, 735 (1965); ibid, 209, 1338 (1966).

19. H. Spinrad, private communication.

TABLE

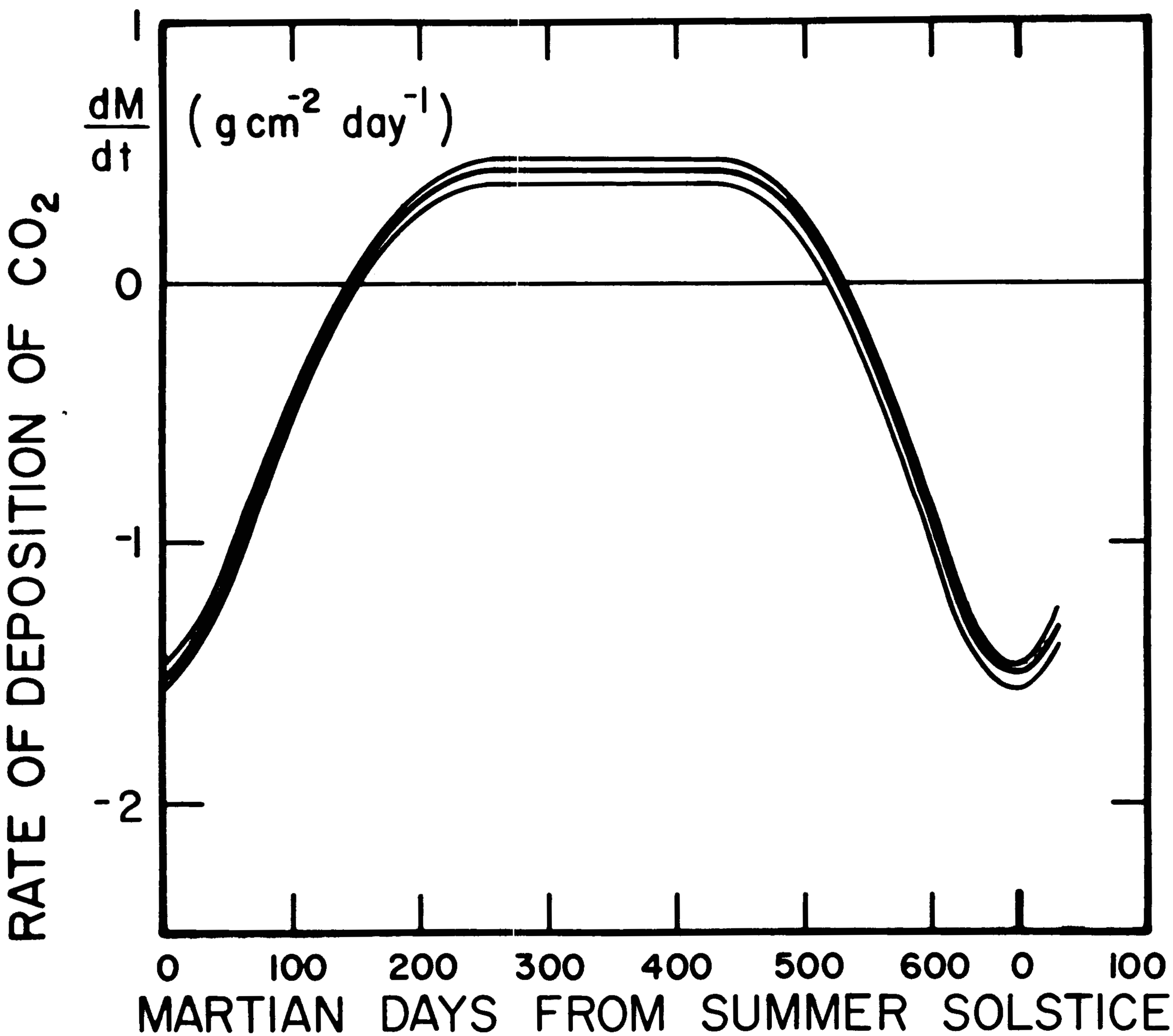
Predicted and observed properties of a solid CO_2 deposit at the latitude of the Mountains of Mitchel ($\phi = 73^{o}$ S). Times are in Martian days after southern summer solstice. The partial pressures of CO_2, $p_s(CO_2)$, assume an exponential atmosphere with a scale height of 7.7 km and $p_s(CO_2)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

Elevation h	$p_s(CO_2)$	Time of beginning of deposition of solid CO_2, t_o	Time of disappearance of solid CO_2	Maximum accumulation of solid CO_2
-5 km	7.7 mb	140^d	29^d	151 g cm^{-2}
0	4.0	147	12	133
+5	2.1	154	-7	115
Observed (mean values)				
Polar cap at $\phi = 73^{o}$ S		?	-51	?
Mountains of Mitchel		?	-27	?

FIGURE CAPTIONS

Figure 1. A photograph of Mars showing a Mountain of Mitchel detached to the left of the southern polar cap (up). The photograph was taken by E. C. Slipher on August 21, 1909, 35 days before summer solstice in the Martian southern hemisphere (ref. 2, plate XVI).

Figure 2. The rate of deposition of CO_2 versus Martian season at the latitude of the Mountains of Mitchel ($\phi = 73^{\circ}$) 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 the Table.



RATE OF DEPOSITION OF CO_2
$\frac{dM}{dt}$ $(g\,cm^{-2}\,day^{-1})$
1
0
-1
-2
0
100
200
300
400
500
600
0
100
MARTIAN DAYS FROM SUMMER SOLSTICE