Mars as an Astronautical Objective

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I. Description

A. General

The planets Mars and Venus approach Earth more closely than any others in the Solar System. Consequently, these two bodies have received more attention from scientists interested in the physics of their surfaces and atmospheres. Since Mars' orbit lies outside Earth's, while Venus' orbit is closer to the Sun than our own, the hemisphere of Mars which is presented to us is fully illuminated at the closest approaches while the corresponding hemisphere of Venus is unilluminated at these times (Fig. 1). Consequently, Mars is more easily studied even though Venus comes somewhat closer to Earth and has a larger absolute diameter.

Clearly, the best occasions for telescopic study occur around the times when Earth lies most nearly between the Sun and Mars; this geometrical configuration is called *opposition*. Mars comes into opposition with Earth at intervals of slightly more than two years (780 days) and the favorable observing periods last only a few months. Unfortunately, Mars' orbit is

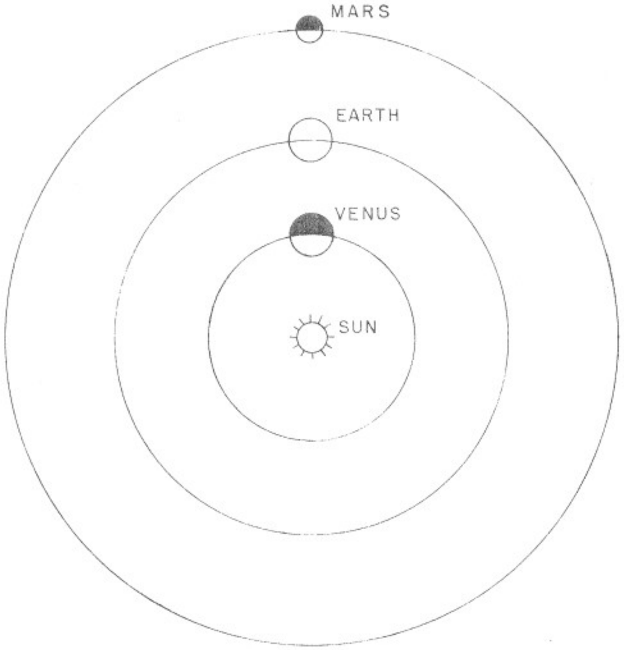

FIG. 1. Schematic representation of the positions of the Sun, Earth, Venus, and Mars at the approximate times of closest approach of the latter two planets to Earth.

appreciably more eccentric than ours, so some oppositions are distinctly closer than others. The closest distance near opposition may range between 34,600,000 and 61,700,000 miles, and the maximum angular diameter ranges between 25 and 14 sec of arc. It is clear that the close oppositions afford distinctly better opportunities for observation than do the more distant oppositions. Table I gives data for oppositions up to 1975.

TABLE I. OPPOSITIONS OF MARS

Date	Minimum distance from Earth (miles)	Maximum angular diameter (sec of arc)
Feb. 3, 1963	61,700,000	14.0
Mar. 8, 1965	61,700,000	14.0
Apr. 13, 1967	56,200,000	15.4
May 29, 1969	45,300,000	19.1
Aug. 6, 1971	34,600,000	25.0
Oct. 21, 1973	40,600,000	21.6
Dec. 13, 1975	53,100,000	16.5

It is a curious accident that the most favorable oppositions come during summer of our Northern Hemisphere as well as during summer of the Martian Southern Hemisphere. At the moment of writing (Fall, 1960) we are in the midst of a long period of geometrically unfavorable oppositions when, however, we have the best opportunity to observe the Northern Hemisphere of Mars. The next optimal opposition will not occur until 1971, since a cycle of oppositions takes about 15 years to complete its course.

Significant physical data for Mars are given in Table II. Certain marked resemblances to Earth are apparent. The length of the Martian day exceeds our own by only 37 min. Since the inclination of the equatorial plane to the orbital plane differs from Earth's by only 1.5 deg, a marked resemblance of seasons must exist. On the other hand, the period of revolution about the Sun is somewhat less than twice our own, so the seasons are correspondingly longer. Because of the smaller planetary mass and size, the surface acceleration of gravity is about one-third of ours. This has a marked effect on the gases retainable in the atmosphere and upon the limiting, adiabatic, vertical lapse rate of temperature in the atmosphere.

Various figures may be found in the literature for the diameter, mass, density, and surface gravity. The values given in Table II are self-consistent and based upon the adopted mean diameter and mass. The effect of centrifugal acceleration owing to the daily rotation has been taken into account also in calculating the surface gravity.

TABLE II. PHYSICAL DATA FOR MARS

Datum	Absolute units	Units relative to Earth
Mean distance from Sun	2.277×10^8 km	1.52
Mean orbital speed	24.1 km sec^{-1}	0.810
Mean diameter	6739 km	0.529
Length of day (solar time units)	$24^h37^m22.6^s$	1.0012
Length of year (solar time units)	686.979 days	1.8808
Eccentricity of orbit	0.0933	5.5
Inclination of equator to orbit	25°	1.06
Mass	——	0.1078
Mean density	4.02 gm cm^{-3}	0.728
Surface gravity at 45° lat.	377 cm sec^{-2}	0.384
Visual albedo	0.15	0.43

It is interesting to note that the greater distance of Mars from the Sun does not decrease the effective available energy as much as one might suppose. At perihelion, when Mars is closest to the Earth as well as the

Sun, the energy received is 0.53 of the corresponding amount for Earth. However, the lower albedo of Mars increases the absorption of this energy by a factor of 1.4. Consequently, the effective solar radiation is 0.74 of the terrestrial amount. Of course, this ratio is much lower at aphelion. As will be noted later, the atmosphere of Mars does not provide as great a barrier to outgoing infrared radiation, so the mean surface temperature is significantly lower than Earth's, even at perihelion. The difference, however, is not so great as the larger separation from the Sun would suggest.

B. The Surface

The telescopic appearance of Mars is shown in Fig. 2. The outstanding features are the dark areas (called maria) against the general reddish-orange background (often fancifully called deserts) and the white polar caps. The polar caps are rather reliably known to be a thin layer of H_2O-frost deposited on the surface. The evidence for this is the infrared reflection spectrum of the caps measured by Kuiper [1, pp. 361-362]. The reflection spectrum of the polar cap shows the same decrease in brightness, beginning at 1.5μ and becoming black at 2.0μ, which is exhibited by H_2O-ice at low temperatures in the laboratory. This reflection spectrum is quite different, for example, from that of solid carbon dioxide which once was suspected as the material of the caps.

The polar caps are observed to expand to lower latitudes during Martian fall and winter, and to shrink to higher latitudes during spring and summer. The Southern Hemisphere cap, which has been better observed, does not disappear completely during summer. However, the small residual cap is not centered on the areographic pole and characteristic latitudinal elongations are noted during dissipation. These facts suggest the existence of topographic features of sufficient relief to cause these departures from latitudinal regularity.

Calculations have been made of the thickness of the polar caps from the rate at which they recede in spring and the known rate of receipt of solar energy [2, pp. 199-200]. The estimated mean thickness is only 1 to 5 cm. Relative profiles of the thickness at various seasonal dates have also been calculated [2, p. 202].

The nature of the dark maria has been a source of speculation for many years. They undergo a well-known seasonal variation, becoming darker (and in some cases larger) in the warm season and fading somewhat in winter. This has led many to suppose they are vegetation of some sort. In addition, erratic changes occur from time to time. For example, in 1954 E. C. Slipher and others photographically recorded a new dark area covering almost 600,000 square miles. Such remarkable events call for explanation and it is not particularly satisfying to say merely that vegetation is capable of such behavior. One wonders what remarkable change in conditions would produce such a phenomenal growth and what were the fundamental causes.

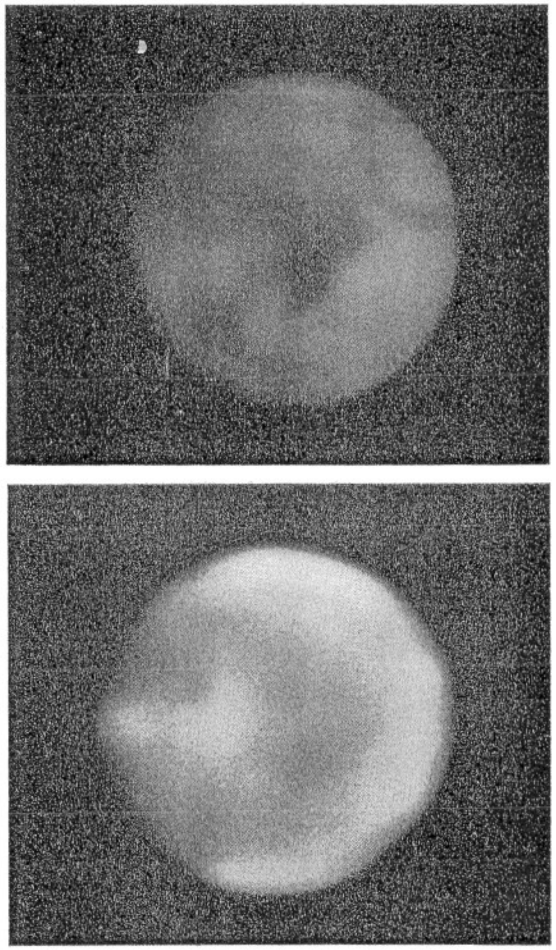

FIG. 2. Normal telescopic appearance of Mars in red light (top) and blue light (bottom). The red photograph shows the characteristic permanent surface markings. The most prominent dark area near the center of the disc is called the Syrtis Major. Note that it is impossible to discern the surface features in blue light. As is usual in planetary astronomy, south is at the top and east is at the left. The rotation of the planet is from right to left. Photographs taken on June 11, 1954 by E. C. Slipher and A. P. FitzGerald of the Lowell Observatory—National Geographic Society Expedition to the Lamont-Hussey Observatory, Bloemfontein, S. Africa.

The dark areas do not have the characteristic infrared reflection spectrum of chlorophyll [1, pp. 362-363]. This does not rule out the presence of chlorophyll, since certain terrestrial plants have natural coatings which prevent this reflection spectrum from being detected. The presence of organic matter has recently been demonstrated by Sinton [3] who recorded the characteristic C-H vibration absorptions near 3.5μ in the reflection spectrum of the dark maria and found them to be absent in the spectrum of the orange deserts. This remarkable observation is a solid substantiation for the view that life does exist on Mars. An interesting discussion from the biological point of view of a way in which vegetation could adapt to the rigorous conditions on Mars has been given by Strughold [4].

The nature of the orange areas which give the planet its characteristic ruddy hue has also been the subject of much thought and investigation. A rather natural assumption is that these areas are dominated by iron oxides, since these would have the right color and provide an explanation for the absence of oxygen in the atmosphere. Kuiper [1, p. 358] has compared the planetary reflection spectrum in the range 0.4 to 2.5μ with those of various samples of terrestrial rock. He finds that red soils and rocks do not match the Mars data, but that a brownish, fine-grained felsite provided a close fit over the entire range. He rejects the iron-oxide hypothesis and tentatively concludes that the bright desert regions are composed of igneous rock similar to felsitic rhyolite. On the other hand, Dollfus [5] has studied the polarization curve of Mars and made comparisons to laboratory data. He finds an exact duplicate in the polarization curve of limonite, which is almost pure hydrated ferric oxide. Clearly these reports are in contradiction to each other and further work is called for. This situation is not surprising, since neither reflection spectra nor polarization curves for solid surfaces provide the kind of unique identification supplied by transmission spectra of gases.

Because of yellowish clouds which appear from time to time it is reasonable to assume these desert areas are at least partially covered with dust or sand. It is not possible at present to give a definitive statement as to their mineralogical nature.

It is well established that no large bodies of water can exist on the surface of Mars. This was argued many years ago by Lowell, who pointed out that substantial bodies of free water ought, sooner or later, to produce a specular reflection of the Sun which should be easily seen. More recent spectrographic data show the atmosphere is so dry that it is inconceivable that bodies of liquid H_2O could last very long.

The degree of relief in the Martian topography is uncertain. Any high mountains could be detected as the axial rotation carried them toward the terminator (border between night and day) because they would appear as projections or tiny detached bright spots. Such features cannot exceed a few thousand feet in elevation [6, pp. 96-107]. On the other hand, the regularly repeated anomalies in the shape of the south polar cap during its recession and certain preferred locations for abnormal brightening suggest the existence of definite orographic features. It should be pointed out also that the negative results of careful, long-continued scrutiny of the terminator rule out only isolated peaks extending a few thousand feet above a plain. It seems possible that gradual slopes extending over wide areas could be present and could produce departures from the spheroid of several thousands of feet.

The final kind of surface feature worthy of comment are the famous "canals" discovered in 1877 by Schiaparelli. Many astronomers have observed visually these difficult objects and have independently recorded the positions of large numbers of them. Comparison of such independent records shows remarkable agreement and makes it clear that something real is being observed.

The so-called "canals" are a network of long, narrow, dark streaks across the planetary surface which not infrequently intersect each other at somewhat enlarged dark spots called "oases." The narrowness of many of these linelike markings and their slight contrast to the planetary surface make them difficult to observe. The terrestrial atmosphere above the telescope must be in a state of minimum turbulence to produce sufficiently good "seeing." A small amount of light diffused across the planetary surface by turbulence suffices to mask the canals from view. Furthermore, one almost never sees the entire recorded network at once. As the seeing fluctuates, moments of good steadiness of image will occur. During these moments the observer may see a few canals. At the next instant of good seeing he will see a few others. The complete complex network which has been described in the literature [6] is a composite of these individual glimpses. Because of their transitory nature, originating in "seeing," it has not been possible to photograph the canal system in a completely satisfactory fashion. The necessary time exposures integrate the rapidly changing seeing effects and mask the canal images. A few photographs have been obtained showing two or more faint linear smudges at the positions of known canals. Nevertheless, this is one area of astronomy in which visual observation is appreciably superior to any other means.

The controversy which has long surrounded the matter of Martian canals stems largely from the interpretation which Percival Lowell [7] placed upon them. He pointed out that the canals were observed to be extremely narrow and followed great circles, and concluded that they were artificial waterways constructed by intelligent beings to convey water from the melting polar caps for irrigation purposes. If correct, the importance of such an argument is obvious. However, we now know, as Lowell did not, that the Martian atmosphere is extremely dry. This means, first, that the polar caps mostly sublime during spring rather than melt and, secondly, that water traveling through open canals thousands of miles in length would undoubtedly evaporate before getting very far. This alone renders his thesis untenable.

A secondary controversy exists over the validity of Lowell's description of them as being extremely narrow and continuous. It has been argued that they are so narrow as to be beyond the resolving power of the telescopes used. This is not a tenable argument, however, because resolving power refers to the ability of an instrument to distinguish between two point sources of light which are close to each other, not to the instruments' ability to reveal a narrow line. Indeed, it is easy to perform experiments to show that narrow lines can be seen and photographed when their width is far less than the theoretical resolving power of the eye or camera lens.

Dollfus [8] has asserted that in moments of perfect seeing certain canals could be resolved into a series of small, irregular, discontinuous spots which were aligned in such a fashion that the blending of the image under less than perfect atmospheric conditions gave them the appearance of continuous lines. If one accepts this observation and a generalization to all canals rather than the few described by Dollfus, it still remains to explain why the discrete spots are aligned over long sweeps of distance. The faint, linelike canal pattern is uniquely a Martian phenomenon and calls for an explanation, probably of a natural geological kind rather than the synthetic explanation by Lowell. It should be noted that the evidence against Lowell's theory removes the question of the canals from the first rank of importance and relegates it to a far less significant position.

C. The Atmosphere

1. COMPOSITION AND AMOUNT

For the sake of brevity we shall omit the long and sometimes misleading history of studies of the composition of the Martian atmosphere and proceed directly to the more definitive modern observations. Attempts have been made to detect spectrographically a fair number of possible atmospheric constituents. Aside from a few reports which could not be verified independently, the only positively identified gas is CO_2. In 1948 Kuiper [1, pp. 358-361] detected small absorptions near 1.6μ and 2.0μ which are characteristic of CO_2. From comparison to the strength of the telluric bands, as revealed in the spectrum of the Moon, he estimated Mars has about twice the mass per unit area of this gas found in our atmosphere. This figure may have to be revised upward because of pressure effects and because of the complex interplay between the telluric and Martian CO_2-lines making up the unresolved bands studied. Goody and Grandjean [9] have attempted to correct theoretically for this second factor, and conclude that Mars may have closer to thirteen times the terrestrial content of gaseous CO_2.

The absorption spectrum of oxygen has not been detected despite exhaustive attempts [10]. One difficulty here is the large amount of telluric O_2 through which the light must pass. The relative radial velocity of Earth and Mars near quadrature produces a Doppler shift equivalent to about one-third the separation between adjacent lines in the tail of the B band of O_2. Consequently, it is possible to achieve a useful separation of the planetary and telluric components if a spectrograph of high dispersion is used. The plates taken by Adams and Dunham do not show any obvious separation of this sort and close study to detect the asymmetries in the telluric lines which would be produced by a small Martian content of O_2 gave negative results. When the minimum effect which the instrumentation could detect was utilized in conjunction with the known curve of growth for oxygen, Dunham [10] concluded that there cannot be more than about 0.0015 as much oxygen per unit area on Mars as on Earth.

Similar efforts to detect water vapor have also given negative results. Dunham [10] concluded that the upper limit again is 0.0015 of the vapor present over Mt. Wilson (California) on a clear winter night. However, it appears that this is not a defensible conclusion. First, the delicate measurement of line asymmetries was not carried out for water vapor but a cruder measure was used. Secondly, the curve of growth for H_2O was not employed and thirdly, the marked pressure dependence of H_2O absorptions was not considered. All that can be concluded now is that no more than an indeterminate but very small amount of vapor can be present on Mars. Even if Dunham's limit must be multiplied by ten, which seems extreme, this will mean a severe upper limit of about 0.1 mm of liquid water. The fact that the polar caps are almost surely composed of H_2O means that some vapor is present in the atmosphere. A subsequent attempt to measure Martian H_2O from an arid mountain site also gave a negative result [11], and a recent attempt to record from a stratospheric balloon platform aborted because of balloon failure.

Of the other possible constituents of the Martian atmosphere which have absorption spectra detectable through our own atmosphere, Kuiper [1, p. 374] has looked for seven gases and reported negative results for all: SO_2, O_3, N_2O, CH_4, C_2H_4, C_2H_6, NH_3.

The number of gases which may be present is limited by the possibility of escape of constituents of low molecular weight. Spitzer [12] has re-examined Jean's theory of escape of planetary atmospheres and has calculated results for Mars. Figure 3, constructed from his values, shows the dependence of the escape time upon molecular weight and temperature of the exosphere. We must require that a significant fraction of any given gas be retained for periods of time comparable to the age of the planet if it is to be considered a possible constituent today. We shall, somewhat arbitrarily, adopt 5 × 10^8 years as the dividing line between total escape and virtually complete retention. Since the time scale of Fig. 3 is logarithmic the results are not sensitive to reasonable modifications in this choice.

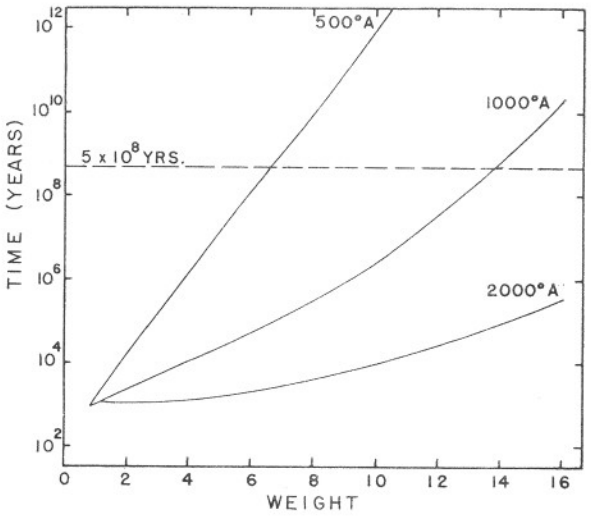

FIG. 3. The time, t, required on Mars for the density of an atmospheric constituent to fall to e^{-1} of its original value, as a function of molecular or atomic weight and the temperature of the exosphere.

A source of uncertainty arises from the effect of the temperature of the upper atmosphere. The exosphere on Earth has a temperature near 1500°K or more because of absorption of ultraviolet solar radiation by monatomic oxygen. The higher value of gravity on Earth permits O to be retained even at such temperatures, but Fig. 3 suggests that Mars would lose oxygen under such conditions. It is tempting to assume that Mars once had oxygen but the high exospheric temperatures produced upon its dissociation caused complete loss of oxygen and a reduction of the upper atmospheric temperature to a smaller value. During the supposed period of high temperatures nitrogen would not have been lost because it does not dissociate easily. Assuming a present temperature of 500°K or less for the Martian exosphere, it is clear that gases of weight less than about 6 are likely to have escaped. Thus hydrogen and helium are improbable but all gases of higher molecular weight are possible. It is especially important that nitrogen could be retained because it is cosmically abundant and so should have been present originally, and it is too inert chemically to permit us the supposition that all of it has combined with the planet's crust. Since N_2 cannot reasonably have been disposed of by escape or chemical means it is a likely major constituent of the atmosphere. Unfortunately, all of the absorptions by N_2 lie in the part of the ultraviolet to which our atmosphere is opaque. Thus, this attractive possibility cannot be checked by Earth-bound spectroscopy.

The photochemistry of the Martian atmosphere is an interesting field capable of much greater development when more basic data become available. Urey [13] has summarized some of the possibilities which include the formation of CO, CO^+, CO_2^+, N_2^+. All of these, of course, could exist only in small amounts. An important point is the fact that CO_2 absorbs in the Schumann region of the spectrum and so protects H_2O in the lower atmosphere from photodissociation.

A number of estimates of the total mass of the Martian atmosphere have been formed based upon the amount of light scattered or the degree of polarization of the reflected light. From visual determinations of the brightness of Martian features at varying angles from the center of the disk, de Vaucouleurs [14] found a surface pressure of 80 millibars with a probable error of ± 13 mb. A similar, later determination by Dollfus [15] gave 95 mb. Lyot's early polarimetric results have been superseded by those of Dollfus [15] in which he found a pressure of 83 mb. Much doubtful material has been published on this subject and is summarized in a critical fashion by de Vaucouleurs [2, pp. 99-127]. He concludes that the most likely value is 85 mb with a probable error of ± 4 mb. The present author feels that the reliability of this estimate is less than is suggested by de Vaucouleurs. The probable error given is mostly due to scatter of observations within any one method. It does not appear to take into adequate account the systematic errors which may be significantly large but difficult to evaluate. It seems reasonable to assert that the surface pressure on Mars probably lies between 70 and 100 mb, which amounts to an atmospheric mass per unit area about 20 percent of that on Earth.

It is clear that CO_2 alone cannot account for this mass because 13 times the terrestrial amount would exert a pressure of only one millibar. The water vapor present cannot make a significant contribution, so the bulk of the atmosphere must be composed of hitherto unidentified constituents. One such possibility is argon. All telluric argon has been generated by *K*-capture in potassium-40 with a half-life of about 1.4×10^9 years. If Mars received the same percentage of crustal K^{40} as Earth it should have an amount of argon capable of exerting a pressure of 5 mb (13 gm cm^{-2}). The remainder may be thought of as being nitrogen, for reasons discussed above. To make a total pressure of, say, 85 mb, the composition would be as given in Table III. Such an atmosphere would have a mean molecular weight of 28.6, insignificantly different from that of nitrogen.

TABLE III. POSSIBLE COMPOSITION OF THE MARTIAN ATMOSPHERE

Constituent	Molecular weight	Mass per unit area (gm cm^{-2})
N_2	28	214
A	40	13
CO_2	44	3
H_2O	18	0.1?
O_2	32	<0.3
	Total	230

2. CLOUDS

In visual wavelengths the atmosphere of Mars is usually free of noticeable clouds except near the morning and evening limbs and over the polar caps. However, from time to time clouds of varying sizes and colors may be seen and photographed over areas far from the edges of the planetary disk. These range from small light spots and thin veils, which can be detected only by one who is well acquainted with the normal appearance of Mars, to large masses which obscure significant fractions of the surface and are apparent to even the most casual observers. Other clouds are not visible but may be detected on photographs taken in blue light.

Although any classification is arbitrary, the cloud observations suggest a division into three major categories: yellow clouds, white clouds, and blue haze.

a. Yellow Clouds

It is reasonable to assume that the visual yellow clouds are composed of dust stirred up by wind storms. Exceptional cases may cover large portions of the planet and last for a number of weeks. Such an occurrence is described in detail by Miyamoto [16]. An example is shown in Fig. 4.

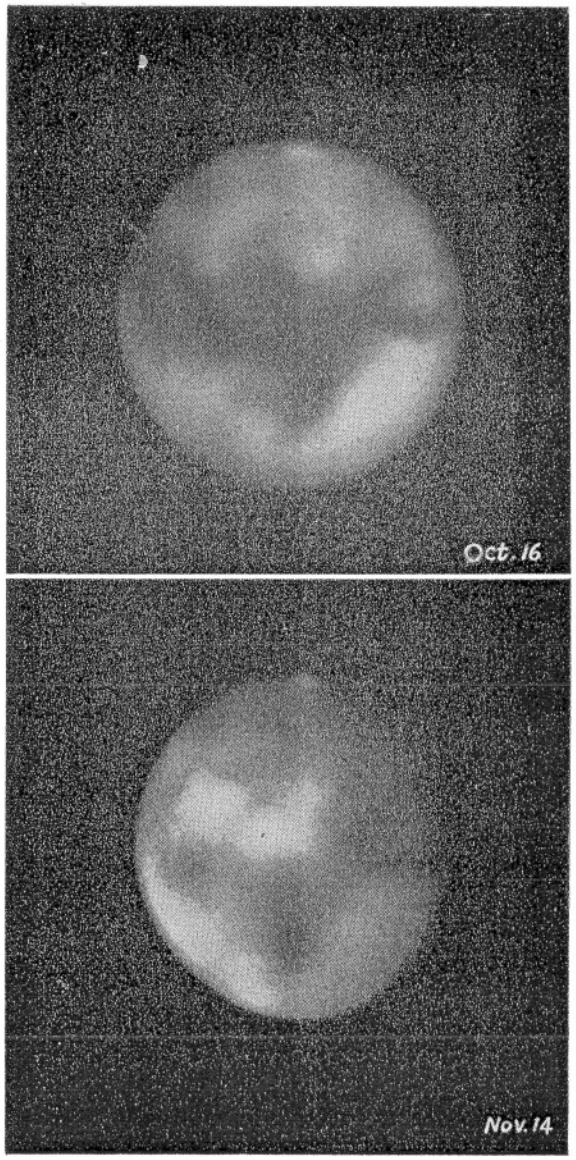

FIG. 4. Mars in yellow light in 1941. In these photographs the dark Syrtis Major is in the lower center of the disc and is recognizable in both cases. The upper photograph (Oct. 16) shows the unclouded view of Mars and the lower photograph shows a large yellow cloud obscuring the left central region. Note also the bright lower left limb which is also clouded. Photographs by E. C. Slipher, Lowell Observatory.

If these clouds are dust, it is disturbing that they do not exhibit the same color as the orange regions which occupy most of the surface of the planet. However, it has been suggested that this is not an insuperable objection because the color of a suspension depends to a large extent on the particle sizes. For sufficiently small particles the apparent color is completely independent of the color of the material in bulk and depends only upon the selective scattering properties of the suspension. Thus it is conceivable that the yellow clouds are composed of intrinsically orange matter but that the scattering is stronger for short wavelengths than long ones and the net result is a yellow appearance. It is tempting to try to use the observed colors to calculate the necessary particle size and size distribution, but subjective estimates of color are sufficiently imprecise that quantitative calculations would not be well-grounded.

b. *White Clouds*

Several factors suggest that the white clouds are composed of solid or liquid H_2O. These clouds are most prevalent over cool regions of the planet, where condensation of the meager water vapor is most likely. Their most common occurrence is on the sunrise limb where the atmosphere has been subject to radiational cooling during the night. They are also rather frequent over the fall and winter polar cap, that is, over the cap which is in the process of being deposited on the surface. Occasional infrared radiometric measurements made when these clouds were present gave abnormally low temperatures for the location and season, suggesting that they form when the temperature is exceptionally low or that they extend to heights of several kilometers and are condensations resulting from a normal decrease of temperature with elevation. All of these facts are consistent with one or the other of the two major processes known to be responsible for cloud formation on Earth: radiational cooling close to the surface and adiabatic cooling owing to ascending motion. Furthermore, Dollfus [5, 17] finds that the polarization curve of these white clouds is identical with that of terrestrial ice crystal clouds. On the plausible assumption that these clouds are composed of H_2O particles, it is possible to draw some conclusions about the vertical structure of the Martian atmosphere, since the condensation process follows well-understood laws.

c. *Blue Haze*

The last general class of atmospheric obscurations of the planetary surface is usually called "blue haze" because it is to be found on photographs taken in blue or ultraviolet light and is not detectable in visual wavelengths. The normal appearance of a blue photograph shows none of the surface features observable in yellow or red light (see Fig. 2). It once was thought that this could be explained without calling upon an atmospheric obscuration because the large orange areas of the planet are darker in blue light and the well-known markings superimposed on the orange background would not change intensity or even become brighter in the blue. Thus, in any case, the contrast between surface features and planetary background is weaker in blue light and this might explain the failure of these features to appear in short wavelength photographs.

This explanation became untenable in 1937 when E. C. Slipher [18] obtained a blue photograph which did show the permanent surface features. This observation has been repeated and verified many times since and the evidence is clear that the Martian atmosphere is normally sufficiently obscure in short wavelengths to prevent photographic recording of the low contrast among the surface features but that occasionally the obscuration weakens to such an extent that a recognizable record of the surface can be obtained.

When the blue haze clears away, it does so on a nearly planet-wide basis. In a very few days it passes from normal opacity to relative clarity, remains clear for several days, then in another few days returns to normal opacity. Thus it is necessary to explain why and how these changes occur so rapidly and over such large areas. Of course, there are some examples of patchy clearing which do not partake of the widespread character just described.

Quantitative studies of the blue haze are difficult because so few reliable numerical data are available. Dollfus [19] has observed the polarization of *visual* light from regions where strong concentrations of clouds are recorded on the blue photographs. He finds the polarization to be different in sign from that of the surface and from that of ice crystals. Thus the polarization from these blue clouds is different from the polarization of the white clouds. This does not necessarily mean that they are composed of different materials, however, because the polarization depends upon particle size in a scattering medium. Various attempts have been made to measure the opacity or optical thickness of the blue haze. De Vaucouleurs [2, pp. 68-73] has summarized the divergent and scanty measurements, and it appears that the optical thickness is 0.1 to 0.2, which means a rather thin cloud with a transmission of approximately 85 percent.

Another fact which must be taken into account is the poor reflectivity of the Mars-atmosphere system at short wavelengths. De Vaucouleurs [20] has measured the albedo at various wavelengths using standard methods of photoelectric photometry. He found that the albedo decreases almost linearly with decreasing wavelength from about 0.25 near 7000 A to about 0.05 near 4000 A. Thereafter, the albedo remains constant down to 3300 A where the observations terminated. To this must be added the single existing rocket determination by Boggess and Dunkelman [21]. The elevation of the rocket permitted extension of the measurements into the region where the Earth's atmosphere is rather opaque. They found the surprisingly high albedo of 0.24 at 2700 A. If this unsubstantiated observation is accepted it suggests the possibility that emission by excited molecules or atoms may play a role.

A number of suggestions have been made to explain the blue haze, none of which is completely satisfactory. The most prevalent hypothesis is that the haze is an optically thin, high-level layer of H_2O-ice crystals [1, pp. 387-395; 22, 23]. Alternatively, the haze may be a layer of CO_2-ice crystals, although it seems that this violates certain requirements of physical theory and the observations [23]. Kuiper has shown how such an H_2O-ice layer, with particle radii of 0.15 to 0.20μ, could produce the known reflectivity and polarization of the blue haze. Furthermore, expected meteorological fluctuations in temperature could cause partial or complete sublimation of the ice-haze and could permit its rapid re-establishment. A difficulty lies in the fact that no one has produced a plausible mechanism to explain the *planet-wide* nature of the postulated warming and cooling.

It has also been suggested that the haze is composed of a suspension of very dark particles such as carbon black [24, 25], formed by photodissociation of CO_2 and CO. This would help to account for the low reflectivity in blue light but it can offer no explanation for the rapid blue clearing. It is easy to show that gravitational deposition of particles of appropriate size is far too slow to explain this aspect of the phenomenon. However, Öpik feels that the ice-crystal hypothesis cannot explain the low ultraviolet and blue albedos and to him this is a fatal objection.

Urey [26] has suggested that the obscuration is due to emission by such ions as CO_2^+, N_2^+, and CO^+ formed by photoexcitation and photodissociation high in the atmosphere. It remains to be shown that such a mechanism is adequate for the purpose and that it is consistent with the low apparent albedo in the blue. Furthermore, such emission is expected to occur in lines and bands rather than in a continuum. The spectrum of Mars has been examined in the blue and violet many times, but no evidence of such discontinuous emission has been reported.

It is the present author's opinion that the ice-cloud hypothesis is the most attractive of the lot, but it must be admitted that no suggestion yet made has been developed to the point where it can offer a reasonable explanation for the entire body of observational material. It is of some importance to settle this question because much of our effort to understand the vertical structure of the Martian atmosphere depends upon the ice-cloud hypothesis [1, pp. 387-95; 23]. This, in turn, is related to the still broader problem of the origin of the Solar System through estimates of the internal constitution of Mars derived from the planetary oblateness. There is a disturbing discrepancy between the oblateness determined from the perturbations of the satellites of Mars (0.0052) and that determined by optical measurement of the polar and equatorial radii (0.013). It has been suggested that the haze layer associated with the Martian tropopause is higher at the equator than at the poles, and that this can account for the excess oblateness obtained by direct optical measurement. Thus a proper explanation of the phenomenon of blue haze is essential to our understanding of the structure of the atmosphere and this, in turn, is germane to our comprehension of the planet's internal constitution. A more detailed discussion of the oblateness determinations has been given by de Vaucouleurs [2, pp. 273-283].

3. Temperature Distribution

The horizontal distribution of temperature near the base of the Martian atmosphere is rather well-known as a result of infrared radiometry. The measurements were carried out by Coblentz and Lampland [27], Pettit and Nicholson [28], and Sinton and Strong [29]. In principle, the method consists of measuring the total radiation received from a portion of the planetary surface, both reflected short-wave energy and emitted long-wave energy. Then the reflected energy alone is measured by inserting a filter which is opaque to infrared radiation. The difference is the emitted energy after correcting for instrumental effects and the long-wave transmission of the telluric atmosphere. If one assumes the planetary surface is a black-body radiator, it is then possible to calculate a temperature of the emitting surface. Technical advances permitted direct measurement of the infrared energy alone in the more recent observations of Sinton and Strong.

Several systematic errors exist if one wishes to interpret these data as the equivalent of standard meteorological temperatures. First, the emitting surface is likely not to be a black body. This means the reported temperatures are too low. Secondly, no account is taken of the absorption and emission of infrared energy by the Martian atmosphere. We may safely ignore any effects of water vapor, since so little can be present, but absorption of ground radiation and its re-emission by CO_2 will have an effect. Since it is quite likely that the atmospheric temperature mostly decreases with height on Mars as on Earth and since some of the radiation must come from CO_2 at elevation, the calculated temperatures again are an underestimate. Thirdly, the temperatures so obtained refer essentially to the surface of the ground and such temperatures are not completely representative from a meteorological point of view. Physical theory indicates, and terrestrial observation confirms, that in the lowest few meters the temperature usually decreases rapidly with elevation during the day. This is why meteorological "surface" temperatures are usually measured at an elevation of about two meters. Thus the radiometric Mars temperatures may be expected to be too high, especially those near midday. All in all, the radiometric temperatures are probably overestimates of the meteorological values, but the fact that the third systematic error listed is partly canceled by the first two suggests that one may look upon these data as representative meteorological temperatures to a first approximation, provided caution is exercised in their interpretation.

Sinton and Strong obtained drift curves across the disk of Mars along several lines perpendicular to the central meridian of the planet (i.e., from morning to afternoon through local noon). Six of these measurements were at latitudes near the equator, and Fig. 5 shows the average of these six in the form of temperature as a function of time of day. They find that the equatorial temperatures are near −60°C at 07 hr, rise to a maximum near +22°C at about 1230 hr, and fall again in the afternoon. Two aspects of their results are noteworthy. First, the 07 hr temperature gives us an upper limit on the nocturnal minimum. From the curve of Fig. 5, it is possible to estimate that the 06 hr temperature, assumed to be the nocturnal minimum, should be some −70°C to −75°C. This means a diurnal range of temperature of nearly 100°C. Although this is certainly extreme by terrestrial standards, we know that the diurnal temperature range on Earth is larger the more arid the climate and the closer the level of measurement to the surface. Since the Martian situation departs from the terrestrial one in both these directions, it is not surprising to find this large diurnal range.

Secondly, Sinton and Strong find a very brief lag of the time of maximum temperature from local noon. Their data indicate a lag of no more than ½ hr. Gifford [30] in analyzing the older results of Coblentz and Lampland found a lag of 1 to 1½ hr. Both estimates give a lag which is smaller than the terrestrial values at *2 meters above the surface.* Observations indicate, however, that the lag decreases as one approaches the solid surface. The lag in the diurnal temperature curve is a result of conduction of heat into the ground and upward eddy-transport into the atmosphere of the energy absorbed at the surface. Heat conduction into

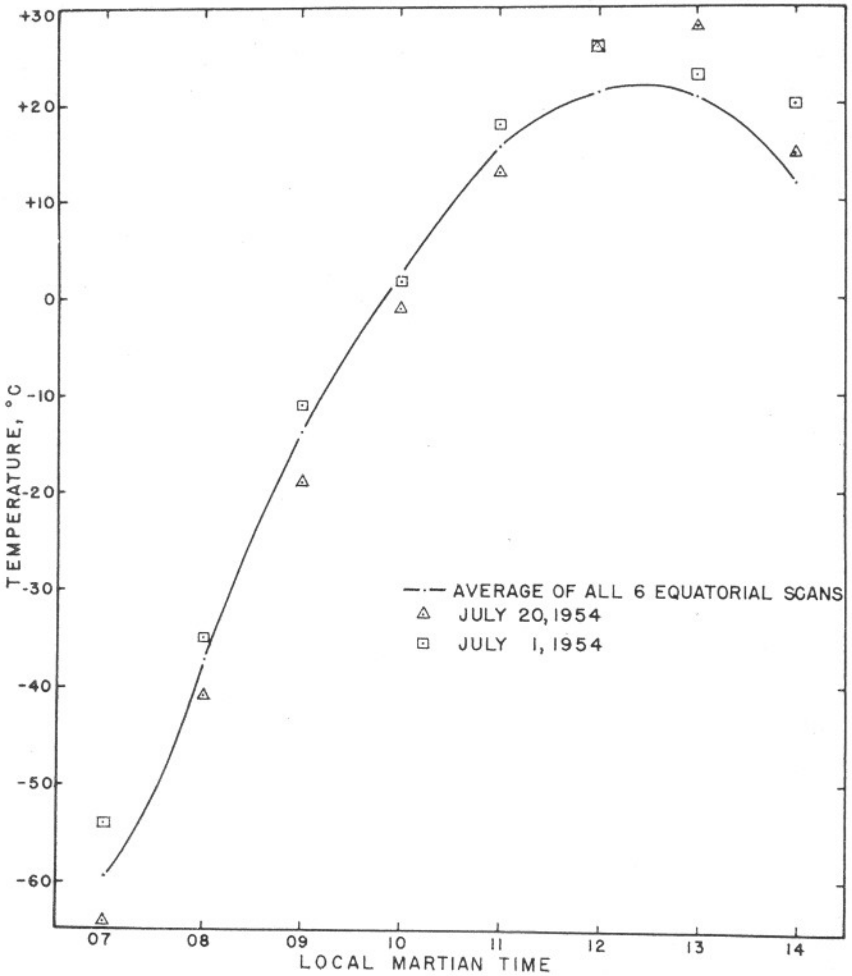

Fig. 5. Diurnal variation of temperature near the equatorial region of Mars from the data of Sinton and Strong [29]. The values for July 20 and 21 are shown to give some idea of the spread of the data and because those scans did not exhibit irregularities due to passage across alternate light and dark areas of the planet.

the surface is more amenable to mathematical analysis, and Sinton and Strong have attempted to account for their data on this basis. They find it impossible to account for the observations completely in this way, and conclude that the discrepancies are due to the atmosphere.

It is interesting to examine these radiometric data by plotting the temperatures obtained during a given Martian season at a given time of day on a map of Mars. It proves possible to draw a rational set of isotherms on such maps which delineate the general decrease of temperature poleward from the "thermal equator," the seasonal wanderings of the "thermal equator" in latitude, and the existence of longitudinal irregularities in temperature in which warm spots are associated with the dark surface markings. These matters are reported in some detail by Hess [22] and Gifford [30]. The observations of Sinton and Strong [29] indicate clearly the temperature excess of the dark areas. They find their data to be consistent with an average increase of 8°C in the pronounced dark areas compared to the lighter surroundings.

The average latitudinal variation of temperature during the various Martian seasons along the noon meridian is shown in Fig. 6, taken from

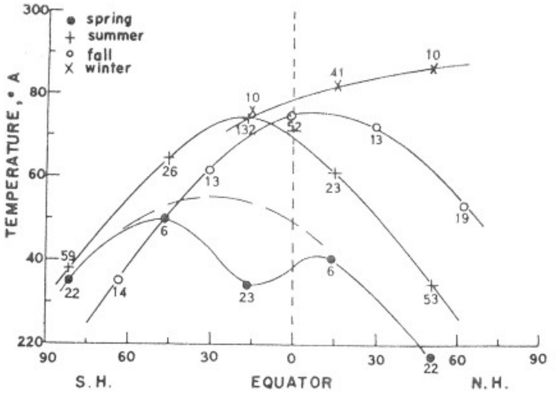

Fig. 6. Average temperatures along the noon meridian for various seasons of the Southern Hemisphere from Gifford [30]. The number of observations averaged at each point is given under the point.

Gifford [30]. These fit well with qualitative theoretical expectation, except for the dip in the curve for spring near latitude 16°S. Gifford says of this: "A check revealed, however, that most of the springtime observations corresponding to the point at 16°S had systematically chanced to fall near the Hellas region, one of the brightest areas of the Martian southern hemisphere. It has been suggested that this region is an elevated plateau, and it is a well-known location of temporary bright markings, resembling frost or low cloudiness. Thus it seems that the low temperature near the equator on the spring-curve is real, although not representative of average conditions."

These temperature data are of value in themselves, but they also have interesting implications for the general circulation of the atmosphere, as we shall see in Section I, C, 4.

Worthy of particular note are those occasional radiometric measurements which were made for an area covered by white or yellow clouds. Coblentz and Lampland [27] made a number of such observations in 1926 and Sinton and Strong [29] report one such case. The 1926 data indicate that the temperatures are about 20°C lower when clouds are present than when they are absent. Three distinct mechanisms may be involved in this matter. First, the cloud (assumed to be composed of H_2O) may have formed as a result of radiational cooling during the night combined with a temporary, relatively high, local concentration of water vapor. If the radiation from the solid surface can cool the air to its frost point, a low-level cloud will form. Water and ice clouds of sufficient thickness are excellent approaches to black bodies in the infrared, so the upper cloud surface can remain quite cold or even cool more rapidly than the adjacent solid surface of the planet. This mechanism, which is most likely to govern clouds on the morning limb, will produce low-level cloudiness analogous to terrestrial fog and low stratus.

Secondly, heating of the planetary surface during the day may cause the establishment of an adiabatic rate of decrease of temperature with height. Again, if this is combined with a temporary, local, high concentration of vapor, the vertical convection which will ensue can lift surface air and cool it at the adiabatic lapse rate. At some elevation, the frost point will be reached and a cloud will form. This mechanism, which is most likely to govern clouds near the afternoon limb, will produce high-level cloudiness comparable to terrestrial cumulus.

Thirdly, exceptional winds, perhaps combined with vertical convection which fails to produce condensation of H_2O when the atmosphere is too dry, may stir up dust clouds. Presumably, these are the yellow clouds and it is the temperature of their upper surfaces which is measured and found to be low.

In both of the last two mechanisms, the maximum temperature difference between solid surface and cloud top is limited by the value of the adiabatic lapse rate of temperature. The probable value of this constant for Mars is some 3.7°C km^{-1}, as will be shown later. Thus a temperature of the cloud top which is 20°C cooler than normal implies a total cloud height of at least 5 to 6 km for both convective water clouds and dust clouds. This, of course, is a rough calculation and individual clouds may go appreciably higher. Such a calculation cannot be performed for clouds produced by the first mechanism (low-level radiational cooling) because the convective process is not involved.

4. Atmospheric Circulation

The nature of the flow patterns of the Martian atmosphere is of interest *per se* but is also of concern in connection with efforts to improve our imperfect understanding of the general circulation of Earth's atmosphere. As we have seen, Mars has certain intriguing resemblances to Earth, the chief of which is the near equality of the two axial rotation periods. This means a nearly identical influence of the Coriolis effect in the dynamics of the two systems. The differences are largely in the direction of making the Mars system more simple. For example, there are indications that the solid surface has less relief than on Earth, there are no oceans, and the lesser frequency of clouds means that incoming and outgoing radiation should be more regular in time than on Earth. Indeed, the Martian general circulation ought to be a less complex version of the terrestrial situation and the hope exists that a good understanding of the Mars circulation is attainable and that this can be helpful in elucidating the more complex terrestrial problem.

Unfortunately, the only present way of observing winds on Mars is to follow the drift of clouds. Clear-cut and distinct clouds are rare on Mars; and, furthermore, they are short-lived. Since it is usually necessary to follow a cloud from one night to the next in order to obtain a reliable drift measurement, there are relatively few such determinations on record. Hess [22] utilized a series of careful measurements made by Lowell and Douglas in 1894 and 1896, supplemented by other data from 1924, to attempt to delineate a global flow pattern. All of these data were observed during Southern Hemisphere summer and so had some degree of homogeneity but it was recognized that firm conclusions could not be drawn from data gathered from several different years. Nevertheless, it was found that a set of schematic streamlines which bore great resemblance to terrestrial flow patterns could be fitted to these data. It cannot be said that this venture did more than dramatize the possibilities inherent in such studies, and it appears that a definitive study of the Martian general circulation will depend upon new methods of gathering the data. This is surely one of the important tasks to be assigned to space probes when they become operational.

One important general characteristic of the Martian flow pattern can be estimated from the temperature data. It is known theoretically, and confirmed by observation on Earth, that a good approximate relationship exists between the rate of change of wind speed with height and the horizontal variation of temperature across the flow. This is known as the thermal wind relationship and may be written

$$\frac{\partial u}{\partial z} = -\frac{g}{fT}\frac{\partial T}{\partial y}, \tag{1}$$

where, in this case, u = wind speed from west to east
z = height
g = acceleration of gravity
f = Coriolis parameter ($2\Omega \sin \phi$, where ϕ is latitude)
T = absolute temperature
y = distance northward.

The derivation of this formula may be found in any standard textbook of theoretical meteorology (see, for example, Hess [31]).

It is clear from this relationship that u will increase with height in a Northern Hemisphere ($f > 0$) and in a Southern Hemisphere ($f < 0$) provided temperature decreases poleward. This is the general temperature distribution on both Earth and Mars. Thus we find an increasing west wind with elevation in most of the terrestrial tropopause and we expect the same result on Mars. It is possible to calculate $\partial u/\partial z$ from Gifford's data and the results are shown in Fig. 7. Calculations were not made for low latitudes since the dynamic relationships which underlie Eq. (1) cannot be expected to hold near the equator. The expected posi-

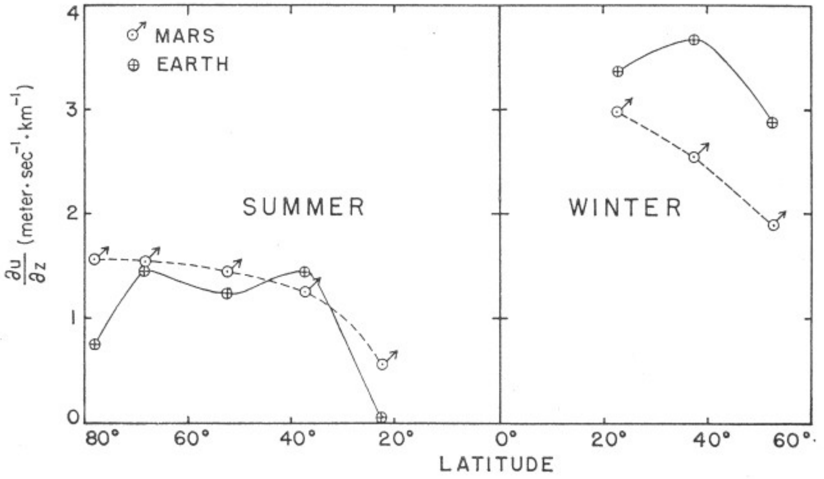

Fig. 7. Vertical shear of the west wind on Mars and Earth, calculated from surface temperature data. The Martian results are from Gifford's temperatures [30] for Southern Hemisphere summer and Northern Hemisphere winter. The terrestrial values are for mean latitudinal surface temperatures in Northern Hemisphere summer and winter.

tive values of $\partial u/\partial z$ are found at all latitudes for which the theory is valid.

Comparable results for Earth are also plotted in Fig. 7. They indicate that on Mars as on Earth the vertical wind shear is smaller in summer than in winter. Further, the summer values are quite similar on the two planets, but the Martian winter shear is clearly only some 75 percent of the average winter terrestrial rate. If one considers that the surface wind speeds are necessarily small, it follows that the wind at elevation is largely determined by the magnitude of these wind shears. Thus we conclude that at elevations of a few kilometers the wind speeds on Mars are quite comparable to those on Earth at the same height in summer, but are somewhat smaller in winter. This argument is not applicable at great heights above the surface because the latitudinal temperature gradient must be expected to vary with height. In connection with this comparison, it is interesting to note that many observed rates of motion of Martian clouds are relatively small (see de Vaucouleurs [2, p. 94]).

In short, the general circulation of any planet rotating reasonably rapidly is intimately tied to the lateral temperature distribution. Since the temperature field of Mars is rather similar in its broad aspects to that of Earth (as shown by Gifford's data [30]) one expects a similar general circulation. Even the incomplete data presently available reveal some differences in degree but the extent of the quantitative comparability is striking.

Reference should be made to a long series of remarkable experiments by Fultz and colleagues [32] in which planetary circulations are simulated by rotating vessels heated at the rim (equator) and cooled at the center (pole) with water as the working fluid. It has been possible to reproduce experimentally in this way a great many features of the observed terrestrial circulation. However, these experiments are better models of the Martian atmosphere than the terrestrial one because they do not incorporate the thermodynamic effects of evaporation and condensation, the radiative effects of clouds, and the hydrodynamic effects of mountains, all of which are minimal on Mars. The success of these experiments in reproducing the general circulation of Earth adds weight to the conclusion that Mars has a similar circulation.

One of the important circulation differences to be expected stems from the longer duration of the seasons on Mars and the greater eccentricity of its orbit. Both factors tend to increase the thermal contrast between the hemispheres in winter and summer. This means that a greater seasonal interhemispheric exchange of air must take place on Mars. Indeed, this is strongly suggested by the observation that each polar cap diminishes to a small size in its summer while the other simultaneously enlarges appreciably. Since the storage capacity of the atmosphere for water vapor is relatively small, it is necessary that the atmosphere transport this H_2O from one hemisphere to the other. This implies a vigorous interhemispheric flow, although it is difficult to make good numerical estimates.

II. Theoretical Considerations

A. The Vertical Variation of Temperature, Pressure, and Density

1. TEMPERATURE

In a thermally active atmosphere under the influence of gravity, heat may be transferred vertically by radiative or by convective processes. Conduction may be ignored in such gaseous envelopes. Convective transfer becomes more important as the rate of decrease of temperature with elevation becomes larger until, at a limiting value of this lapse rate, vigorous vertical mixing occurs uninhibited by any static stability, and convection becomes the dominant transfer mechanism for heat. In an atmosphere of essentially constant composition this limiting lapse rate of temperature has the value, $\Gamma = g/c_p$, where Γ is called the adiabatic lapse rate, g is the acceleration of gravity, and c_p is the mean value of the specific heat capacity at constant pressure. If, for some reason, the lapse rate should exceed Γ then convection will transfer heat upward so rapidly that the temperature profile will be restored to the slope Γ. Thus, the adiabatic lapse rate is a limiting value which cannot be exceeded in the free atmosphere except temporarily and locally.

Since on Mars g is known to be 377 cm $\sec^{-2}$, it remains only to determine c_p in order to be able to calculate Γ. If one accepts the idea of a predominately nitrogen atmosphere then c_p cannot be far from the value for pure nitrogen, namely, 0.248 cal gm^{-1} $°\mathrm{C}^{-1}$. Indeed, if one calculates the mean value of c_p from the suggested composition of Table III, one gets 0.240 cal gm^{-1} $°\mathrm{C}^{-1}$, which happens to be the mean value for Earth's atmosphere. There is no strong reason to reject this coincidence, and it proves to be very convenient since in thermodynamic calculations one can take advantage of the existing tabulations of functions involving the value of c_p for terrestrial air.

With this choice we find

$$-\frac{\partial T}{\partial z} = \Gamma = 3.77°\mathrm{C\ km}^{-1} \tag{2}$$

This is to be contrasted to the value on Earth which is $\Gamma = 9.76°\mathrm{C\ km}^{-1}$

and to the mean lapse rate of temperature in the terrestrial troposphere which is about 6°C km^{-1}. Thus it is clear that temperature decreases less rapidly with height on Mars than on Earth.

2. Pressure and Density

In an atmosphere having the adiabatic lapse rate of temperature there is a well-known relationship between pressure and temperature, called Poisson's equation:

$$\frac{T}{T_0} = \left(\frac{p}{p_0}\right)^{R/c_p} \tag{3}$$

where T is the temperature at the pressure p, T_0 is the temperature at some reference pressure p_0 (usually taken to be the surface value), and R is the gas constant for the atmosphere involved. Since T is a known function of height determinable from Eq. (2), it is possible to determine p as a function of height from Eq. (3). Furthermore, the result will be the most rapid decrease of pressure with elevation that is possible since the largest possible lapse rate of temperature is assumed. We shall assume the exponent R/c_p has the terrestrial value for reasons like those given above in connection with Γ and so use existing tabulations of results from Eq. (3).

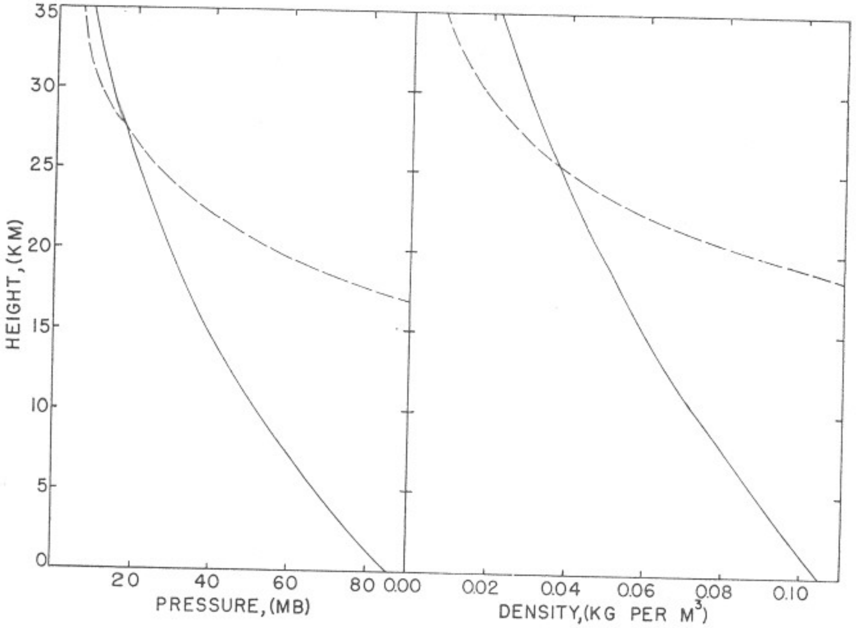

FIG. 8. The variation of pressure (left) and density (right) with height in the atmospheres of Mars (solid lines) and Earth (dashed lines). The Martian curves are for an adiabatic lapse rate of temperature assuming $T_0 = +10°\mathrm{C}$, $p_0 = 85$ mb. The terrestrial data are for the NACA Standard Atmosphere (see List [33]).

The Martian dependence of pressure on height is shown in the left side of Fig. 8 compared with mean terrestrial values. Note that the two curves cross at about 26 km; above that elevation the pressure is greater on Mars than on Earth. Since we now have pressure and temperature at each elevation, it is possible to calculate the densities. These are presented on the right side of Fig. 8, again compared to the mean terrestrial values. These curves cross at about 25 km and above this height the Martian atmosphere is more dense. It is obvious from Eq. (3) that the level for equality of pressure is too high since the choice of the fastest rate of decrease of temperature with height means the fastest possible decrease of pressure also. It may be shown without difficulty that the level for equality of density is also too high on the same grounds. These levels will also be affected by the choice of surface temperature and pressure on Mars. However, it seems reasonable to conclude that Martian pressure and density exceed the terrestrial values at the same elevation above a height of 20 to 30 km. This is a result which will be useful in planning the entry of instrument packages into the atmosphere of Mars.

B. The Martian Stratosphere

The reasons for the existence of a nearly isothermal stratosphere on Earth are complex and imperfectly understood. A first approach to an understanding of this phenomenon was given by Emden [34] who calculated an approximation to the vertical distribution of temperature on the assumption of purely radiative transfer of energy. He found that in the lower layers the temperature decreased rapidly with elevation but that in upper layers the value of the lapse rate decreased and became nearly zero above about 10 km. Thus it is suggested that the stratosphere should be thought of as a region of radiative equilibrium.

In the lower layers of Emden's model the radiative equilibrium lapse rate exceeds the adiabatic rate. Consequently convection will take place and the troposphere cannot be governed by radiative transfer of heat but must be dominated by convective transport. The elevation of the base of the stratosphere will then be dictated by the height to which the convective regime penetrates. This is not presently susceptible to theoretical treatment.

As useful as these ideas may be for a preliminary orientation, it must be recognized that many other physical factors must play a role and that the details may be quite different from simple theoretical predictions. For example, long ago Humphries suggested an extremely easy way to calculate the temperature of the stratosphere. If this layer is in radiative equilibrium, it must radiate energy upward and downward at a total rate equal to the rate of receipt of infrared energy from below. Thus, since it gains from one direction but radiates in two:

$$2T_s^4 = T_t^4 \tag{4}$$

where T_s is the stratospheric temperature and T_t is the mean effective radiative temperature of the troposphere below. The Stefan-Boltzmann constant and the emissivity appear originally on both sides of Eq. (4) but they cancel.

This simple formula gives a good over-all result for Earth's stratosphere. The known mean temperature at the surface of the Earth is 285°K and the mean lapse rate in the troposphere is some 6°C km^{-1}. Thus if the 5-km level is adopted as the middle troposphere the mean temperature to be used is $285° - 30° = 255°$. Then Eq. (4) requires $T_s = 214°\text{K}$ which is close to the mean observed temperature of the stratosphere. However, the concept is clearly too simple, for it implies that the tropical stratosphere should be warmer than the arctic stratosphere because the troposphere is warmer in the tropics than in the arctic. In fact, precisely the opposite is true and the tropical stratosphere is appreciably cooler than the arctic one.

If we apply this approach to Mars, having due regard to the rough nature of the concept, we may proceed as follows. Let the mean lapse rate of temperature in the troposphere be γ. Then

$$T_s = T_{0p} - \gamma H \tag{5}$$

where T_{0p} is the mean surface temperature over the entire planet and H is the mean height of the tropopause. In equatorial regions at the time of maximum temperature, T_{0e}, we assume the lapse rate has the adiabatic value, Γ. Then

$$T_s = T_{0e} - \Gamma H \tag{6}$$

Now the mean temperature of the troposphere is approximately $T_t = T_{0p} - \frac{1}{2}H\ \gamma$, and inserting the expression for H from Eq. (6) we get

$$T_t = T_{0p} - \frac{\gamma}{2\Gamma}(T_{0e} - T_s) \tag{7}$$

Next we insert this value of T_t in Eq. (4) and solve for T_s. The result is

$$T_s = \frac{T_{0p} - (\gamma/2\Gamma)T_{0e}}{2^{1/4} - (\gamma/2\Gamma)} \tag{8}$$

For T_{0p} we shall use Kuiper's estimate [1, p. 388] of 217°K and for T_{0e} we shall adopt 283°K. Then T_s can be calculated for several values of γ/Γ. The results are given in Table IV along with calculated heights of the tropopause.

TABLE IV. THEORETICAL ESTIMATES OF THE TEMPERATURE AND HEIGHT OF THE MARTIAN TROPOPAUSE AS A FUNCTION OF THE MEAN LAPSE RATE OF TEMPERATURE IN THE ATMOSPHERE

γ/Γ	T_s (°K)	H (km)
1.0	110	46
0.8	131	40
0.6	144	37
0.4	162	32
0.2	173	29
0.0	182	27

This procedure is an elaboration of the one presented by Kuiper [1, p. 388] who assumed that $T_t = T_{0p}$. This is mathematically equivalent to assuming $\gamma = 0$ and so our value of the stratospheric temperature for $\gamma = 0$ is the same as Kuiper's, 182°K. However, with this generalized procedure it is possible to examine the implied stratospheric temperatures for other values of the mean lapse rate. It is clearly wrong to assume that $\gamma/\Gamma = 1$, because this implies an adiabatic lapse rate at night which, in turn, means that the stratosphere must cool nocturnally as fast as the planetary surface. Since the surface can radiate nearly as a black body but the upper atmosphere can only radiate in bands of CO_2, this is clearly to be ruled out. Likewise, we cannot accept $\gamma/\Gamma = 0$ because this means an isothermal troposphere. From Fig. 5 we can estimate that the surface temperature varies diurnally by about 90°K near the equator. Taking this and the expected decrease of lapse rate toward the poles into account, it is possible to estimate that γ/Γ should be about 0.6. This means a value of T_s of 140° to 150°K and a height of the base of the stratosphere of 30 to 40 km.

The calculations above are consistent with an earlier calculation by Hess [22] based upon a completely different physical principle. He showed that for comparable investments of thermal energy on Mars and Earth, the convective regime should extend some 4.5 times higher on Mars. Taking 10 km for the depth of the terrestrial troposphere this means a depth of roughly 45 km on Mars, a result which is quite comparable to the estimate obtained here.

These results are, however, in sharp disagreement with those obtained by Kuiper [1, pp. 388, 421-422]. He obtained the high value $T_s = 182°K$, because he assumed the stratosphere to be exchanging radiation with the warm surface of the planet rather than with the cooler troposphere as was assumed here. However, his assumption will give an incorrect result for Earth and can hardly be expected to be valid for Mars. Also he estimates the height of the tropopause at 9 km in one calculation and 16 km in another. The procedure was to assume an adiabatic temperature curve in the troposphere passing through $T_s = 182°K$ and through estimated mean surface temperatures of 217°K and 245°K in the two cases. These tropopause heights are too low for two reasons. First, the adopted stratospheric temperature is too high and second, one cannot assume that the lapse rate is adiabatic when the surface temperature is equal to the low values of a global and diurnal mean (217°K) or a global mean of maximum temperatures (245°K). Establishment of an adiabatic lapse rate is to be expected only near the equator at midday, at which time the surface temperatures are closer to 283°K.

C. The Blue Haze

It is desirable to examine quantitatively the implications of various theories of the blue haze to see if there is consistency with known facts and with independent theoretical results. So far this has been done only for the hypothesis that the haze is composed of crystals of H_2O-ice or CO_2-ice. The other hypotheses in which it is assumed that the haze (1) consists of dark dust or soot particles or (2) is a result of emission by excited molecules have not, by and large, been subjected to such quantitative examination. With respect to the dust or soot suggestion, it is difficult to see how a suspension sufficiently fine to produce appreciable scattering could clear away (by gravitational settling) in a few days [23]. As to the emission suggestion, one expects the radiation to be in recognizable lines and bands, rather than in a continuum. Such a discontinuous nature of the spectrum of Mars has never been observed, to the present author's knowledge. Furthermore, one should try to show that the conditions necessary to produce enough emission to explain the phenomenon are possible on Mars.

An argument for feasibility of the ice-crystal hypothesis has been given by Hess [23] and goes as follows. Kuiper [1, pp. 391-393] has shown that the reflectivity of the blue haze and the polarization of the reflected light imply a mean particle radius of 0.15 to 0.20μ. Furthermore, the optical depth of the haze layer appears to be 0.1 to 0.2 according to de Vaucouleur's [2, pp. 68-73] summary of the pertinent data. Thus we are required to deal with an optically thin layer composed of particles of the indicated size. Next, in order to explain the occasional clearing of the haze we must assume, under this hypothesis, sublimation of the particles as a result of a rise in temperature at the level of the haze layer. Since it is not reasonable to assume increases of tens of degrees, we find that we must produce a quantitative theory of the mechanism of the formation of the haze which gives results falling within two kinds of loose bounds: (1) the haze must give sufficient obscuration but must still be optically thin, and (2) the temperature at the haze level must be low enough to produce condensation but only a few degrees rise in temperature should suffice to sublime the haze.

In order to proceed quantitatively it is necessary to know a surface temperature, the lapse-rate of temperature, and the H_2O or CO_2 content of the atmosphere at all levels. There is little difficulty in specifying an appropriate surface temperature from the radiometric data, but the only situation in which we can be reasonably confident of the lapse rate is over equatorial regions near midday. Then it is highly likely that an adiabatic lapse rate is established. Thus the temperature at all levels in the troposphere can be specified. Furthermore, vertical convection is vigorous in such an atmosphere, so we may assume a constant mixing ratio for the condensable substance (mixing ratio is mass of vapor per unit mass of atmosphere). Thus, in this atmosphere alone can we specify temperature and vapor content at all levels.

The procedure is then to assume an adiabatic decrease of temperature up to a certain level and isothermal conditions above. A specific value of mixing ratio will then yield condensation for a layer of calculable geometric thickness whenever the temperature falls below the saturation temperature for a given mixing ratio, as shown in Fig. 9. Calculations may be performed for various values of mixing ratio, each of which corresponds to a certain frost point at the surface of the planet. The geometric thickness will vary with the height of the tropopause and the surface frost point, and for each geometrical thickness it is possible to calculate the optical thickness for spherical particles of radius 0.2μ from the Mie theory of scattering. Thus, in the end, it is possible to represent curves of surface frost point as a function of geometrical and optical thicknesses and to see whether acceptable combinations of these parameters can exist.

The first noteworthy result obtained was that for the amount of CO_2 present on Mars, a cloud only 1 km thick would have an optical thickness of 50. Now such a geometric thickness is too low because a fluctuation of only 3 to 4°C would suffice to evaporate the cloud completely. This is so small a variation by terrestrial standards that we expect it to occur frequently, and such a cloud should constantly evaporate and then re-form, contrary to observations. Moreover, even for such a geometrically thin cloud the optical thickness is two orders of magnitude too high. Thus, we conclude that for this method of formation the haze cannot be composed of CO_2-crystals.

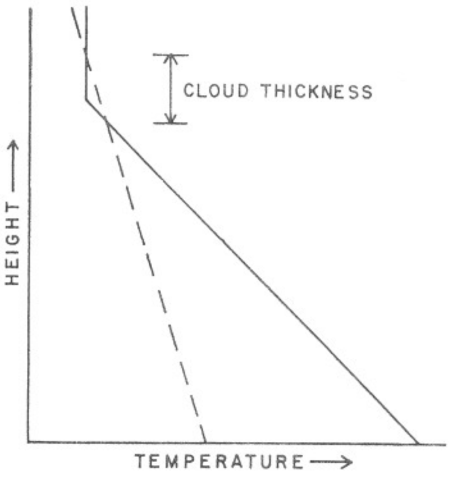

FIG. 9. Schematic representation of temperature as a function of height with an adiabatic lapse rate in the troposphere and isothermal conditions in the stratosphere (solid line). The saturation temperature curve for a fixed value of mixing ratio is given by the dashed line.

The results for H_2O-ice are shown in Fig. 10. We shall require that the optical thickness be about 0.2 and that the geometric thickness be approximately 3 km. This last choice is made because it then would take a warming of about 10°C to evaporate the haze. Such a warming could occur occasionally but would not be very common, just as blue clearing is not very common. These choices imply a surface frost point of about −90°C. This is lower than has been suggested by some authors, but there is no observational evidence to indicate that an equatorial surface frost point of −90°C must be ruled out. Furthermore, in the real Martian atmosphere there may well be some decrease of mixing ratio with height even in the presence of vertical convection. Therefore a surface frost point of, say, −80°C is not inconsistent with this theory.

Considering the roughness of some of the theoretical estimates, this result is quite consistent with the evaluation of the height of the tropopause given in Section II, B. There we found 30 to 40 km, and here a surface frost point of −90°C means a cloud base at about 29 km,

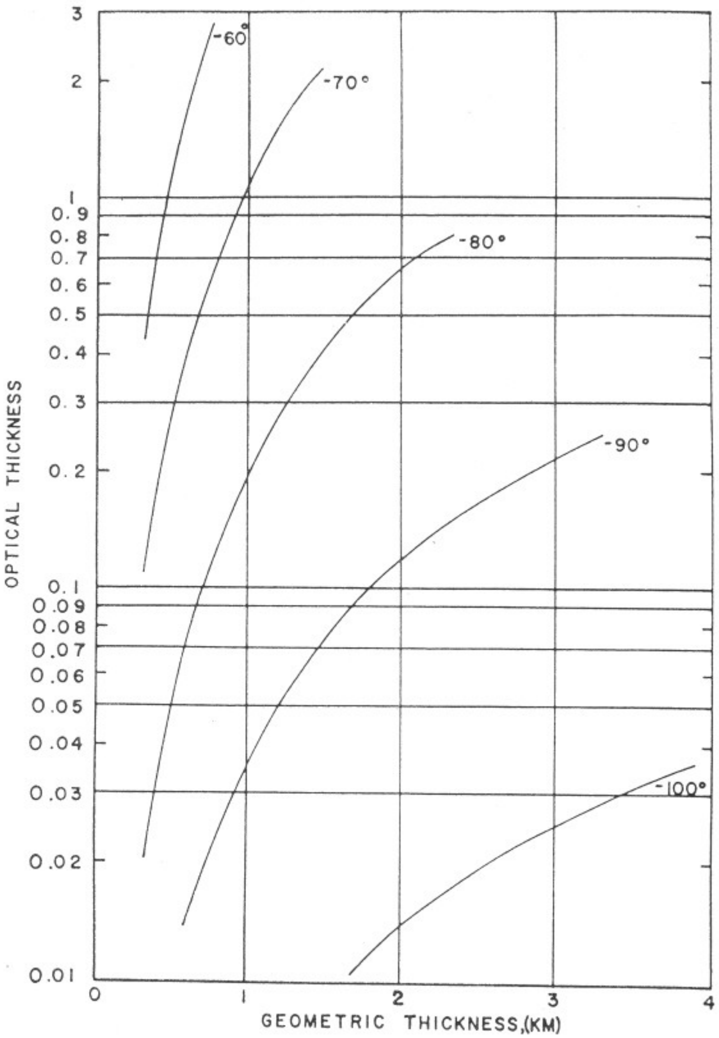

FIG. 10. Surface frost point for H_2O in a convectively mixed atmosphere as a function of optical and geometric thickness of the cloud layer at the top of the convective region.

which is very nearly the tropopause height. This result is also consistent with the long-standing failure to identify water vapor spectrographically because a surface frost point of −90°C means a tropospheric content equivalent to 2×10^{-3}mm of liquid water. Such an amount is quite undetectable by present means.

We may conclude, for a convective mechanism of formation of the blue haze, that the haze cannot be composed of solid CO_2 but can be composed of H_2O-ice.

As is to be expected, there are still other facts to which any explanation must conform. Since the blue haze frequently clears away on a virtually planet-wide scale, and since we have postulated a modest increase of temperature at the tropopause level as the reason for this clearing, we are confronted with the problem of a mechanism which could produce this planet-wide warming. No definitive statement can now be made on this matter, yet a possibility may be mentioned. There is some evidence that ice crystals decrease in reflectivity far in the ultraviolet. Furthermore, this is a region of the spectrum where we expect considerable multiple scattering. Thus a substantial fraction of the energy in this region may be absorbed by the haze. Now if the solar output in the ultraviolet changes from time to time this could result in occasional and temporary warmings of the blue haze layer which could result in planet-wide clearing of the haze. This, of course, is almost a pure speculation but it does perhaps show that answers to the remaining problems may be found and that one should not reject a hypothesis simply because it does not as yet explain everything.

III. A Space-Observation Program[1]

A. General Considerations

It is now highly probable that during the next decade space probes will be used to gather information on Mars and other planets. This program will undoubtedly use more and more sophisticated vehicles which will carry heavier and heavier payloads. Ideally, three principles should govern such an expensive research program. First, it is necessary to integrate the space research program with other means of investigation because it would be wasteful to use precious payload in a space probe to make observations which could be made as well or better by less expensive means. It cannot be said that the resources of ground-based astronomy have been exhausted and that no more can be learned of the planets in this way. Furthermore, the development of techniques for using telescopes carried to great heights by balloons has progressed rapidly in the past few years. It is therefore possible to overcome some of the drawbacks of ground-based astronomy, primarily the "seeing" problem, without actually going into space. Secondly, the program should be geared to the rate of growth of technological feasibility in rocketry. For example, there is little point in giving high priority to a program of observations from a satellite orbiting Mars until we have learned how to place a vehicle reasonably close to the planet. It is not unlikely that the first rocket launched towards Mars will miss the target by a margin of one or more planetary radii and that the most we can hope for initially is a short period in which to observe Mars from a closer vantage point than was previously possible. Thirdly, we should not let our long-range thinking boggle at *any* planetary investigation of scientific importance no matter how complex the instrumentation and procedures will have to be. The rockets of the next ten to twenty years will be capable of launching payloads which are staggering by present standards so it is possible to contemplate large and complex programs.

Although prediction of the sequence of events in so rapidly developing a field as space science is a hazardous process, it seems reasonable to set down the following probable time-sequence for investigations of Mars:

(1) Accelerated ground-based and balloon-borne observations, which can be performed virtually immediately.

(2) Observations from an orbiting astronomical telescope system; one such system is now under development by the Grumman Aircraft Engineering Co. for the National Aeronautics and Space Administration.

(3) Observations from a space vehicle passing near the planet. Such a probe, which neither orbits Mars nor penetrates the atmosphere, is the most likely first effort in the vicinity of the planet and is sometimes referred to as a "near fly-by." The first such effort will likely occur somewhat after balloon-borne and orbiting-telescope observations have begun, but it is likely to overlap these programs eventually.

(4) A sufficiently close fly-by to permit the launching of instrument packages which can penetrate the atmosphere and fall to the surface of Mars. The first such packages may experience moderately hard landings which will destroy the instruments, but it should be possible to achieve soft landings relatively quickly so the instruments can continue to operate. Indeed, this may be accomplished in the first attempt.

(5) A satellite orbiting Mars.

(6) A full-fledged landing on Mars of the entire space probe carrying a greater complement of instruments than is possible in the small ejection packages referred to above.

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[1] The author makes no claim that the formulations and ideas presented in this section are completely original with him. Many are the result of formal and informal discussions with scientific colleagues vitally concerned with space research. This section represents the author's current view of the approach which should be taken, and it rests upon his evaluation of the ideas of many people, of whom the author is only one.

Each of these probable means of gathering data will be discussed in more detail below.

B. Observations from Earth

This classification includes items (1) and (2) in Section A above. With respect to observations from Earth's surface, it must be said that the field of planetary astronomy has been somewhat neglected for many years. Relatively few astronomers have devoted part of their time to such problems and our present knowledge is due to their efforts. With the resurgence of interest in the field which now seems to be occurring one hopes that more scientists will devote time to planetary studies and that financial support for their efforts will be forthcoming.

The most important advantage of observations from Earth's vicinity is the possibility of maintaining nearly continuous observations over periods of months. Many of the physical problems on which we need information require such continuity of observations. For example, determination of the atmospheric circulation requires a sequence of observations of drifting clouds, and better quantitative knowledge of the seasonal changes in the dark areas requires an extended series of data. Radiometric infrared observations for temperature data also share this characteristic.

To do things of this sort from the ground will require more than sporadic effort on the part of a few institutions and men. It will require a global chain of cooperating observatories, the coordination of techniques and procedures, and the assignment of more observing time at major telescopes than is now the case.

The chief advantage of observation from a balloon platform is that the telescope is carried above the major turbulent layers of our atmosphere which produce a decrease in resolution and contrast of the image. It has already been demonstrated, through photography of the Sun, that a significant improvement in image quality can be so achieved and preparations are under way to apply the technique to the planets. It has been estimated that a balloon-borne 36-in. telescope should produce a resolution of 0.1 sec of arc, or a several-fold improvement over observation from the ground. Such high resolution photographs should reveal a great deal about the fine structure of the dark maria, the polar caps, and the canals.

Some degree of continuity of observation can be obtained using balloon flights. For example, in a minimal system of three balloon-telescope units, one could be flying while a second is being prepared for flight and the third is having repairs of landing damage or is in a stand-by status. As soon as the first begins to descend, the second can be launched, and so on.

A second advantage of the balloon technique is the greater infrared transparency which is achieved at heights near 80,000 ft. One is then above virtually all the water vapor in our atmosphere and the infrared region is blocked only by the carbon dioxide bands, with the result that excellent transparency out to nearly 15μ is obtained. This is of the essence in a spectrographic search for water vapor on Mars, but will be useful also in extending the range of photometric information in the region 4-8μ which is blocked by absorption by terrestrial water vapor.

Until now we have said nothing about an ionosphere on Mars because virtually nothing is known. However, there is reason to believe that we will soon have ground-based radars sufficiently powerful to yield good signal-to-noise ratios in a planetary echo and, at appropriate wavelengths, this could yield information about the existence of an ionosphere and even the integrated ion density in a Martian ionosphere. For example, a radar beam operating at short wavelength would penetrate an ionosphere and be reflected by the solid surface. But a radar operating at longer wavelength would be reflected by the ionosphere and the echo would arrive back at the detector with a different time delay than the beam reflected from the solid surface. Such measurements would be most useful in establishing the primary facts and suggesting the nature of more detailed experiments to be performed from space probes.

A partial list of useful observations which can be performed from Earth follows:

(1) Long-term detailed photometry of surface features.

(2) Time-lapse motion picture photography in blue light to reveal rapid variations in the blue haze.

(3) Additional infrared radiometric observations.

(4) Radar observations to reveal surface roughness and presence of an ionosphere.

(5) High resolution photography.

(6) Spectrographic and photospectrometric measurements, primarily in the infrared.

(7) Laboratory studies of suspected atmospheric constituents at low pressure and temperature.

C. Observations from Earth Satellites

Development has already begun on an orbiting astronomical telescope system which will make possible observations from a platform outside Earth's atmosphere (see, for example, Meinel [35]). Even though large reflectors are contemplated, it is not likely that direct photography of Mars from such a space telescope will provide very much improvement in resolution over photographs from a balloon-borne telescope. This is because the balloon can rise above the tropopause layer in which much of the seeing fluctuation occurs. The satellite telescope will still be many millions of miles away from Mars and it will remain impossible to obtain the very high linear resolution needed to further our knowledge of the nature of the surface.

The most probable area of contribution arises from the opening of the ultraviolet spectrum which occurs when Earth's atmosphere is no longer in the path. This will permit positive identification of nitrogen if it is indeed present on Mars. Moreover, it should be possible to determine quantitatively the amount of N_2. It is important that such a determination be made, if possible, before we send space probes to the planet because many of the theoretical estimates which will determine design characteristics of entry vehicles and of instruments are based upon loose estimates of the amount of nitrogen present.

Opening of the ultraviolet will also permit a spectrographic search for other possible atmospheric constituents and will make possible measurements of reflectivity and polarization in this presently inaccessible region. Thus, the three problems most suitable for a terrestrial orbiting telescope are:

(1) Measurements of the amount of nitrogen.
(2) A search for new atmospheric constituents.
(3) Reflectivity and polarization measurements.

D. Observations from Space Probes

Three distinct phases of capability may be discerned here: (1) a near fly-by providing temporary opportunity for observation at close range, (2) instrumented packages dropped into the atmosphere, and (3) a space probe orbiting Mars to provide continuous observation at close range.

A transient passage near the planet could provide very high resolution data from the surface by telemetry of television images. These should provide an improvement over photographs from Earth, whether ground or balloon based, by several orders of magnitude despite the necessary use of much smaller optical apertures. Advantage should be taken of the opportunity to utilize much greater phase angles than are available from Earth; high resolution photographs at large phase angles should reveal much about surface relief on Mars and the height of clouds, just as such data for the surface of the Moon are determined. Needless to say, such images will resolve many long-standing questions about the canals, oases, and maria, and will lead to a far greater understanding of these famous features.

There is no theoretical reason why we could not do detailed infrared and ultraviolet spectrometry, polarization measurements, oblateness determinations, magnetic field measurements, etc. from a near fly-by. No doubt, payload considerations will limit the number and complexity of these experiments on any given probe, but when we consider the rapid strides under way in rocketry and the fact that suitable opportunities to probe near Mars come at intervals of two years, it seems likely that each successive probe will carry significantly more instrumentation and will be appreciably more versatile than its predecessor.

It is technologically feasible, even from the first fly-by, to launch a complex package of instruments into the atmosphere and down to the surface. The payload will experience appreciable heating during its high-speed entry into the upper atmosphere but definite techniques are available to protect the payload during this brief period of thermal stress. Thereafter, the package can be lowered more gently under a parachute or a balloon so that the instruments may continue to operate after landing. Undoubtedly, this entry package will be insufficiently powered to transmit data back to Earth; it will be necessary to relay information to the larger parent probe and then to Earth.

Such an initial attempt to penetrate the atmosphere of Mars should surely be made capable of measuring temperature and pressure during the descent. If in addition to these data, a few absolute height determinations can be made (perhaps using the principle of the radio altimeter), the data can be used to calculate the mean molecular weight of the atmosphere via the equation of hydrostatic balance. Be this as it may, the prospect exists of obtaining an observed curve of temperature versus pressure or height to which theories discussed earlier may be compared. The importance of such knowledge has been pointed out already.

In addition to measuring meteorological parameters during the descent, it may be possible to add a television system which will transmit images of the surface below. These will be of higher resolution than those taken by the parent probe by several orders of magnitude and would be incomparably more detailed than anything we have ever had from Earth. The implications of such photographs for the questions of plant life and the geology of the planet are surely immense but are not predictable. The feasibility of this observation depends only upon the payload which is practicable.

After arrival at the surface the atmospheric probe should be engineered to continue transmission of temperature and pressure data at intervals of at least one-half hour. In this way directly measured portions of the diurnal temperature and pressure curves may be obtained. It is important that such observations continue through as much of a rotation of Mars as possible. However, it is clear that radio transmission from the surface to the parent probe will be line-of-sight. Therefore, the combination of rotation of the planet and continued motion of the parent probe will inevitably cause interruptions of transmission. Clearly, there are optimal combinations of a path for the parent probe in relation to the rotation of the planet and an impact point of the surface probe which will prolong this radio contact. These optimum characteristics should be built into the system if other practical considerations will permit.

It is conceivable that a simple system can be devised to make a crude chemical analysis of the surface matter for transmission to Earth. Such a system deserves high priority because of the important biological and geochemical implications of the results. Indeed, it may be possible to gather particulate matter from the atmosphere during descent and to use the same chemical analysis system to determine the composition of the blue haze. This measurement could eliminate either the ice-crystal or the carbon-dust hypothesis of the blue haze.

It is probably pointless to continue to elaborate further observations from such an atmospheric and surface probe because the possibilities are enormous but are limited by practical technological factors which the author is not in a position to evaluate. The program outlined above is ambitious and is probably the maximum that can be hoped for in an initial attempt.

The time will come, however, when we can hope to place a large probe in orbit around the planet. This will provide continuity of observations for the first time in a space planetary program. One of the most interesting possibilities is to use such a satellite to monitor the reports of a number of surface probes. From a meteorological point of view, we should look forward to the possibility of placing a number of instrument packages on the surface which will make synchronous measurements of pressure, temperature, wind speed, and wind direction. The basic techniques for doing these things are well established; the technical problems will be in determining the position and orientation (for wind direction) of the instruments. Such a network will then increase our knowledge of the low-level characteristics of the general atmospheric circulation at a rapid rate.

Finally, one can envision the possibility of placing in the Martian atmosphere a number of constant-pressure or constant-density balloons. These have been used in our atmosphere, where they float at a given pressure (or density) and successive measurements of position give the upper-level winds. This experiment on Mars will supplement the surface meteorological data and will afford a description of the upper general circulation. There is no question in the writer's mind that such data will afford theoretical meteorologists an incomparable opportunity to confront their understanding of planetary circulations with pertinent data which are unobtainable in any other way. Appreciable advances in this difficult and important field are bound to follow.

We shall not attempt at this time to suggest what observations should be made when an entire space vehicle is landed on the planet, nor what the role of manned missions to the surface of Mars should be. The wealth of new data which will be supplied by earlier less ambitious programs will indicate what are the outstanding problems that can be solved only by such means.

E. Conclusion

The era of exploration of the planets, at the threshold of which we stand, is one of enormous intellectual interest. For the first time, man will be able to supplement the data produced by astronomical means with information gathered by bringing his instruments into direct physical contact with planetary matter. No further justification for such a program need be offered than man's desire to satisfy his curiosity and the vital intellectual need we have to answer the significant questions that existing knowledge raises. However, even after recognizing this fundamental truth, we can see the possibility of achieving results which go beyond it and which may be of practical benefit to man. We have offered as an example the contribution to our understanding of general atmospheric circulations that can come from observing the circulation on Mars. Since man lives at the bottom of a planetary atmosphere and depends upon it and its behavior for his life and welfare, it is hard to exaggerate the practical benefits that can come from increased understanding of such media.

Investigation of life on Mars may also have a vast impact of a practical as well as an intellectual nature. It is impossible to predict the consequences to biology of detailed study of a life form which has evolved and lives in an environment so different from our own. Yet it is likewise impossible to set limits on the effect such observations may well have. We find ourselves faced with the necessity of pursuing these investigations, regardless of their difficulty and expense, for our very nature demands it and our practical self-interest will most likely be well-served in the process.

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