1926ApJ....63..177M

PLANETARY TEMPERATURES DERIVED FROM WATER-CELL TRANSMISSIONS

By D. H. MENZEL, W. W. COBLENTZ, and C. O. LAMPLAND

ABSTRACT

In this paper the measurements of the planetary radiation transmitted through a water cell as observed by Coblentz and Lampland at the Lowell Observatory during the summer of 1924 are reduced by Menzel by the method published by him in this *Journal* in 1923.

The *results* obtained seem to prove quite conclusively that the *bright areas are at a lower temperature than the dark areas*, and that the *equatorial (black-body) surface temperature of Mars at perihelion rises above 0° C.* The true temperature, corrected for emissivity, would be about *10°* higher. The temperature of the *south polar cap was −100° C.* on August 14, gradually *increasing to about −15° C.* on October 22, indicating that the cap is probably composed of ice and snow. The low temperature of the east limb, which was down to *−85° C.*, is definite proof of an *enormous diurnal fluctuation.* Various methods of combining the observations give concordant results.

The temperature of the *moon reached 120° C.* under perpendicular insolation. The distribution of energy in its heat spectrum is not consistent with a radiating surface of quartz.

The temperatures of *Jupiter, Saturn, and Uranus* are *low*, the values calculated from the water-cell transmissions being *−130° C.*, *−150° C.*, and *−170° C.*, respectively. There is little evidence of internal heat.

I. THEORY

During the summer and fall of 1924 an extensive series of radiometric measurements was made on the planets, especially Mars, by Coblentz and Lampland at the Lowell Observatory, Flagstaff, Arizona.[1] By means of suitable screens of water, quartz, glass, and fluorite the radiation emanating from the planets was separated into spectral components and thereby an estimate of planetary temperatures was obtained. At the conclusion of these measurements it seemed fitting to have Menzel participate by calculating the planetary temperatures from the observed water-cell transmissions employing the method used by him[2] on similar data obtained by these same observers in 1922. The present paper contains a discussion of the planetary temperatures as deduced by Menzel from the water-cell transmissions.

A water cell 1 cm in thickness transmits radiation which lies between 0.3 and 1.4 μ, while the screens of quartz, glass, and fluorite

[1] *Journal of the Franklin Institute*, **199**, 785; **200**, 103, 1925.

[2] *Astrophysical Journal*, **58**, 65, 1923.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1926ApJ....63..177M

are transparent up to 4 μ, 8 μ, and 12.5 μ, respectively. For further details regarding the method, etc., see previous publications.[1]

The radiation which falls upon the thermocouple is made up of two parts: reflected solar energy of short wave-length and radiated planetary energy of long wave-length. Certain fractions of each are absorbed in passing through the earth's atmosphere. The derivation of the transmission coefficients has been fully discussed in the earlier paper by Menzel[2] and need not be repeated here. New values were calculated for the long-wave transmissions, since the earlier measures were made with a thermocouple having a fluorite window. As a rock-salt window was employed in the present observations, it was necessary to consider the additional energy lying between 12.5 μ and 15 μ, the latter being the limit of transparency of the earth's atmosphere. The values of the atmospheric transmission for this long-wave radiation, computed from two sources,[3] gave almost exact agreement, suggesting that little error is introduced here. The final data are contained in Table I.

TABLE I

TRANSMISSION OF BLACK-BODY RADIATION THROUGH ATMOSPHERE

Temperature	100	150	200	250	300	350	400	500	600
Percentage	0.5	5.7	14.6	22.4	27.4	29.7	30.5	30.4	30.1

The connection between the water-cell transmissions and planetary temperatures[4] is as follows:

$$\frac{t}{t'}\frac{q}{\phi A}\frac{e}{x}\frac{T^4}{T_0^4}=\frac{0.755}{W}-1\,. \qquad (1)$$

In this equation t and t' are the atmospheric transmissions for long-wave and short-wave radiation, respectively. The former is also multiplied by 1.1 because the infra-red is more completely reflected

[1] Coblentz, *Scientific Papers of the Bureau of Standards*, Nos. 438 and 460, 1922.

[2] *Loc. cit.*

[3] *Smithsonian Physical Tables* (7th ed.), p. 308, and Edison Pettit and Seth B. Nicholson, *Publications of the Astronomical Society of the Pacific*, **35**, 195, 1923.

[4] Menzel, *op. cit.*, p. 67.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1926ApJ....63..177M

than the visual at the mirror of the telescope. A is the planet's albedo, q is a factor which takes account of the variation of the light with phase. The factor x allows for any spottedness or inequalities of illumination of the planet and may be defined as the ratio of the brightness of the region under investigation to the average brightness of the entire surface. The factor e is the emissivity; for a perfect radiator, $e=1$. T_0 is defined by the following equation,

$$T_0=392^\circ \cdot R^{-\frac{1}{2}} ,$$

where R is the planet's distance expressed in astronomical units. The logic of equation (1) may be summed up as follows. T_0^4 is proportional to the intensity of incident solar radiation; combined, as above, with t, q, ϕ, A, and x, it represents the quantity of reflected energy which reaches the thermocouple. As the values of all these factors are known, the amount of this energy can be computed with considerable accuracy. The long-wave planetary radiation is proportional to T^4, T being the surface temperature.

Since the water-cell transmission, W, is an indirect measure of the ratio of solar to the total energy, the value of T, the only unknown, may be derived. The planet's albedo for the total incident sunlight is assumed to be equal to the visual albedo. For Mars this is probably a good approximation; the albedo for the blue being less, and for the red, greater. When only a portion of the illuminated disk was on the thermocouple, x was taken equal to the ratio of the illuminated portion of the apparent disk to the area of the entire disk regarded as circular, this quantity being tabulated in the *American Ephemeris and Nautical Almanac*. When the thermocouple covers the whole planet, x is unity.

The two factors, W and x, though somewhat uncertain, enter into the equations only as the fourth root; a condition which is fortunate, considerably reducing the errors in the computed temperature. The numerical value of $W=0.695$ in the original equation has been divided by 0.92, to correct for reflection. Since the observed water-cell transmissions are treated in the same manner, the factor cancels and the equation has the same meaning as in the earlier paper.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

2. TEMPERATURE OF MARS FROM WATER-CELL TRANSMISSIONS

Table II contains the temperatures of Mars expressed on the absolute scale and the observed water-cell transmissions (W) from which they are computed. Since e was here assumed equal to unity,

TABLE II

TEMPERATURES OF MARS COMPUTED FROM WATER-CELL TRANSMISSIONS

Date	East		West		North		South		Center		Remarks
	W	$T°$	W	$T°$	W	$T°$	W	$T°$	W	$T°$	
June 24 ..	......	......	......	......	......	......	......	......	0.418	237	
June 25...	......	......	......	......	......	......	......	......	.511	250	Fluorite windows
June 25...	......	......	......	......	......	......	......	......	.388	242	
July 22...	......	......	......	......	......	......	......	......	.374	254	
Aug. 1...	0.423	243	0.370	256	......	......	......	......	.370	256	Short focus
Aug. 14...	.520	227	.354	268	0.741	150	0.720	165	.308	282	
Aug. 15 ..	.542	222	.364	266	......	......	......	......	.324	278	
Aug. 18...	......	......	......	......	......	......	......	......	.311	277	
Aug. 21 ..	......	......	......	......	.790	?	.716	165	.325	276	
Aug. 21 ..	......	......	......	......	......	......	......	......	.349	268	
Aug. 23 ..	.558	218	.356	266	.734	155	.695	180	.328	275	
Aug. 25 ..	......	......	......	......	......	......	......	......	.337	266	
Aug. 28...	......	......	......	......	......	......	......	......	.312	277	
Sept. 11...	.663	187	.364	260	.725	160	.625	200	.308	274	
Sept. 12...	.661	187	.336	266	.693	180	.605	205	.324	270	South cap
Sept. 12...	......	......	......	......	......	......	.545	220	......	......	Meridian
Sept. 13...	0.382	255	0.253	295	.336	266	.264	292	.251	295	Short focus
Sept. 13...	......	......	......	......	......	......	......	......	.271	287	Short focus
Sept. 13...	......	......	......	......	......	......	......	......	.296	275	
Sept. 14...	......	......	......	......	......	......	.292	279	.293	279	Short focus
Oct. 15 ..	......	......	......	......	......	......	......	......	.332	273	
Oct. 22 ..	......	......	......	......	0.795	?	0.329	260	0.295	268	

the true surface temperatures will be higher. For the range considered, t varies approximately as T^2, and the observed black-body temperatures must therefore be multiplied by $e^{-1/6}$. Assuming $e=0.8$, a reasonable estimate, then all the temperatures are to be multiplied by 1.03, amounting to an increase of approximately 10° in each case.

Unless a note is affixed to the contrary, the observations were all made at the long focus (53.3 ft.) of the 40-inch reflector, the diameter of the receiver being only 0.11 that of the planet's disk during August and September and 0.2 during October. In the observations at the short focus (18.4 ft.), the relative diameters were 0.35 on August 1 and 0.5 for the remaining dates. In the first four measures (June and July) the receiver covered the entire disk of the planet. The temperatures at the two foci are only to be compared judiciously; note the observations of September 13. Obviously, when observing at the shorter focus, the higher temperatures of the poles and limbs are owing to the greater and warmer area near the

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1926ApJ....63..177M

equator falling on the receiver. For similar reasons, the lower temperatures on the equator are owing to the colder areas of the temperate zone intercepted by the receiver.

The observed decrease in the temperature of the east limb, while the west, north, and center remain approximately constant, is striking, and is quite in accord with what might be expected.[1] Figure 1 shows the relative positions of the earth and Mars on the

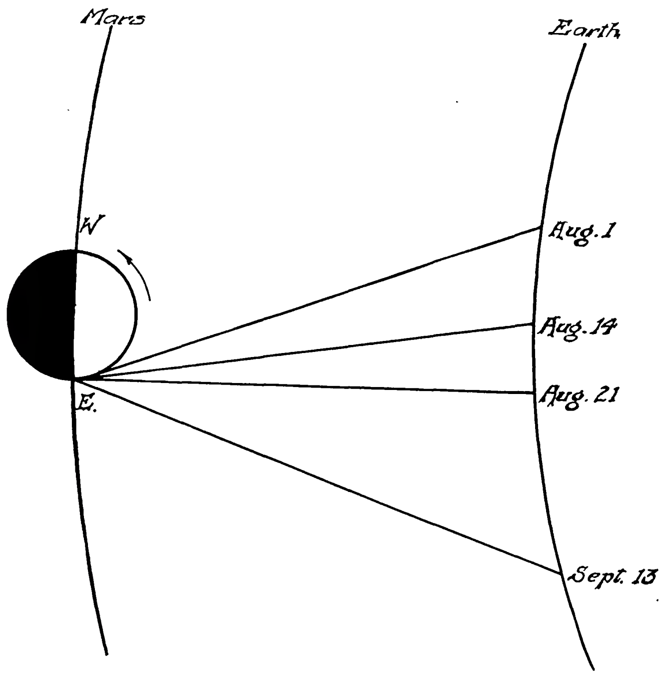

FIG. 1.—Relative positions of earth and Mars

various dates. When, on August 1, the thermocouple was set upon the east limb, it covered an area at a considerable distance from the limb, while on September 13 the limb itself was observable. The observations, therefore, record the rise in temperature as the surface is warmed by the morning sun. The lowest temperature recorded for the east limb is 187° Abs., which is probably near to or somewhat greater than the night temperature of the planet, agreeing well with the previous estimate.[2] The measures show that the Martian afternoon is considerably warmer than the morning.

[1] Coblentz and Lampland, *Journal of the Franklin Institute*, **199**, 1925.

[2] Menzel, *loc. cit.*, p. 72.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1926ApJ....63..177M

The rise of the south polar temperature as the season advances also might have been predicted. The temperatures given in Table II were computed, using $x=1$. Since the polar cap is considerably brighter than the rest of the planet the foregoing values must be considered as a minimum. For $x=3$, which is not unreasonable, the temperatures for the first six observations become 195°, 195°, 210°, 236°, 245°, and 264°, respectively, allowing the possibility that, at the edge of the cap, the temperature may read 0° C., the necessary condition that the phenomenon of disappearance be ascribed to melting snow and ice.

The high temperature of the south polar region is no doubt owing to the fact that this portion of the planet is turned toward the sun and does not have to undergo the extreme diurnal fluctuations of the lower latitutes. The order of magnitude of the temperature is confirmed by the well-known argument concerning the relative behavior of the southern and northern caps. The former is often seen entirely to disappear while the latter never quite vanishes. This is explained by the great eccentricity of the planet's orbit—the south pole being turned toward the sun at perihelion and away at aphelion.

The equatorial midday temperatures are approximately constant and above 0° C., being somewhat lower for the bright than for the adjacent dark areas.

3. THE SPECTRAL DISTRIBUTION OF PLANETARY RADIATION

If a planet were a perfect radiator, its temperature could be derived from the spectral distribution of the energy in its heat spectrum. The fluorite and glass screens are transparent as far as 12.5 μ and 8 μ, respectively. From their values the observed ratio of the energy in the region 8 μ–12.5 μ to that in 12.5 μ–15 μ may be obtained.[1] The observed distribution, when compared with the theoretical, calculated from Planck's formula taking into account the absorption by the atmosphere and various screens, gives values of the Martian temperature in good agreement with the temperatures derived from the water-cell transmissions.

Various factors, such as atmospheric absorption, emissivity, and

[1] Coblentz and Lampland, *Journal of the Franklin Institute*, **199**, June-July, 1925.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1926ApJ....63..177M

deviation from black-body law, affect the temperatures calculated by this method much more than those computed by the formula of section 1, since the latter depends on the quantity of radiated energy which is not as sensitive to these factors as is the spectral distribution. Therefore, even if the ratio method fails, the method of water-cell transmission will still give at least the order of magnitude of the temperature. The observed spectral components for the moon show that there is more energy in the region 8 μ–12.5 μ in proportion to the amount in 12.5 μ–15 μ than a black-body of similar temperature would radiate. In passing, it may be pointed out that this behavior indicates that the lunar surface is evidently not composed of quartz, which has a reflection maximum at 9 μ and should, therefore, exhibit a smaller instead of a greater relative emissivity in this region.

The planets with heavy atmospheres—Venus, Jupiter, and Saturn—show a marked selectivity, the observed ratios being much greater than black-body conditions would allow.

4. WATER-CELL TRANSMISSION TEMPERATURES OF OTHER OBJECTS

Venus, Jupiter, Saturn, and Uranus were also observed. The resulting temperatures are given in Table III. The value for Venus is somewhat in doubt, owing to the uncertainty in x. The temperatures calculated from the recent measurements by Coblentz and Lampland on the giant planets confirm the preliminary investigation by Menzel. The lower values are a confirmation of the work of

TABLE III

WATER-CELL TRANSMISSIONS AND CALCULATED PLANETARY TEMPERATURES

	Date, 1924	W	$T°$
Venus	Aug. 25	0.634	330
Jupiter	June 20	.728	140
	Aug. 16	.746	120
Saturn	June 20	.669	130
	June 21	.682	125
Uranus	....	0.755	100*

* Upper limit.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1926ApJ....63..177M

Jeffreys,[1] who, independently and on theoretical grounds, suggested that the temperatures of these planets are low and maintained by solar radiation alone, internal heat contributing little or nothing. There is, therefore, no necessity for assuming the large quantities of radioactive material necessary to explain the higher provisional temperatures, as Jeffreys does in a more recent article.[2]

The temperature assigned to Uranus is a maximum. Any body with a temperature less than 100° Abs. will radiate practically all of its energy in wave-lengths longer than 15 μ, which are not transmitted through the atmosphere.

Table IV sets forth the results of the observations on the moon. W is the water-cell transmission, i the altitude of sun above the lunar horizon (greater than 90° for the afternoon), and T_w the

TABLE IV

LUNAR TEMPERATURES

Date	W	i	T_w	T_d
June 24......	0.126	105°	390°	382°
Aug. 6*.....	.101†	65	395†	365
Aug. 15......	.241	16	320	236
Aug. 18......	.171	55	360	352
Aug. 20......	.155	78	370	377
Aug. 25*.....	.158	140	365	354
Sept. 12......	.174	138	350	356
Oct. 5......	0.132	80	380	379

* Poor series.

† Observation and therefore T_w, uncertain.

observed temperatures. In the last column, for the sake of comparison, are given the temperatures, T_d, computed by Dietzius[3] for corresponding insolation. They were derived by an application of the well-known heat theorems and the Fourier series for its conduction.

In general, a very good agreement is indicated for T_w and T_d, except on August 15, when a temperature some 80° higher was observed.

[1] *Monthly Notices of the Royal Astronomical Society*, **83**, 350, 1923.

[2] *Ibid.*, **84**, 537, 1924.

[3] *Sitzungsberichte der Akademie der Wissenschaften*, **132**, 194, 1924.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1926ApJ....63..177M

5. FURTHER NOTES REGARDING PLANETARY TEMPERATURES

If the observations could be made outside the atmosphere, a given planet would have the same water-cell transmission no matter what its distance from the sun—and this would be independent of its surface temperature, provided that the planet has no internal heat. This may be proved as follows:

Let A be the planet's albedo and E the amount of energy it receives at any given distance. The quantity reflected will be AE; that absorbed will be $(1-A)E$; and that re-radiated in the direction of the earth will be $K(1-A)E$, K being a constant less than unity, taking care of the possibility of some of the heat being carried by rotation to the far side of the planet. For a non-rotating body $K=1$.

The transmission, then, is proportional to

$$\frac{AE}{AE+K(1-A)E}=\frac{A}{K+(1-K)A} .$$

Since the energy cancels out, the transmission is mainly a function of albedo and not of position.

The presence of the earth's atmosphere alters the case. Since it transmits practically only the energy which lies between 8 μ and 15 μ, the amount of planetary energy which gets through depends upon its spectral distribution and therefore upon the temperature. While the ratio of solar to planetary energy is constant outside the atmosphere, a greater amount of the latter will be absorbed the lower the temperature of the radiating surface. The observed water-cell transmissions of the same object should increase with distance from the sun.

The fact that Mars and the moon are somewhat similar explains the relation exhibited by curve A (Fig. 2). The higher albedo and lower temperature cause the water-cell transmissions of Mars to lie on the same straight line as those of the moon. Table V, column 5, gives the Martian temperatures read off from the curve.

Curve B (fig. 2) also shows that the ratio of the spectral components (see sec. 3) for Mars and the moon are connected by an approximate linear relation. A few lunar observations (which are known to be defective) are so discordant that it is practically

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1926ApJ....63..177M

impossible to judge the position of the line from these measures alone. Taken with the water-cell transmission temperatures, how-

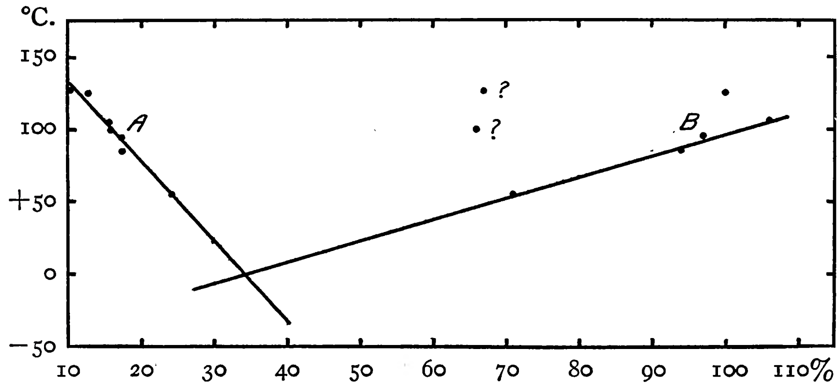

FIG. 2.—Lunar temperatures calculated from the observed water-cell transmissions (curve *A*) in percentage. In curve *B* the temperatures calculated from the water-cell transmissions are plotted against the observed ratios *A* : *B* of the spectral components of planetary radiation.

TABLE V

TEMPERATURE OF MARS

Date, 1924	*W* Percentage	Ratios *A*:*B*	Temperatures, °C. 1	2	3	Mean	Remarks
Aug. 14....	30.5	41.3	9	16	10	12	Aug. 1–Sept. 13, 53-ft. focal length
Aug. 15 ...	32.4	43.1	5	9	13	9	Mare Sirenum, dark
Aug. 18....	31.1	38.6	4	15	6	8	Mare Sirenum, dark
Aug. 21....	32.5	40.7	3	8	9	7	Mare Sirenum dark
Aug. 21....	34.9	39.1	−5	−4	7	−1	Bright area north of Mare Sirenum
Aug. 23....	32.8	36.6	2	6	3	4	Bright area north of Mare Sirenum
Aug. 25....	33.7	38.3	−7	2	5	0	Bright area north of Beak of Sirens
Aug. 28....	31.2	50	4	15	24	14	Solis Lacus, dark
Sept. 11....	30.8	47.8	1	16	20	12	Syrtis Major, dark
Sept. 13....	29.6	39.3	5	23	7	12	Syrtis Major, dark
Sept. 13....	25.1	55.8	22	50	32	34	18.4-ft. focal length; Syrtis Major
Sept. 14....	29.2	46.4	6	24	18	15	South Pole, 18-ft. focal length
Sept. 14....	29.3		6	24		16	Mare Cimmerium, dark
Oct. 15....	28.0		0	33		16	....

Col. 1 is calculated from the observed water cell transmissions (*W*) of the radiation from Mars, using the fourth-power law; col. 2 by extrapolation from the water-cell transmissions and similarly calculated temperatures of the moon; col. 3 by extrapolation from the ratios of the observed spectral components *A* : *B* of the radiation from the moon and the lunar temperatures calculated from the lunar water-cell transmissions, to the observed spectral components, *A* : *B* of Mars.

ever, they serve to define the end-points and general slope. The ratios of the observed Martian components and their corresponding temperatures are given in column 6 of Table V. The true tempera-

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1926ApJ....63..177M

tures would be 8° to 10° C. higher. The mean values are given in column 7 of the table, but, since the temperature data on Mars given in the last two columns are obtained by a large extrapolation from the temperatures of the moon, more weight should be given to the values in column 4 of Table V, which were computed from the formula in section 1, than to the extrapolated values. However, they are interesting in confirming the direct measurements on Mars which show that the bright areas are cooler than the dark areas.

July 4, 1925

© American Astronomical Society • Provided by the NASA Astrophysics Data System