THE ATMOSPHERE OF MARS

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ABSTRACT

The appearance of a planet depends on the selective absorption and scattering of its atmosphere. Using the known values of the visual and photographic albedos, it is possible to evaluate the maximum quantity of atmosphere which Mars possesses. *The amount per unit surface* is not greater than one-fifth that above the earth. Under the lesser gravity, *the corresponding pressure* will be less than 5 cm of mercury—equivalent to the pressure in the terrestrial atmosphere at a height of 18 km.

The foregoing amount of atmosphere is insufficient to account for the appearance of *Wright's photographs* (*Publications of the Astronomical Society of the Pacific*, **36**, 234, 1924), which showed no detail in the ultra-violet, but strong contrast in the red. This is probably a characteristic of the material which composes the planet.

The Martian polar caps are not an atmospheric but a surface phenomenon. Their relative prominence in the two pictures is due mainly to the difference in visual and photographic albedos.

The greenish color of Uranus and Neptune are due to the absorption, by their atmospheres, of the red end of their spectra.

The recent opposition of Mars has shown the importance of photography in interpreting physical conditions on the planets. Photographs taken in different colors reveal a wide range of contrast, presumably due to the character of the surface and atmosphere.[1]

Up to this time the influence of the atmosphere on the appearance of the planet has been considered only in a qualitative way. Believing that a quantitative discussion of the matter would be of value, I have undertaken to determine the contribution of a planet's atmosphere to the total light from the planet.

THEORY

Let the total energy, between a small range of wave-lengths, incident on the planet's atmosphere be denoted by I. Of this a fraction x is scattered back to space and a fraction x' is absorbed. Thus Ix is reflected from the atmosphere and $I(1-x-x')$ will reach the planet. Similarly, if J denotes the amount of energy which goes out from the planet, the amount sent back by the atmosphere will be Jx and that which gets out to space $J(1-x-x')$. Therefore the total

[1] Wright, *Publications of the Astronomical Society of the Pacific*, **36**, 239, 1924; Hubble, *ibid.*, Plate XXIII.

light received by the planet is $I(1-x-x')+Jx$. Let y represent the albedo of the surface for the light in question, then

$$J=yJx+yI(1-x-x')\ ,$$

or

$$J=\frac{y}{1-xy}(1-x-x')I\ .$$

That part which escapes from the planet to space

$$=J(1-x-x')=\frac{y}{1-xy}(1-x-x')^2I\ .$$

When we add to this the contribution by the atmosphere, the total light reflected is

$$fI=Ix+\frac{y(1-x-x')^2}{1-xy}I$$

$$f=x+\frac{y(1-x-x')^2}{1-xy}\ ,$$

where f, the fraction of the incident energy eventually returned to space, is evidently the planet's albedo for light of the particular color under consideration.

Expanding and collecting terms,

$$f=\frac{x+y-2xy}{1-xy}-x'y\frac{2-2x-x'}{1-xy}\ . \tag{1}$$

All the quantities f, x, x', and y are less than one and greater than zero, and are functions of the wave-length of the light under consideration. If f is constant for all wave-lengths, the character of the sunlight would be unaltered by reflection. If f increases with wave-length, the planet will appear red; if it decreases, blue. Equation (1) may be written in the form

$$f=y+\frac{x(1-y)}{1-xy}-\frac{x'y(2-2x-x')}{1-xy}\ . \tag{2}$$

For the simplest case, assume simple Rayleigh scattering, x inversely proportional to the fourth power of the wave-length, and y constant. If there is no absorption present, equation (2) shows that f will increase with x. This is a formal proof of the somewhat obvious fact that a "gray"[1] planet with a selectively scattering atmosphere will always appear blue. For the planet to appear blue with absorption only ($x=0$) requires increased absorption for the red, and vice versa.

APPLICATION TO MARS

In applying the foregoing to Mars, the assumption that $x'=0$, both for that planet and the earth, is probably near the truth.

Let $y=af$, where a is a constant which represents the ratio of the albedo of the surface to the total albedo of the planet.
From equation (1)

$$x=\frac{f-y}{1-(2-f)y} . \tag{3}$$

Combining,

$$x=\frac{f(1-a)}{1-2af+af^2} . \tag{4}$$

In the following, the subscripts p and v are used to denote the specific values of x, f, and a for photographic and visual light, respectively. The effective wave-length for the former is approximately 4400 A, and for the latter 5600 A. For Rayleigh scattering, x is inversely proportional to the fourth power of the wave-length, therefore

$$x_p=3x_v . \tag{5}$$

Using this relation in connection with equation (4), the following relation is derived:

$$\frac{f_p(1-a_p)}{1-2a_pf_p+a_pf_p^2}=3\,\frac{f_v(1-a_v)}{1-2a_vf_v+a_vf_v^2} . \tag{6}$$

For Mars, the albedos f_p and f_v are equal to 0.09 and 0.15, respectively.[2] Substituting the numerical values, equation (6) reduces to

$$\frac{0.09(1-a_p)}{1-0.17a_p}=\frac{0.45(1-a_v)}{1-0.28a_v} .$$

Solving,

$$a_v=0.85+\frac{0.63a_p}{4.72-0.57a_p} ,$$

or $a_v>0.85$.

[1] y=constant.

[2] Russell, *Astrophysical Journal*, **43**, 173, 1916.

From equation (3), $x_v < 0.03$ and, using equation (5), $x_p < 0.09$ Table I gives various possible values of x and y computed from equations (3) and (5). It is necessary to evaluate x, the total scattering over a hemisphere in terms of the fraction scattered perpendicularly from the zenith (unit air-mass).

TABLE I

x_v	0.03	0.02	0.01
x_p	.09	.06	.03
y_v	.12	.13	.14
y_p	0.00	0.03	0.06

Figure 1 represents the appearance of the planet, the inner and outer circles marking the boundaries of the surface and atmosphere, respectively. Let r be the radius of the planet. The solar rays are incident from above, the shading denoting the night hemisphere. The distance CB represents unit air-mass, which scatters the fraction Q of the incident energy. The amount of scattering over any other distance, DA, will be approximately proportional to the length of the path. The angle of incidence of the solar rays upon the planet will be ϕ. Thus the reflecting power of any point of the atmospheric surface is $Q/\cos\phi$, i.e., constant on concentric circles perpendicular to the direction of the incoming solar energy. Consider the planet's surface. A circular element of area of constant albedo about OC, as an axis, is $2\pi r^2 \sin\phi d\phi$. Since the surface is inclined to the direction of the beam, the intensity of the incident radiation per unit surface is $l\cos\phi$ where l is the intensity perpendicularly incident on unit area. Therefore, the total amount of energy falling on the strip is

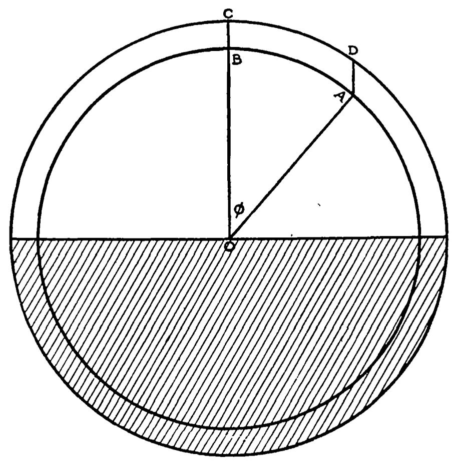

FIG. 1

$$2\pi l r^2 \sin\phi \cos\phi d\phi .$$

Integrating between 0 and $\pi/2$, the total energy falling on the planet is πlr^2.

The light reflected from the strip will be $2\pi lr^2 Q \sin \phi d\phi$, which integrated gives, from the entire planet, $2\pi lr^2 Q$. Taking the ratio of the reflected to incident energy, the effective albedo of the atmosphere $x = 2Q$.

This is the extreme case. Actually it will be less than $2Q$. Schuster[1] has shown that

$$k = \frac{1}{1 + \frac{st}{2}} , \tag{7}$$

where k is the fraction of light from the incident beam which is transmitted through a scattering atmosphere of thickness t. The scattering coefficient is s. Since half the scattered light goes upward and half downward, for air-mass 1,

$$\frac{st}{2} = Q ,$$

and for any other air-mass

$$\frac{st}{2} = \frac{Q}{\cos \phi} .$$

The fraction reflected back to space equals

$$1 - k = \frac{\frac{Q}{\cos \phi}}{1 + \frac{Q}{\cos \phi}} ,$$

which represents the effective albedo at any point.

As before, the light falling on the strip is

$$2\pi lr^2 \sin \phi \cos \phi d\phi .$$

That reflected is

$$\frac{2\pi lr^2 Q \sin \phi}{1 + \frac{Q}{\cos \phi}} d\phi ,$$

[1] *Astrophysical Journal*, **21**, 6, 1905.

or the total reflected from the planet's entire hemisphere is

$$2\pi l r^2 Q \int_0^{\frac{\pi}{2}} \frac{\sin\phi \cos\phi}{Q+\cos\phi}\, d\phi = 2\pi l r^2 Q[1+Q \log Q - Q \log(1+Q)] \, .$$

The total incident light is $\pi l r^2$.

The ratio of these two quantities gives the atmospheric contribution to the total albedo

$$x = 2Q[1+Q \log Q - Q \log(1+Q)] \, . \tag{8}$$

Table II gives x for different values of Q.

TABLE II

$Q=$	0.2	0.1	0.05	0.025	0.02	0.01
$x=$	0.26	0.15	0.085	0.045	0.038	0.019

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From these and other considerations an upper limit to the quantity of atmosphere on Mars is estimated. Above Mount Wilson, for unit air-mass, 0.20 of the energy at λ 4400 is scattered out of the direct beam of the sun.[1] Of this, 0.10 goes upward and 0.10 downward. Therefore $Q_e=0.10$, the subscript referring to the earth. Referring to Table I, it is shown that $y=0$ if $x_p=0.09$. This would require a surface entirely black for short waves, a condition not found in nature. Wilsing and Scheiner[2] have measured many rocks spectrophotometrically. While they have not observed the reddest rocks known, in no case is the photographic reflectivity less than half the visual. If, as an extreme, it is assumed that the average rocks on Mars are as red as those found in the region of the Arizona "painted desert," it is possible that the ratio of visual to photographic albedo might approach three, that is,

$$y_v = 3y_p \, . \tag{9}$$

Table I shows that this will occur only when $x_p=0.045$. From Table II, Q, for this value of x, equals 0.025, just one-fourth of Q_e. If the scattering were directly proportional to the masses of the atmos-

[1] *Smithsonian Physical Tables* (7th rev. ed.), p. 418.

[2] *Publikationen des Astrophysikalischen Observatoriums zu Potsdam*, **20**, No. 61, 1909; *ibid.*, **24**, No. 77, 1921.

pheres, the quantity of the atmosphere per unit area above the surface of Mars would be one-fourth that above Mount Wilson, or one-fifth that above sea-level, since the pressure at the higher altitude is four-fifths the sea-level pressure.

More accurately, applying the Schuster approximation, equation (7), the fraction scattered for the earth by unit air-mass ($t=1$) is

$$Q_e=1-k=\frac{\frac{s}{2}}{1+\frac{s}{2}}\ ,$$

or

$$\frac{s}{2}=\frac{Q_e}{1-Q_e}=0.11\ .$$

The same equation may be applied to Mars, to determine t, the thickness of its atmosphere per unit area in terms of the earth's as unity, assuming the scattering coefficient, $s/2$, to be approximately the same for both.

$$Q=\frac{\frac{s}{2}t}{1+\frac{s}{2}t}\ ,$$

therefore,

$$t=\frac{Q}{\frac{s}{2}(1-Q)}=0.23\ .$$

Multiplying by $\frac{4}{5}$ as before to reduce to sea-level, it is found that the quantity of atmosphere per unit area on Mars cannot be greater than 0.18 that of the earth. The Schuster approximation thus introduces no great improvement in determining the atmospheric thickness on Mars.

The pressure at the surface of the planet varies as the product of the quantity of material and the surface gravity. For Mars the later factor equals 0.38. The total pressure, as measured by an aneroid barometer, cannot be greater than 5–6 cm of mercury. This is equivalent to the pressure in the terrestrial atmosphere at a height of 17–18 km (11 mi.) above the surface of the earth.

This is a maximum value for the atmospheric pressure on Mars. It may be less, according to the degree of redness assumed for the planet's surface. If $x=0.02$, $Q=0.01$, giving for $\frac{4}{5}t$ the value 0.07, corresponding to a pressure of only 2 cm of mercury.

Without additional assumptions, the minimum quantity of atmosphere cannot be evaluated. Even the maximum quantity here deduced is insufficient to account entirely for the variations in Wright's observations. His photographs show the blue almost devoid of detail, which effect he considers atmospheric.[1]

The foregoing discussion shows that the photographic brightness of the image of the planet's surface must at least be equal to that of the atmosphere (i.e., $x_p \gtreqless y_p$). The observed effect is quite in accord with theory. The spectrophotometric measures of Wilsing and Scheiner[2] show that many rocks, while having widely different values of the albedos in the red, show little contrast in the photographic region. In support of this argument it should be stated that some of the photographs in the blue do show a faint indication of surface markings. The impression, however, which one receives from the pictures is that part of their appearance is an atmospheric phenomenon. The red photographs show a fading toward the edge which apparently cannot be explained on any other basis.

Wright also calls attention to the fact that the blue images are larger than the red, and attributes this radial excess to the overlying atmosphere.[3] The maximum quantity of atmosphere just derived is insufficient to give an effect of the magnitude Wright observes. The edge effect just mentioned suggests that the inconsistency may be due as much to a radial deficiency in the red images as an excess in the blue. Further investigation is desired, and it should not be difficult to prove whether the result is entirely a planetary condition or whether it should be attributed in part to irradiation or other photographic causes.

Lowell's reduction of the observations of Douglass[4] is additional evidence that such an effect should be small. He finds that a twilight arc of 10° is present on Mars, i.e., the sun's rays continue to reach

[1] *Op. cit.*, p. 246.

[2] *Loc. cit.*

[3] *Op. cit.*, p. 250.

[4] *Astrophysical Journal*, **2**, 136, 1895.

the planet's surface until the sun has sunk 10° below the Martian horizon.

From the geometry involved[1] it may easily be shown that h, the height in the atmosphere at which the solar illumination becomes inappreciable, is given by the equation

$$h=r(1-\sec \tfrac{1}{2}T) ,$$

where T is the twilight arc and r the planet's radius. For Mars, h equals 13 km (8 mi.), far less than Wright's[2] value of 200 km (120 mi.).[3]

The density of the earth's atmosphere is approximately halved for every 5 km (3 mi.) ascended above the surface. For Mars, since the density varies inversely as the force of gravity, the corresponding figure will be 13 km (8 mi.). Thus the pressure at the Martian surface is only twice that at which the last trace of sunlight is visible.

Since the intensity of solar radiation on the earth is double that on Mars, it will be able to illuminate a rarer layer, therefore the density of the Martian atmosphere at the height h will probably be about twice the density of the corresponding layer of the terrestrial atmosphere. The pressure on the surface of Mars will be, therefore, four times the pressure in the earth's atmosphere at the height h_e, where, as seen from Mars, it ceases to be appreciably illuminated.

No direct method is available to evaluate h_e. If the pressure at the surface of Mars is taken to be 5 cm, the terrestrial pressure at h_e will be 1.25 cm, or, approximately, $h_e=27$ km (16 mi.).[4]

It is well known that a sufficient quantity of air for deflecting an appreciable quantity of sunlight extends to a height of 63 km (39 mi.) above the earth's surface, where the pressure is only about one-hundredth that at h_e. As seen from Mars, the outermost layers would probably be invisible, so it is impossible to judge at what point h_e would lie, but the evidence that the 5-cm surface pressure is a maximum certainly seems to be substantiated. The minimum defined by the twilight arc is far less. From the foregoing it appears that the

[1] See Milham, *Meteorology*, diagram on p. 19.

[2] *Op. cit.*, p. 251.

[3] See my n. 1, added to proof in December, p. 58.

[4] *Smithsonian Physical Tables*, p. 421, Table 560.

pressure certainly is greater than one-hundredth, and probably greater than one-tenth, the indicated maximum. No weight should be attached to this evidence. Its real importance lies in showing that the height to which the atmosphere is visible by scattered sunlight is far less than Wright's value of 200 km.

The fact that persistent cloud effects, covering large areas, as observed by Lowell, Slipher, and others, are found on Mars is proof that the atmospheric density is great enough to support the fog, mist, or whatever it may be. In passing, it is sufficient merely to point out that the terrestrial pressure at a height of 15 km (9 mi.), above which level clouds are seldom found, is of the same order of magnitude as the maximum surface pressure for Mars.

Throughout this discussion, the implicit assumption has been made that the atmosphere of Mars is similar in constitution to that of the earth. There is no assurance that oxygen is present[1] but, for the purpose of scattering, nitrogen would suffice as well. If carbon dioxide is present in any large quantity, the mean molecular weight, and therefore the pressure of the atmosphere, would be inappreciably greater than here computed.

One possible experimental investigation which may reveal the minimum value suggests itself. The photographic albedo is measured at λ 4400 A. For the stated quantity of atmosphere, about half the total albedo, or 0.045, is due to the air. At λ 3600 A the scattering would be twice as great and the albedo should be about 0.13 instead of 0.09. A determination of this physical quantity at as short a wave-length as possible, by using a reflecting telescope, would probably provide an absolute criterion for determining a minimum limit to the atmosphere, for if the albedo of Mars does increase in the ultra-violet, it should certainly be attributed to scattering, while the absence of any increase would be conclusive evidence that the quantity of atmosphere is certainly much less than the maximum amount here quoted.

THE MARTIAN POLAR CAPS

From the fact that the polar cap appears very strong on the violet and very weak in the infra-red photographs, Wright suggests that it may possibly be counted an atmospheric phenomenon—perhaps a

[1] See my n. 2, p. 59.

fog or haze transparent to the infra-red but opaque to the ultraviolet. In the light of the preceding a different explanation may be advanced. The cap is probably merely the surface covering of snow and ice, as previously assumed. The intrinsic albedo of the surface in the red is so much greater than in the blue that the contrast between it and the more brilliant snow is much less marked. E. C. Slipher, who also interprets the phenomenon in this way, has pointed out that the observed changes in the appearance of the cap as it melts could not be accounted for if it were atmospheric.

FURTHER APPLICATION

Equation (2) will account for the color of the giant planets, particularly Uranus and Neptune. Their blueness is to be attributed, not to scattering, but to absorption. The spectra of both planets are crossed with heavy absorption bands in the red, thus explaining the color on the basis of an increase in x' for the red light. Since the absorption is beyond the range of either the effective vision or photographic wave-lengths, the blueness of these planets would probably not be revealed by their color-indices.

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NOTE 1 (see p. 56).—Since the above was written, Wright has reduced his original estimates to approximately half (*Lick Observatory Bulletin*, No. 366). Even this new value (60 mi.) is more than could be allowed on the assumption of a perfectly scattering atmosphere. He suggests, however, that the photographs could be explained on the assumption that the Martian atmosphere is opaque to violet light. Scattering would not suffice in view of the small photographic albedo; the opacity, therefore, would have to be attributed to molecular absorption. This is, I believe, not in accord with certain physical principles, for a gas cannot, aside from scattering, exert a general absorption over a wide region of the spectrum. The quantum theory demands that it take place in distinct bands. The spectrum of Mars apparently shows no indication whatever of these ultra-violet bands, which should exist for this planet in the same way that the red bands appear in the spectra of the giant planets. It is not likely that any of the gases which probably compose the Martian atmosphere would be more efficient in absorption than in scattering.

If an atmosphere as extensive as that found by Wright really exists, it would be necessary to assume the presence of a peculiar mist at a very high altitude (above almost the entire atmosphere), with the particular property of absorbing 90 per cent of the blue light and none of the red. A haze with properties such as this could hardly be constructed even artificially; neither clouds of dust nor of water-vapor would suffice, for the presence of either one would raise the albedo of the planet above the observed value.

NOTE 2 (see p. 57).—The recent note by Adams and St. John (*Publications of the Astronomical Society of the Pacific*, **37**, 158, 1925) is of interest in this connection. They have detected the presence of both water-vapor and oxygen. They state that "for equal areas, the water-vapor above the surface of Mars at the time of observation was of the order of 5 and the oxygen of the order of 15 per cent of that normally in the earth's atmosphere, that is, the oxygen was less than above Mt. Everest." Compare this result with the statement which occurs in the paragraph following equation (9) of the text. This shows the order of magnitude of the minimum quantity.

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