# A METEOROLOGICAL APPROACH TO THE QUESTION OF WATER VAPOR ON MARS AND THE MASS OF THE MARTIAN ATMOSPHERE[1]

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## SOME OF THE KNOWN FACTS CONCERNING WATER VAPOR ON MARS

It is well known that the Martian atmosphere contains little, if any, water vapor. The chief indication of the presence of some water is the existence of the white polar caps which disappear almost completely in Martian summer and reform in winter. It has been suggested that the substance forming the caps is frozen carbon dioxide rather than ice. This implies that the temperature of the dissipating cap is close to the sublimation point of $CO_2$. Carbon dioxide sublimes at about —80° C at atmospheric pressure and at still lower temperatures for lower pressures. The Martian atmosphere is thought to be more rare than ours and on that account, as well as because of Mars's lesser gravity, to exert a smaller pressure than does earth's atmosphere. If the mass of gas above a given area on Mars were one-half that on earth, $CO_2$ would sublime at —92° C; for a mass only one-fifth that on earth, the sublimation point is —105° C. Consequently the $CO_2$ hypothesis requires a summer polar temperature of about —100° C, while the ice hypothesis would require that temperature to be 0° C.

In view of this large difference it would seem that radiometric measurements of the temperature of the dissipating cap could decide conclusively in favor of one substance or the other. Such temperatures obtained in 1924[2] range from +22° C to —108° C, the average being —38° C. The lower temperatures, which were observed mainly close to opposition, are verified by

[1] Contribution No. 2 from the Project on Planetary Atmospheres, a joint research project between Lowell Observatory and the U.S. Weather Bureau.

[2] W. W. Coblentz, *A.N.*, **224**, 362, 1925.

Pettit and Nicholson,[3] who obtained an average south polar temperature of —70° C. The low values were attributed by Coblentz to the interference of an overhanging mantle of water vapor or cloud, but the higher values are also open to objection on the basis that the radiometric receiver covered not only the cap, but the surrounding warmer regions as well. Thus no clear decision can be made on the basis of the 1924 data. In 1926[4] both of the above complicating factors were eliminated to a great extent, in that apparently no veil of cloud interfered with the observations, and receivers were used that occupied less than one-tenth of the diameter of the disk of Mars. The results for such small receivers ranged from —28° C to +27° C, the average temperature of the south cap being —7° C. This is so far from the sublimation point of $CO_2$ as to make it extremely difficult to conceive of the polar caps as being composed of carbon dioxide.

It seems fairly safe, from this evidence alone, to assume that some water is present on the surface and in the atmosphere of Mars. The clouds which have been seen and photographed many times are further evidence of the presence of water vapor. It is possible, however, that these clouds may not be due to water or ice droplets but are in part due to dust raised by the wind from the desert-like Martian surface.

In contradiction to the visual and photographic indications of water on Mars, we have the essentially negative results of careful spectroscopic studies with large telescopes and high dispersion. Such spectroscopic measurements are seriously hindered by the fact that the large water-vapor absorptions of our atmosphere completely block the weak absorptions that may exist in the Martian spectrum. The usual way of partially circumventing this difficulty is to obtain a Martian spectrogram at a time when the relative velocity of earth and Mars is great and depend upon the Doppler effect to move the possible Martian water-vapor bands out from behind the strong telluric bands. This approach was first suggested by Lowell,[5] and has been applied at the

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[3] *Pop. Astr.*, **32**, 601, 1924.

[4] W. W. Coblentz and C. O. Lampland, *Bur. Standards Sci. Papers*, **22**, 237, 1927.

[5] *Lowell Obs. Bull.*, No. 17, 1905.

Lowell Observatory and elsewhere with varying results. The very earliest attempts failed to detect water vapor on Mars,[6] but this was attributable to lack of sensitive plates and to insufficiently developed technique. Subsequently some positive results were obtained, among which are those of W. S. Adams and C. E. St. John,[7] who found 0.44 mm of precipitable water in the Martian atmosphere near the center of the disk. Attempts to repeat the measurement at the same observatory using greater dispersion and a more suitable portion of the spectrum have led to negative results and to the conclusion that Mars must have less than 5 percent of the water vapor present in the atmosphere of the earth.[8]

The spectroscopic picture in itself is therefore somewhat confused, since both positive and negative results have been reported. This may well be due to the fact that any water vapor on Mars must undergo a seasonal variation and is surely not evenly distributed in latitude. Thus the observer who is fortunate enough to set his slit on a moist region is more likely to report the presence of water vapor. Nevertheless, if we accept the latest and most delicate determination, we are faced with a contradiction of one sort of evidence (visual and radiometric) by another type of evidence (spectroscopic). The question then arises quite naturally: Can we reconcile these two points of view by a quantitative consideration of the known meteorological behavior of water vapor? In other words, is it possible that the quantity of water sufficient to produce the clouds seen on Mars is usually so small as to defy spectroscopic detection?

### THE POSSIBLE TYPES OF MARTIAN CLOUDS

In answering these questions we must first consider some of the types of clouds that may be possible on Mars. Among these are dust clouds. It cannot be denied that the surface conditions of Mars, in so far as they are known, are conducive to the formation of clouds of dust. There are at least two arguments, how-

[6] V. M. Slipher, *Lowell Obs. Bull.*, No. 17, 1905.

[7] *Ap. J.*, **63**, 133, 1926.

[8] W. S. Adams, *Annual Report of the Director of Mt. Wilson Obs.*, p. 12, 1940.

ever, that can be raised which point to a lesser importance of dust clouds than has hitherto been supposed. First, the wind velocities on Mars are so low (on the average about 10 miles per hour[9]) that dust storms covering sufficient horizontal area to become visible, and extending as high as many of the clouds that have been observed, are unlikely. The wind speeds measured are determined from the motion of the clouds themselves and so represent the presumed dust-raising winds.[10] A necessary condition for terrestrial dust storms of any considerable magnitude is a horizontal wind of at least 30 miles per hour.[11] The Martian winds associated with clouds fall far short of this, and indeed, E. C. Slipher reports that he has never observed a Martian cloud moving faster than 22 miles per hour.

Second, a dust cloud covering thousands of square miles, as do many of the Martian clouds, must be expected to remain in the atmosphere for several days. It is our experience on earth that so extensive a dust pall could not be raised and then settle to the surface in the space of a day. However, only the exceptional Martian cloud is visible on two consecutive nights. While one must exercise caution in applying empirical terrestrial criteria, such as the above, directly to another planet, these arguments do supply one with some reason for doubting that visible Martian clouds are exclusively composed of dust.

When water is taken as the cloud-producing substance, at least two types of clouds immediately present themselves as possible. One is a low-lying cloud, similar to fog or low stratus, which may form on the night side of the planet due to the high rate of loss of heat by radiation. We may feel certain that the temperature on Mars falls more rapidly as night approaches than it does on earth because Mars lacks sufficient water vapor to provide a good "greenhouse" effect.[12] Radiometric measures

[9] E. C. Slipher, *Publ. A.S.P.*, **39**, 214, 1927.

[10] One must recognize the possibility that a large cloud may not move with the wind velocity if it is forming on one edge and simultaneously dissolving on the opposite edge. Thus the above statement is not necessarily true but is probably correct to a sufficient degree of approximation.

[11] H. Byers, *Synoptic and Aeronautical Meteorology*, p. 264, 1937.

[12] Kuiper at McDonald Observatory has recently detected the ab-

show that the temperature decrease from the center of the planet to the limb is quite great (at least 30° C) thus substantiating this view. Observations show a relatively frequent cloudiness at the limb of the planet and most, if not all, of these clouds are presumably of the type described. They could not be accounted for by dust, since then no preference for the limb should be exhibited.

The second possible type of aqueous cloud is a high-level phenomenon with its base at some considerable elevation above the surface of the planet. This is analogous to our towering cumulus. They should form at noon and in the afternoon, owing to heating of the ground by insolation and the establishment of a rapid decrease of temperature with height. They are presumably the clouds observed near the center of the disk and the clouds of great height that have been observed on the sunset terminator from time to time.

### SOME CONSEQUENCES OF THE EXISTENCE OF LOW-LEVEL CLOUDS

We shall now make the assumption that the nocturnal temperature does drop sufficiently to cause the frequent formation of perceptible fog and attempt to determine the amount of water vapor in the Martian air that is consistent with this and the observed limb temperatures.

Radiometric measurements by Coblentz and Lampland[4] indicate that the temperature of the sunrise limb of Mars is —20° C when no limb clouds are present and —35° C when clouds are present. This last value is presumably the temperature of the upper surface of the clouds. The figure when clouds are absent is undoubtedly somewhat higher than the dew point by virtue of the very lack of clouds. Consequently the aqueous saturation vapor pressure corresponding to —20° C should represent an upper limit for the amount of water vapor present on Mars which can account for the sunrise limb clouds. This vapor pressure is 1.0 mb. In order to convert this to the amount of pre-

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sorption bands of $CO_2$ in the spectrum of Mars, and estimates the amount to be double that in our atmosphere. This will provide some greenhouse effect but cannot represent as great a barrier to outgoing radiation as does water vapor.

cipitable water, the usual measure of moisture in planetary work, we employ the equation of state:

$$\varrho_w = \frac{m_w e}{RT},$$

where $\varrho_w$ is the density of water vapor, $e$ is the vapor pressure, $m_w$ is the molecular weight of water, $R$ the universal gas constant, and $T$ the absolute temperature. Now the product of $\varrho_w$ and the height of the layer possessing this average density of water vapor gives the number of grams of precipitable water per $cm^2$, and this is numerically equal to the water content of the atmosphere expressed in cubic centimeters. Thus the only quantity which we must estimate is the height of the moisture-bearing stratum.

We are aware that this stratum must be a relatively thin one hugging the ground because the phenomena of condensation into clouds, frost, or snow caps occur almost exclusively close to the ground. Thus there is a preponderance of processes which concentrate the water vapor in the very lowest portion of the atmosphere. Confirmation of this view exists in earth's atmosphere where it is well known that the water-vapor content decreases rapidly with elevation.

Based upon these considerations, let us assume that the major water-bearing layer is 0.5 km thick. This yields a Martian water-vapor content of about 0.4 mm. It should be remembered that this is an upper limit, since the temperature measurement upon which it is based is undoubtedly higher than the dew point. In other words, *a total water-vapor content of 0.4 mm, or less, in the Martian atmosphere will suffice to explain the sunrise limb clouds as aqueous condensation products due to radiational cooling.*

Let us now determine how this compares with the results of spectroscopic measurement. Adams and Dunham[13] found that the water content of Mars's air must be less than 5 percent of that in our atmosphere. The amount in our atmosphere was taken to be that above Mount Wilson where the observations were

[13] Adams, *loc. cit.*

made. This was approximately 7 mm.[14] Thus the spectroscopists find that Mars must have less than about 0.35 mm of water.

We have therefore shown on the basis of reasonable meteorological calculations that the amount of water vapor sufficient to produce nocturnal clouds and observed sunrise limb clouds on Mars is at or below the limit of spectroscopic measurement. This, then, is one of the pieces of evidence for consistency of the hypothesis of the existence of clouds of water substance with the negative results from the spectroscope.

## SOME OF THE CONSEQUENCES OF THE EXISTENCE OF HIGH-LEVEL CONVECTIVE CLOUDS

If we make the assumption that convective clouds exist at relatively high levels, it will be possible to obtain another independent meteorological estimate of the water-vapor content of Mars's atmosphere, and also to compute the approximate pressure at the bottom of the Martian atmosphere.

In order to accomplish these aims we recognize that the lapse rate of temperature between the ground and the base of such a convective cloud must be at or close to the dry adiabatic lapse rate, $\Gamma = g/c_p$. Here $\Gamma$ is the dry adiabatic lapse rate, $g$ the acceleration of gravity on Mars, and $c_p$ the specific heat at constant pressure of the Martian atmosphere. Since the acceleration of gravity has been computed, we can determine the dry adiabatic lapse rate if we know $c_p$. This depends upon the constitution of the air of Mars, about which little of a positive nature is known. Mars cannot have retained any of the lighter gases such as hydrogen and helium, owing to its low gravity. Also the amounts of oxygen and water vapor present are known to be so small that they may be neglected for the purpose of estimating $c_p$. Carbon dioxide is known to be present to a slightly greater extent than in our air, that is, in rather small quantities. Nitrogen is not susceptible of spectroscopic detection but probably is present in considerable amounts, since it is heavy enough to be retained even by the low Martian gravity and is sufficiently inert to resist chemical combination into the crust of the planet. The other

[14] Adams, private communication, 1948.

elementary gases are sufficiently rare in nature that they may probably be neglected, and the various other gaseous compounds would, in general, reveal themselves spectroscopically if they were present to any important extent.

Fortunately all the gases whose presence is known or suspected have values of $c_p$ that are closely the same as that of air. This can be seen from Table I.

TABLE I

Molecular Weights and Specific Heats at Constant Pressure of Certain Gases. (One Atmosphere and 0° C).

| Substance | $m$ $\frac{\text{gm}}{\text{mol}}$ | $c_p$ $\frac{\text{Joules}}{\text{gm deg}}$ | $mc_p$ $\frac{\text{Joules}}{\text{mol deg}}$ |
|---|---|---|---|
| Air | 29.0 | 1.00 | 29.0 |
| $N_2$ | 28.0 | 1.04 | 29.2 |
| $O_2$ | 32.0 | 0.91 | 29.2 |
| $CO_2$ | 44.0 | 0.83 | 36.3 |

We shall make no serious error, therefore, if we assume a value of $c_p$ for Mars equal to that for our own atmosphere. The value of $\Gamma$ is then about 3.7° C per km on Mars. It may be well to point out that this constitutes a rate of decrease of temperature with height which cannot be exceeded for long without causing sufficient convection and vertical mixing to restore the lapse rate to 3.7° C/km. This is a restriction which astronomers have not always heeded in discussing Martian phenomena.

Knowing the lapse rate of temperature below the base of the cloud and having an estimate of the surface temperature from radiometric measurements, we may now deduce the temperature at the base of the convective cloud as a function of its height. But this is the temperature of saturation and so we will have found the saturation water-vapor pressure (a function of temperature only) at the base of the cloud. This may be reduced to the unsaturated vapor pressure at the ground by making use of the fact that the water-vapor pressure in this adiabatic column below the cloud must closely obey Poisson's equation:

$$\left(\frac{e_b}{e_o}\right)^{\frac{R}{mc_p}} = \frac{T_b}{T_o}$$

where $e$ is the vapor pressure, $R$ is the universal gas constant, $m$ is the molecular weight, $T$ is the absolute temperature, and the subscript $b$ identifies quantities at the base of the cloud while the subscript $o$ identifies quantities at the ground. It can be seen from Table I that the variation of $m$ among the reasonably possible constituents of Mars's atmosphere will not matter much since the relatively constant product of $m$ and $c_p$ appears in Poisson's law. Thus again we cannot be much in error if we proceed on the assumption that the exponent $\frac{R}{mc_p}$ has the same value as in our air.

In this way the vapor pressure at the Martian surface is determined as a function of the height of the base of an aqueous convective cloud. This relationship is shown graphically in Figure 1. In order to estimate the vapor pressure at the surface of Mars we must determine the base height of such clouds. This is a

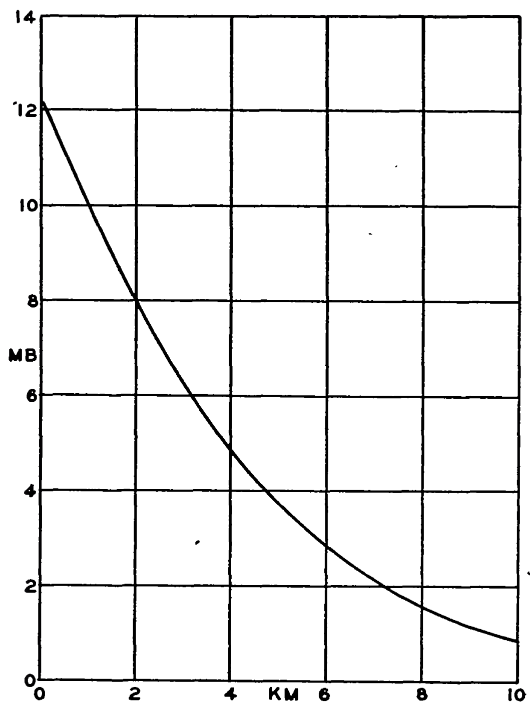


FIG. 1.—Aqueous vapor pressure (millibars) at the surface of Mars as a function of the height (km) of the base of a convective cloud. The dry adiabatic lapse rate was taken to be 3.72° C/km, the surface temperature to be +10° C, and the values of $m$ and $c_p$ to be the same as for terrestrial air.

quantity that is not ordinarily observed. However, there have been several occasions upon which a cloud observed on the terminator of Mars was found to be completely detached from the underlying surface.[15] Of the observations that Antoniadi reports, the lowest cloud base, giving the highest vapor pressure, was 8 km above the surface. From Figure 1 this implies a surface vapor pressure of about 1.5 mb. This is in excellent agreement with the value obtained from temperature observations at the sunrise limb. This figure represents the vapor pressure in a layer of air close to the ground which suffices to produce a cloud when solar heating is sufficiently intense to produce an adiabatic lapse rate over great elevations. The result of this calculation is again an upper limit for the amount of water in Mars's atmosphere. Under the same assumption as before as to the depth before convection of the moisture-bearing stratum, we find 0.6 mm of water. In other words, *a total water-vapor content of 0.6 mm or less will suffice to explain the clouds at the center of the disk and the high sunset limb clouds as aqueous condensation products due to convection.* Since such clouds are rare, the actual mean water content should be considerably less than this.

Thus we find once again that, on the basis of reasonable meteorological calculations, the water-vapor content of Mars's atmosphere is at or less than the order of magnitude of the limit of spectroscopic measurement.

## THE MASS OF THE MARTIAN ATMOSPHERE

Having already taken advantage of the fact that $\Gamma$, the dry adiabatic lapse rate, is a constant whose value we can specify with some confidence, let us now consider the lapse rate of temperature within a convective cloud. This is the moist adiabatic lapse rate $\Gamma'$, which is in general different from $\Gamma$ and is not a constant. We may write a simple expression for the temperature at the top of a convective cloud:

$$T_t = T_o - \Gamma z_b - \Gamma' (z_t - z_b)$$

[15] Antoniadi, *La Planète Mars*, p. 48, 1930.

Here $z_b$ is the height of the base of the cloud and $z_t$ is the height of the top. It is shown in textbooks on theoretical meteorology[16] that $\Gamma'$ is given by the following function of pressure and temperature, to a good degree of approximation:

$$\Gamma' = g \frac{1 + \frac{m_w e}{RT}\frac{L}{P}}{c_p + \frac{m_w}{m_d}\frac{de}{dt}\frac{L}{P}}.$$

Here $m_d$ is the molecular weight of dry air, $L$ the latent heat of condensation or sublimation, and $P$ the pressure. All the other symbols have their previously assigned meanings. We shall make the simplification of assuming $\Gamma'$ to be constant within the cloud, its value being given by the above expression when the mean values within the cloud of $P$, $T$, $e$, and $de/dT$ are used. We then solve the equation for the mean pressure inside the cloud:

$$P = -m_w L \left[ \frac{\frac{1}{m_d}\frac{de}{dT}(\Delta T - \Gamma z_b) - \frac{e}{RT} g(z_t - z_b)}{c_p(\Delta T - \Gamma z_b) - g(z_t - z_b)} \right],$$

where $\Delta T$ is the temperature difference between the ground and the top of the cloud, $T_o - T_t$. Since $e$ and $de/dT$ within the cloud are functions of temperature only, we have an expression for the average pressure within the cloud as a function of the temperature at the cloud top, the temperature at the ground, the height of the base, and the height of the top of the cloud. Various constants also appear but these are either known or can be determined with some confidence. Thus if we can measure or estimate these four variables, we can compute the mean pressure. It is a relatively simple matter to reduce this to the surface pressure by means of the hydrostatic equation. The result is that we can obtain an estimate of the mass of the Martian atmosphere (its pressure) merely by observation of its high-level convective clouds.

Unfortunately two of these quantities are not accurately

[16] B. Haurwitz, *Dynamic Meteorology*, p. 55, 1941.

known. These are the temperature at the tops of such clouds and the height of the bases. The other two quantities, the surface temperature and the height of the tops, are somewhat more easily observable and so values for them are known more accurately. In no case have all four of the needed quantities been measured for the same cloud. It will therefore be necessary to use average or typical values. We shall use 15 km for the height of the tops of convective clouds, since this is closely the average value for projections on Mars's terminator in the equatorial regions.[17] For the surface temperature we shall take 10° C, which seems like a representative figure for the region from the center of the disk to the sunset limb near the equator. With these two values fixed, Figure 2 gives the surface pressure on Mars as a function of the other two variables.

The value of the remaining pair of quantities that should be used are, of course, open to question. As to the height of the base, we may use the previously mentioned observation of 8 km given by Antoniadi. For the temperature at the top of the cloud, it would seem reasonable to use the figure —30° C, which is given by Coblentz and Lampland as a representative value near the sunset limb when that area is clouded. With these values, Figure 2 gives a surface pressure of about 80 mb. Owing to the reduced gravity, our atmosphere would exert a pressure of only 380 mb if it were located on Mars. Thus the theory indicates a Martian atmosphere having some 20 percent of the mass of our gaseous envelope. This is equivalent to an amount of air which is one-third less than that above Mt. Everest.

It cannot be emphasized too strongly that this result depends entirely upon the numerical values assumed for the four variables and upon the approximations in the theory. The best result could be obtained if all four of the needed quantities could be measured for the same cloud. Since this has never been done, nor is such a happy situation likely to occur in the near future, we must content ourselves with using nonsynchronous measurements which appear to be representative. The effect of some of the approximations in the underlying theory can be easily determined

[17] Lowell, *Annals of the Lowell Obs.*, 2 (Part II), 494, 1900.

by applying these ideas to a convective cloud on earth, thereby computing the surface pressure. When this is compared with the known pressure, we will have some idea of the precision of the method.

The U.S. Weather Bureau Thunderstorm Project has kindly supplied us with the measurements made by radiosonde ascents and by radar on a convective cloud near Wilmington, Ohio, on August 25, 1947. This cloud had a base about 4500 feet above the ground, its top about 36,000 feet above the ground, the surface

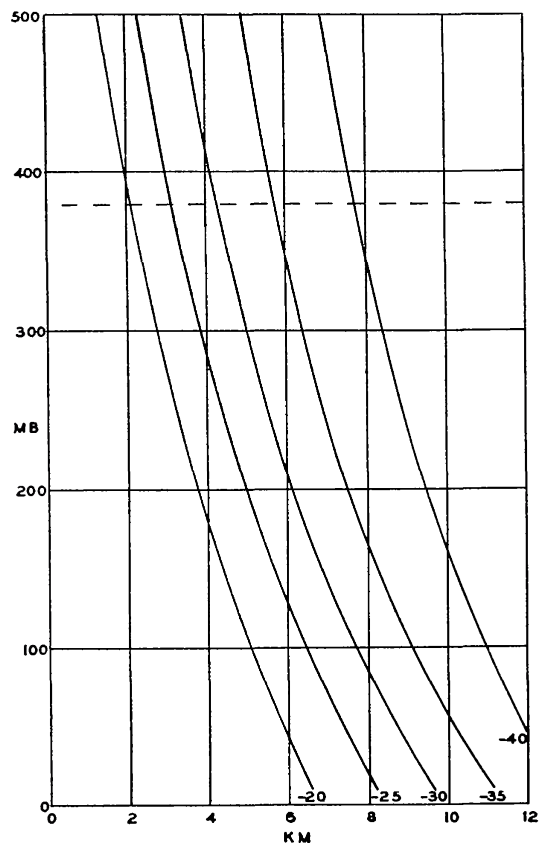


FIG. 2.—Atmospheric pressure in millibars at the surface of Mars as a function of the height in kilometers of the base of an aqueous convective cloud and the temperature at the top of the cloud (curved lines) in degrees centigrade. The cloud is assumed to be 15 km high and the surface temperature is assumed to be +10° C. The dashed line gives the Martian pressure of an atmosphere equal in mass to that of the earth.

temperature was +33.2° C, and the temperature at the top was —35.7° C. These values and the constants for the earth's atmosphere give a computed pressure of 1090 mb at the surface, where the actual measured pressure was 978 mb. The error was, therefore, about 10 percent of the computed pressure. For the purpose of obtaining the order of magnitude of the pressure on Mars, this is by far sufficient accuracy. Thus the major difficulty in applying these ideas lies in the fact that the four required quantities are known rather poorly. It seems probable, however, that these quantities may be better determined in the future since we now know which are the important variables, and when an appropriate Martian cloud presents itself, a special effort can be exerted to make the required measurements.

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