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MEASUREMENTS OF PLANETARY RADIATION

BY

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ABSTRACT

The purpose of the present paper is, (1) to give some preliminary results on the radiation emitted by planets, (2) to describe the improved radiometric apparatus used in the measuring the heat radiated by celestial objects, and (3) to describe the verification of the procedure used by COBLENTZ in 1921, at the Lowell Observatory in determining stellar temperatures by means of special transmission screens.

By means of a cell of water 1 cm. in thickness, the planetary radiation was separated from the reflected solar radiation, and in this manner a measurement was obtained of the infra-red thermal radiation emitted by the planet, within the spectral transmission range of the radiometric apparatus and the *Earth's* atmosphere.

In per cent of total radiation from the planets the values of measured planetary radiation are as follows: *Jupiter* (3), *Venus* (9), *Saturn* (15), *Mars* (30), and the *Moon* (80). Apparently the intensity of the planetary radiation increases with decrease in density of the surrounding atmosphere, though doubtless other factors are also involved.

The intensity of the planetary radiation from the northern hemisphere of *Mars* was found to be less than from the southern hemisphere. All measurements indicate an appreciable rise in temperature of the Martian surface as a result of heating by solar radiation.

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INTRODUCTION

The present research was undertaken primarily for the measurement of planetary radiation, and preliminary results are given of radiometric measurements on *Venus*, *Mars*, *Jupiter*, *Saturn*, the *Moon*, and the *Sun*. But the purpose of the paper is also to describe the radiometric apparatus, and their improvements, used in measuring the heat radiated by celestial objects. In Appendix I of this paper is described a verification of the procedure used a year ago, from measurements made at the Lowell Observatory, for determining stellar temperatures by means of spectral transmission screens.

The many outstanding planetary problems indicate the opportunities still open for gathering improved data and also for the development of new lines of investigation. More extensive and more accurate data, and work in neglected or new fields may be expected to throw light on many questions, by wholly independent or original information brought out, and also by supplementing in essential ways other observational data awaiting more satisfactory interpretations.

COBLENTZ'S successful radiometric measurements at the Lowell Observatory in the autumn of 1921, and also his earlier observations of the same kind at Mount Hamilton in 1914, led to the plan of undertaking at this Observatory more extensive planetary measurements at the earliest favorable opportunity A beginning was made the past summer. Owing to various circumstances it was possible to devote only a short time to the observational work, but it was felt that a beginning, even if the observations were few in number and could cover only a short interval, would give some preliminary data and be highly instructive in bringing out certain essential modes of procedure and various phases of such investigations which should be helpful guides in formulating more comprehensive programs of research.

1. PLANETARY RADIATION DEFINED

In this paper, by planetary radiation is meant the emission of thermal radiation from a planet as a result of warming of its surface (and its atmosphere) by exposure to solar radiation, including also the heat that may be radiated by virtue of a possible high internal temperature of the planet itself. The temperature of the surface, and probably the lower strata of the atmosphere, due to absorbed solar radiation and from internal heat, if such exists in sufficient amount to influence radiation from the surface, is at most probably of the order of only a few hundred degrees centigrade, and hence the radiated energy will be predominantly of long wave length. Taking into account the selective absorption of the earth's atmosphere — mostly due to water vapor, carbon dioxide, and ozone — and the spectral transmission range of the radiometric apparatus, the planetary radiation measured in the present observations

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is largely the energy included between the limits 7μ and 12μ (μ=0.001mm). By means of a cell of water, 1 cm. in thickness (which has the property of absorbing wave lengths greater than 1.5μ) interposed in the path of the total radiation from the planet, in so far as it is transmitted by the *Earth's* atmosphere and the measuring instruments, this long-wave length radiation can be separated from the solar radiation reflected by the planet. In this manner a measurement may be obtained of the planetary energy radiated. This will be less than the true planetary radiation in proportion to the depletion suffered through the selective action of the *Earth's* atmosphere and the instruments employed in the measurements. If there is planetary radiation then the water cell transmission of the radiation from the planet will be less than that of the direct solar radiation.

A complete definition of planetary radiation must necessarily refer to the total radiation outside the *Earth's* atmosphere, when measurements are made with instruments which are perfectly non-selective for all wave lengths. This ideal case can not of course be realized in practice and the investigator must do as well as he can with the fragmentary data he is able to gather.

It is relevant to add that the water cell cannot separate the radiation due to internal heat (if such is present in appreciable amount) from the energy reradiated as a result of warming of the surface by solar radiation. If the planet is subject to eclipse, or change in phase of illumination, as for example our *Moon* or *Venus*, then it is possible to determine whether the unilluminated surface is warm and emits heat radiation. Radiometric measurements of the unilluminated surfaces of planetary bodies have a direct bearing on the question of diurnal rotation.

It is desirable and necessary to supplement the radiometric measurements on the planets with other information as to composition, density, and other properties of the atmospheres in order to determine the proportions of the reradiated energy emanating from the surface or interior of the planet and its surrounding atmosphere. In the present state of our knowledge it is difficult to judge as to what extent planetary atmospheres are warmed by the absorption of radiation, and as to the functions they perform in the complex processes of the radiation exchanges set up between the absorbed solar energy and internal planetary energy in the way of emission of long-wave-length thermal radiation. In the case of the *Earth* the researches of astrophysicists and meteorologists have established that its planetary radiant properties must be largely those of its atmosphere. Except for airless bodies such as the *Moon* it is reasonable to suppose that the atmospheres also play a highly important role in the energy exchanges of the planets. The spectral regions of selective absorption and emission of the *Earth's* atmosphere, predominantly due to water vapor and carbon dioxide, must in some cases profoundly modify the actual radiation from other planets in their passage to the measuring instruments. The selective absorption, transmission, and emission, which we may plausibly expect to be at work in the energy exchanges of planetary bodies,

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combined with the difficulties introduced by the selective action of the *Earth's* atmosphere make investigations on planetary radiation and planetary temperatures complicated problems. In our measurements we can at the best isolate only a part of the actual planetary energy. The observer has before him the task of measuring as great a spectral range as possible of the radiated energy curves of the planets, and also to delimit this energy.

II. Apparatus and Procedure

The apparatus used in this work consisted of the 40-inch reflector (focal length 220 inches) of this Observatory (Altitude 7250 feet) to which was attached a spectral radiometer, consisting of transmission spectral screens and a vacuum thermocouple of low heat capacity and hence, quick action.[1]

1. Description of the Vacuum Thermocouples Used in the Present Work

The vacuum containers for the thermocouples were of the same general design used in the previous work. Four containers were taken to the observatory, a distance of 2500 miles, without breakage. No vacuum pump was taken as it had already been demonstrated, in 1914 and again in 1921, that metallic calcium is a reliable means of vacuum maintenance.[2]

An electric heater was provided for heating the metallic calcium to incandescence. It consisted of a thin porcelain tube about 10 cm. long and 1.5 cm. internal diameter. On the outside of this tube was wound about 2 meters of fine (0.2mm) platinum wire, having a resistance of 12 ohms. This was covered with alundum cement, such as is used in pyrometric work. A small rheostat was provided and the whole operated on a 110 volt circuit. It required less than 2 amperes to raise this heater to a low red temperature, and, being of low heat capacity, this was accomplished in a few minutes.

The evacuation was tested by means of an induction coil as previously described. The thermocouple containers leaked but little, as was evidenced by the cathode fluorescence of the glass that continued for days when the calcium was not heated. In practice the calcium evacuator was heated on the afternoon preceding the observations.

The new thermocouples used in the present investigation were made of pure bismuth wire which was very strong and pliable. The thermocouple receivers were made small, with the view of obtaining measurements on the bright and dark regions on *Mars* and *Jupiter*.

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[1] This method of determining the spectral energy distribution of stars was worked out early in 1919. Since then the device has been given a thorough trial and found to fulfill all the claims made for it, — See *Bureau of Standards Scientific Paper* No. 438, 1922. By means of these transmission screens it was possible to obtain for the first time an insight into the radiation intensities in the complete spectrum of a star.

[2] *Bur. Standards Sci. Papers*, 17, p. 187; 1921.

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CONTAINER NO. 7 remained the same as used in the measurements of 1914, except that about three years ago a new quartz tube containing new metallic calcium was provided. This container was opened and re-evacuated with a pump a year ago, since which time its vacuum has been maintained by means of the metallic calcium.

CONTAINER NO. 11 was No. 8 previously used, but new thermocouples of bismuth wire[3] 0.025 mm in diameter and platinum-rhodium wire[4] 0.020 mm in diameter. The bismuth wire was 3 mm long and it was kept straight in order to prevent radiation from falling on both receivers when the planetary image was focused on one of them. The resistance of thermocouple No. 1 was 7.7 ohms; the diameter of the receivers being 0.28 mm. The resistance of thermocouple No. 2 was 5.5 ohms; the receivers were 0.23 and 0.27 mm respectively. The receivers were small globules of tin, attached to the Pt-Rh wire and pressed flat between glass plates as described in previous publications. These receivers were not so large in diameter as those used a year ago, and attained temperature equilibrium in 2 to 3 seconds (instead of 8 to 10 seconds) which was the time of swing of the galvanometer.

CONTAINER NO. 12 was the old mounting, No. 9, used in 1921, but with new thermocouples of 0.025 mm bismuth wire, and of 0.020 mm Pt-Rh alloy wire. The bismuth wire (length 2.5 to 3 mm) was bent U-shaped in order to bring the receivers close together, so that the star image could be quickly changed from one receiver to the other receiver. The resistance of thermocouples No. 1 and 2 were 4.7 and 4.4 ohms respectively; the diameters of the receivers (of tin pressed flat) were 0.31 and 0.32 mm respectively.

CONTAINER NO. 10 remained as used in 1921. In containers No. 10 and No. 12 the fluorite windows were attached by means of BOLTWOOD'S[5] low vapor pressure cement. This cement has a low melting point which enables one to attach the fluorite window without cracking it. The vacuum in these two containers remained unusually constant so that, for weeks at a time, it would have been unnecessary to heat the calcium.

In the previous paper[6] it was shown that a thermocouple of tellurium is twice as sensitive as that of bismuth. This is to be expected in view of the fact that its thermal e.m.f. is twice that of bismuth. It may therefore be used for stellar radiometry provided it can be made of sufficiently small size in order to reduce its heat capacity and hence its lag in attaining a maximum temperature. The thermocouples of tellurium wire (0.13 mm in diameter) tested required 6 to 8 seconds to attain a maximum galvanometer

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[3] From Adam Hilger, Ltd., 75A Camden Road, London, England.

[4] From Baker & Company, Newark, N. J.

[5] From PROF. B. B. BOLTWOOD, Yale University, New Haven, Conn.

[6] *Bur. Standards Sci. Paper* No. 438; 1922.

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deflection which was entirely too prolonged for the purpose of the present work. The thermocouples used in this present research were practically instantaneous in their action so that, as already stated, a galvanometer reading was obtained in 2 to 3 seconds which was the time of swing of the galvanometer.

The radiation sensitivity of the thermocouples of pure bismuth wire, in containers No. 11 and 12, (used in 1922) was practically the same as that of the alloys in containers No. 7 and No. 10, used in the stellar measurements of 1921. This is interesting in showing that aside from a reduction in heat capacity, and hence an increase in speed and accuracy of observation, there was no great gain in radiation sensitivity by increasing the thermoelectric power or by reducing the size of the wire. However, by using very fine wires a considerable gain in radiation sensitivity is to be expected, provided a higher vacuum is maintained.

The glass container is shown in Fig. 1 in which *Ca* represents the quartz tube containing the metallic calcium; *F*, the fluorite window; *T*, the thermocouple; and *P*, the potential terminals for testing the evacuation by means of an induction coil, automobile spark coil, or transformer of 2000 to 10,000 volts. For further details of construction and manipulation of the thermocouples, (also the iron clad THOMSON galvanometer for measuring the electric current generated by the thermocouples), the reader is referred to previous papers.[7]

Two thermocouples were placed in each of the three new mountings. Either one of these could be used without delay in changing the connections. As shown in the lower left hand corner of Fig. 2, these thermocouples (in containers No. 10 and 12) were bent U-shaped so that the two junctures were close (0.5 to 1 mm) together, in order to facilitate exposing them alternately to the star image as previously described.[8] The lead-in wires, of silver, were bent into the peculiar U-shape to facilitate placing the receivers normal to the incident radiation, and to prevent breakage from jarring in shipping.

For measuring the direct solar radiation a special thermopile (in air) was used. It consisted of two elements of No. 38 constantan and No. 40 copper wire connected in series, with tin receivers, 1.5 by 2.2 mm, mounted in a brass box, with an opening 8 mm in diameter covered with a fluorite window. The cold junctions were inside the brass box and shielded from the incident parallel light. This brass box was the same size as the glass container, Fig. 1, and it was mounted in the holder shown in Fig. 2.

2. DESCRIPTION OF THE TRANSMISSION SCREENS

The function of the screens is to transmit radiation extending over fairly narrow regions of the spectrum. By means of such screens which, either singly or in combination, are placed in front of the

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[7] *B. S. Bulletin*, 11, p. 131, 1914; 11, p. 613, 1915; 17, p. 726, 1922.

[8] See Fig. 2, *B.S. Bulletin* 11, p. 622, 1914.

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thermocouples, one can obtain some idea of the spectral energy distribution of the stars. Screens were selected which had a uniformly high transmission over a fairly narrow region of the spectrum, terminating abruptly in complete opacity in the rest of the spectrum. While it is not necessary, it is desirable to use screens which terminate the spectrum sharply at a particular wave-length. In this manner the results will be comparable with what would be obtained by dispersing the radiation into a spectrum and shutting out parts of the same with a knife-edge screen. In this manner, no correction was necessary to the observations, other than that for surface reflection, which is of the order of about 9 percent for the two surfaces of the screen. A slight amount of dust will raise the reflection losses to 10 per cent or even higher.

The screens selected have the following properties (see Figs. 3 and 4):

FLUORITE — which was used as the window of the vacuum container transmits uniformly (i.e. without bands of selective absorption) all radiations from the extreme ultra-violet to 12μ in the infra-red.

QUARTZ — thickness 4.77 mm is transparent to all radiations from the extreme ultra-violet to 4.1μ in the infra-red. This gives the spectral radiation extending from 0.3μ to 4.1μ. The quartz plate was selected because of the sharpness of its termination of the spectrum, at 4.1μ. A thin glass screen might have been used, but the transmission does not terminate so abruptly in the infra-red.[9]

WATER — Thickness 1 cm. in a cell containing thin quartz windows, is transparent from the extreme ultra-violet to 1.4μ in the infra-red. Used as a screen this gives the spectral radiation between 0.3μ and 1.4μ.

YELLOW GLASS — SCHOTT'S Jena 5560, thickness 2.97 mm is opaque to radiations of wave-lengths less than 0.43μ. The infra-red transmission is not very abrupt. Hence it was used in combination with the water cell, giving the spectral radiation between 0.43μ and 1.4μ.

RED GLASS — SCHOTT'S Jena 4512, thickness 1.97 mm is opaque to radiations of wave lengths less than 0.6μ. It was used in combination with the water cell, giving the spectral radiation between 0.6μ and 1.4μ. The difference between the galvanometer deflection when the water cell is interposed and when the water cell plus the red glass are interposed (corrected for reflection) gives the radiation in the spectral region from 0.3μ to 0.6μ. Similarly, the difference between the galvanometer deflection for the water cell plus the yellow glass and the deflection for the water cell plus red glass represents the spectral radiation between 0.43μ and 0.60μ.

By means of these screens it was possible to obtain the radiation intensity in the spectrum from the extreme ultra-violet (which is limited by atmospheric transmission and the low reflectivity of the silvered mirrors) at 0.3μ to 0.43μ; 0.43μ to 0.60μ; 0.60μ to 1.4; 1.4μ to 4.1μ; and 4.1μ to 12μ.

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[9] See "Investigations of Infra Red Spectra." Publ. No. 65, p. 64 and No. 97, p. 45, Carnegie Institution of Washington, 1906-1908.

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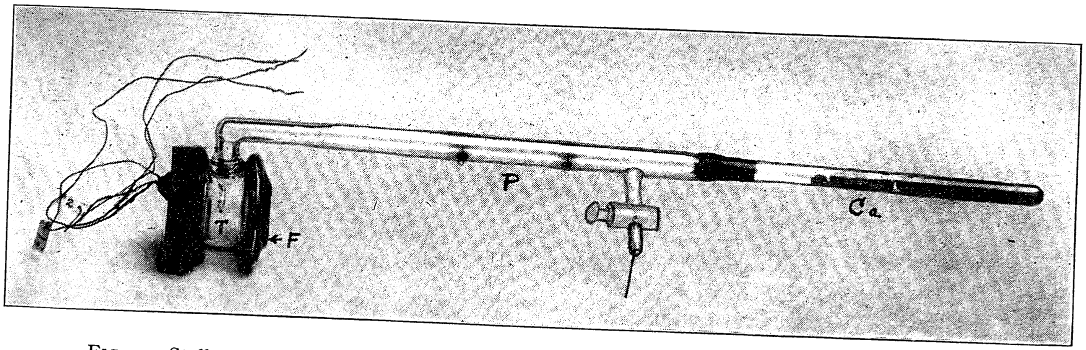

FIG. 1. Stellar thermocouples mounted in an evacuated glass container, with Fluorite window.

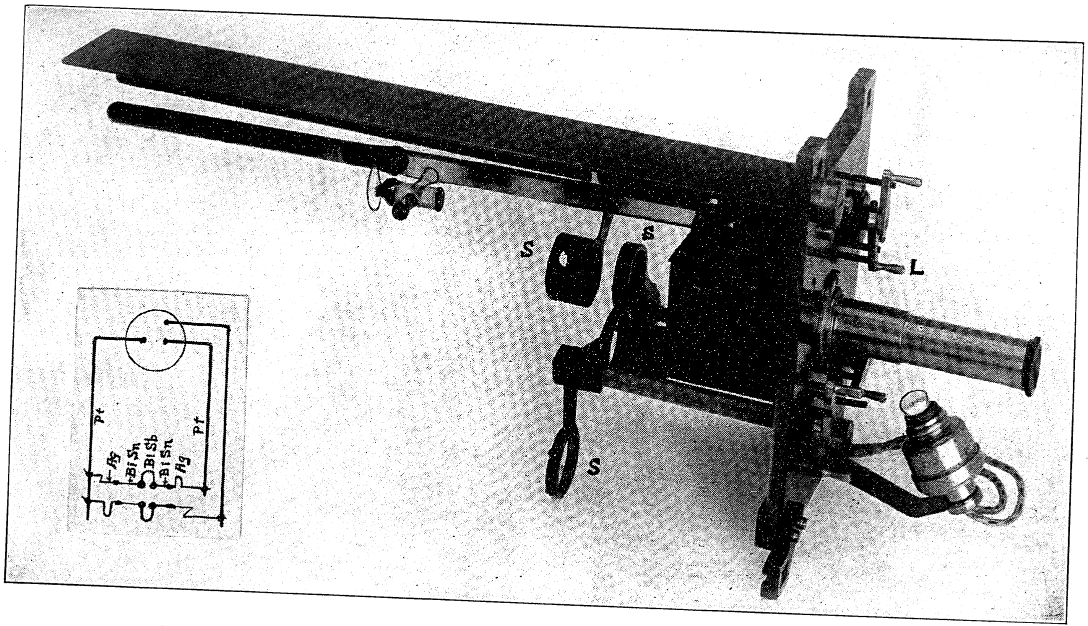

FIG. 2. Mounting for stellar thermocouple container and transmission screens.

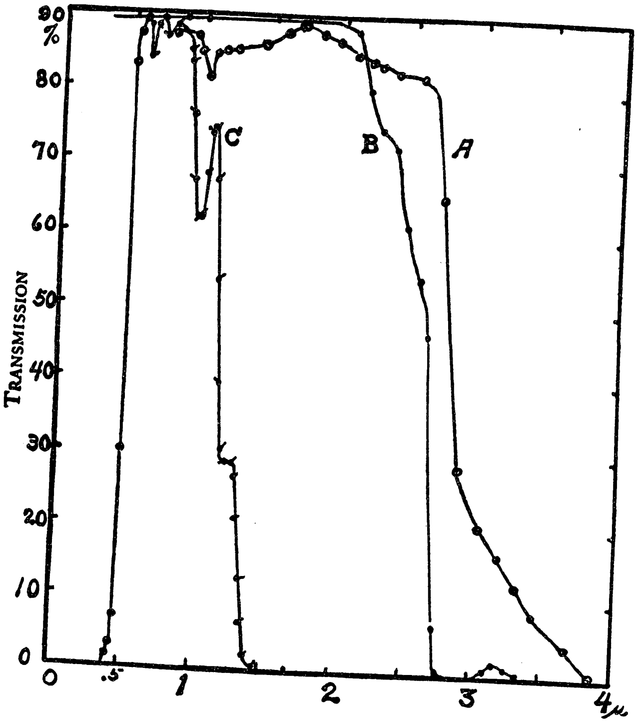

FIG. 3

Transmission curves of screens: A, yellow glass; B, pyrex glass; C, water, 1 cm. in thickness.

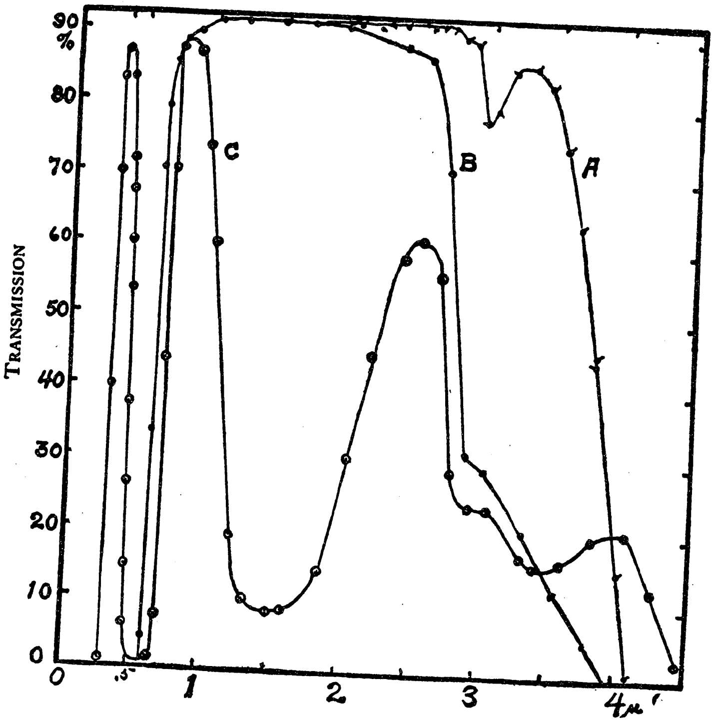

FIG. 4

Transmission curves of screens: A, quartz; B, red glass; C, blue-purple, glass.

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These screens, *S*, which were in the form of disks 25 mm in diameter, were mounted in brass supports which in turn were mounted upon brass rods and sleeves, as shown in Fig. 2. Each rod and sleeve could be rotated independently by means of a lever *L*. In this manner, the various screens either singly or in combination could be interposed in the optical path.

In Fig. 2, the vacuum thermocouple mounting of Fig. 1 is shown in its holder. The small eye-piece, to the right, is for setting the star image on the thermojunction. The incandescent lamp is for illuminating the levers when operating the transmission screens. The whole mounting takes the place of the plate holder in the telescope; and it required only a few minutes to interchange it with the plate holder.

In view of the limited time available and also the preliminary nature of the planetary radiation measurements, a complete analysis could not be undertaken of the spectral components of the radiation emanating from the different planets. It was therefore necessary to choose between the water cell and the quartz plate for measuring the planetary radiation.

As shown on a subsequent page (Table 1) the spectral component radiation of wave lengths greater than 4μ is only about 1 per cent of the total incident solar radiation.

Hence, if a transmission screen of quartz is used, one would expect to find but a small amount of solar radiation mixed with the planetary radiation, unless there is strong selective reflection.

On the other hand, if there is planetary radiation of wave lengths shorter than 4μ it is missed in the transmission measurements made with the quartz screen. For, while the low temperature (planetary) radiation from solids is predominantly of long wave lengths (6μ to 12μ) the radiations emitted, of wave lengths 3μ to 4μ, are of measureable intensity. Similarly, the emission bands, at 3μ to 4.2μ, of water vapor and carbon dioxide, even when heated to less than 100° C., are also of measurable intensity. This is of importance, in view of the question whether some of the planets are still hot.

Hence, if a water cell is used, one is certain of obtaining all the planetary radiation. The proportionate part of solar radiation will, of course, be greater than when using the quartz screen; but there is nothing to indicate that this is disadvantageous. For, it does not appear that the atmospheres of the planets exert a selective reflection. It has been found that, as a general rule, the bands of selective reflection are not found in the short wave length infra-red region of the spectrum, but occur at wave lengths greater than 6μ. If the atmospheres of the planets modified the composition of the reflected solar radiation, and hence greatly vitiated the measurements of the planetary radiation, then one would expect to find this to occur in the case of the planets having the greatest atmospheres. As will be shown presently, the greatest amount of planetary radiation comes from the planets having the smallest, least dense, atmospheres.

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The planetary radiation emanating from the *Moon*, as observed through the water cell is in substantial agreement with the measurements made years ago by VERY, who used, as a screen, a plate of glass which, like quartz, is opaque to radiations of wave lengths greater than 4μ.

For the present investigations, the water cell was therefore adopted to obtain a uniform comparison of the measurements of the (planetary) radiation from the various planets.

III. RADIOMETRIC MEASUREMENTS

Under this caption are given some of the experimental details relevant to obtain a clear understanding of the scope and the reliability of the data obtained. By comparison of the water cell transmissions of the radiation emanating directly from the *Sun* with similar measurements of the radiation emanating from the planets, a measure is obtained of the radiation emitted directly by the planet — in so far as such radiation is transmitted by the *Earth's* atmosphere and the measuring instruments — as a result of warming of its surface and atmosphere, and as a consequence of a high internal temperature, if such a condition exists.

THE *Sun* — A crucial part of this research consisted in obtaining an exact measurement of the water cell transmission of the direct solar radiation, for comparison with that of the planetary radiation. For this purpose the great mirror and the end of the telescope tube were covered, and the telescope was sighted upon the *Sun*. Parallel light entering a small 6-inch (15 cm) hole in the cover of the telescope tube, fell upon a small (5 cm) plane, silvered mirror placed in the axis of the tube and from thence reflected upon the diagonal mirror, to the thermopile. In this manner a measurement was obtained of the solar radiation after reflection from two silvered surfaces just as obtained in the stellar and planetary radiation measurements. The plane mirror was used because of the high intensity of the solar rays. Even then it was necessary to insert 3000 ohms into the galvanometer circuit in order to keep the galvanometer reading on the scale.

The observations consisted in noting the galvanometer reading when the end of the telescope tube was entirely covered. Solar radiation was then admitted upon the thermopile and a series of readings made with and without the intervening water cell. Readings were made also with the other transmission screens in order to obtain data given in APPENDIX I. The day selected for observations was perfectly cloudless and the galvanometer deflection remained steady to 0.5 mm. This was a source of marvel to one who is accustomed to sea level measurements, with continuous galvanometer scale fluctuations caused by (visually) almost imperceptible clouds of water vapor.

The transmission measurements are given in Table 1. In column 3, a "set of measurements" consisted in observing (1) the "zero reading" of the galvanometer with the end of the telescope tube covered,

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then (2) a series of galvanometer readings on exposure of the thermopile to the *Sun*, but without the water cell, then (3) a series with the water cell interposed, followed (4) by another series without the water cell and (5) finally another series of galvanometer zero readings.

Table 1. — Transmission of Planetary Radiation through a Cell of Water 1 cm in Thickness; Also the Per Cent of Planetary Radiation Emitted.

Object	Date June, 1922	Per cent Transmission				Planetary radiation in per cent of the total
		No. of sets of measurements	Deviation from mean	Mean value 1922	Mean value 1914	
Sun	17th 11.30 A.M.	5	1.2%	69.3	....	.....
	4.15 P.M.	4	0.5	69.8	....	.....
Jupiter						
Central disk	14th 10.15 P.M.	2	1.4	69.7	65.6	0
South polar region	10.20 P.M.	2	3.0	66.8	65.8	.....
Venus	15th 8.00 P.M.	2	2.3	63.6	59.0	9
Saturn { disk	14th 9.00 P.M.	2	1.1	60.0	55	15
Saturn { rings		1	1.5	64.5	....	.....
Mars	15th and 18th	—	6.0	50.3	....	30
Moon	....	.....	.....	....	14.7	80

The water cell transmission is about 70 per cent, which is in agreement with measurements at sea level (Washington) which gave a transmission of 76 per cent (*B. S. Technologic Paper* No. 93, third Edition, p. 25) for this same cell. For the latter measurement, no reflecting mirrors were used and hence the higher per cent transmission may be ascribed to depletion of infra-red radiation by atmospheric water vapor.

Venus — The water cell transmissions on *Venus* were made with thermocouple No. 2 in container No. 11. The method of observation consisted in exposing both of the thermocouple receivers to the sky, then moving one of them upon the planetary image by turning the slow motion declination screw, Similar measurements were made also in the reverse order. The ratio of the galvanometer deflections. with and without the water cell, gives the transmission data desired. These data are given in Table 1.

Mars — The transmission measurements on *Mars* were obtained by means of two thermocouples differing widely in construction, as described on the preceding page.

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Table 2. — *Mars*; Transmission of the Planetary Radiation through 1 cm of Water, using Vacuum Mounting No. 11, Thermocouple No. 2

Date June 15, 1922 M. S. T.	Per Cent Transmission							Observed galvanometer deflection in cm.
		Southern Hemisphere		Equatorial region		Northern Hemisphere		
	No. of sets of galvanometer readings	Maximum deviation of a single galvanometer deflection from mean	Mean value of transmission	Maximum deviation of a single galvanometer deflection from mean	Mean value of transmission	Maximum deviation of a single galvanometer deflection from mean	Mean value of transmission	
10:58 to 11:05	2	6%	45.8%	.....	.....	.....	.....	4.8
11:07 to 11:10	2	10	51.6	.....	.....	.....	.....	3.4
11:12 to 11:13	2	8	49.5	.....	.....	.....	.....	.....
11:16 to 11:18	2	.....	.....	8%	44.4	.....	.....	5.4
11:22 to 11:24	2	.....	.....	12	47.4	.....	.....	5.5
11:24 to 11:28	2	.....	.....	12	49.4	.....	.....	5.2
11:44 to 11:48	2	.....	.....	5	46.8	.....	.....	6.1
11:55 to 11:58	2	.....	.....	.....	.....	8	52.8	3.8
12:05 to 12:12	3	.....	.....	.....	.....	6	53.8	3.3
12:20 to 12:27	3	.....	.....	.....	.....	12	46.6	3.6
Mean value			48.9		47.0		51.1	

Mean value of all = 49.0 per cent

In order to obtain the galvanometer deflections quickly when using thermocouple No. 2 in container 11, the procedure was to tilt the telescope tube a slight amount so that the image of *Mars* was "on" or "off" the thermocouple receiver (i.e. both receivers were exposed to the clear sky). The data are given in Table 2, in which the second column gives the "number of sets of galvanometer readings", the first set being made without the water cell interposed, and the second set being obtained with the water cell in the path of the incident radiation. This was sometimes followed by a third set of readings without the water cell. The ratio of the average values of two such sets of observations is the transmission recorded in column 6. The 3rd, 5th, and 7th columns give the maximum deviation of a single set of observations. (The 9th column gives the mean value of the direct deflection). Since the mean value of the set of observations is the result of 10 to 15 single galvanometer deflections, a large variation of a single reading has no serious effect upon the results.

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As already described, the bismuth wire of the thermocouple in container No. 12, was bent into a U-shape, the receivers being separated about 1 mm. The diameters of the receivers were about 0.4 of the diameter of the planetary disk.

The method of observation consisted in exposing alternately the two junctures of the thermocouple (No. 1 was used) thus doubling the galvanometer deflection. The procedure was to expose the left thermocouple receiver to the planetary image and record 5 to 6 galvanometer scale readings. The image was then focused on the right-hand thermocouple receiver and a similar series of galvanometer scale readings was recorded. The difference of the average of the "left" and "right" scale readings constituted a "set of galvanometer readings." Several such sets were then obtained alternately with and without the water cell interposed. The number of sets of readings are given in column 2 and Table 3.

Table 3. — *Mars*; Transmission of Planetary Radiation through 1 cm of Water, using Vacuum Mounting No. 12, Thermocouple No. 1.

Date June 18, 1922 M. S. T.		Per Cent Transmission						Observed galvanometer deflection in cm.
		Southern Hemisphere		Equatorial Region		Northern Hemisphere		
	No. of sets of galvanometer readings	Maximum deviation of average galvanometer deflection from mean of several sets	Mean value of transmission	Maximum deviation of average galvanometer deflection from mean of several sets	Mean value of transmission	Maximum deviation of average galvanometer deflection from mean of several sets	Mean value of transmission	
10:25	6	.....	.....	1.5%	48.8	.....	.....	27.5
10:30	6	.....	.....	4.3	44.7	.....	.....	.....
10:40	12	.....	.....	1.2	51.3	.....	.....	8.2
10:50	10	1.4%	52.3	.....	.....	.....	.....	7.1
11:10	5	.....	.....	.....	.....	1.3%	54.5	5.4
11:15	7	.....	.....	.....	.....	2.5	55.7	.....
11:25	12	.....	.....	2.8	45.7	.....	.....	8.1
Mean value June 18			52.3		47.6		55.1	
Mean value June 15			48.9		47.0		51.1	
Mean value June 15 and 18			50.6		47.3		53.1	

Mean value of all = 50.3 per cent

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Columns 3, 5, and 7 of Table 3 differ from similar data in Table 2, in that the maximum deviation is not that of a single reading from the mean of series of readings, but is the percent deviation of the mean of a single set of galvanometer readings forming the mean of the 3 to 6 sets taken with (or without) the water cell intervening. The various sets of readings being average values, the percent deviation from the mean of several sets is smaller than that given in Table 2 for single readings. The deviations are smaller also for the reason that there was less unsteadiness in the galvanometer reading when the thermocouples were exposed alternately to the planetary image than when a single receiver was exposed alternately to the sky and the planet.

In Table 3, all the data following the first two series of transmissions were obtained with a (low and) constant galvanometer sensitivity. Hence the galvanometer deflections recorded in column 9 are proportional to the radiation emanating from *Mars*, and show that the intensity of the radiation emanating from the region of the southern hemisphere, the equator and the northern hemisphere on June 18th, was respectively proportional to 7.1, 8.2 and 5.4 cm. In this connection it is interesting to note that while making observations on the equatorial region, meteorological conditions continued so uniform for an hour, that the observations at the beginning and the end are in agreement within one percent.

Details of the measurements are given in Table 2. The mean values of the water-cell transmissions of the radiations are:

Southern hemisphere	50.6%
Northern hemisphere	53.1%
Equatorial or tropical belt	47.3%

Some remarks on these results are given under the general discussion of the data.

Jupiter — The water cell transmissions of the radiation from *Jupiter* were determined with thermocouple No. 2 in the vacuum container No. 11. The receiver was about ¼ of the diameter of the image of the disk of the planet. The measurements were made by exposing one receiver alternately to the planetary disk and then (when conditions were steady) to the sky, thus obtaining a set of galvanometer deflections. Several such sets of observations were obtained, with and without the water cell interposed. The data are given in Table 1 — from which it may be noticed that the average value of the transmission is about 68 per cent; also that the observations are in agreement with those obtained in 1914, at Mt. Hamilton, which is at a considerably lower altitude.

Saturn — The water cell transmission measurements on the center of the ball of *Saturn* were made with thermocouple No. 2 in vacuum mounting No. 11. The diameter of the receiver was about one-half

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of the planetary disk. The procedure was to expose one thermocouple receiver to the planetary disk, and, when the galvanometer was steady, expose both receivers to the sky, by slightly tilting the telescope tube.

The transmission data are given in Table 1. The average value (60%) of the water cell transmission is appreciably lower than that of the direct solar radiation, and it is in agreement with the observations of 1914, showing a considerable amount of infra red radiation from the planet that is not present in the direct solar radiation.

The Moon — No observations of the water cell transmission of the radiation from the *Moon* were obtained this year for an air mass comparable with that through which the planetary measurements were obtained. The present (as well as the 1921) radiation measurements on all of the other objects are in agreement with the observations of 1914 and we shall provisionally assume that the water cell transmission is of the order of 15 per cent (see table 1) as observed in 1914. But more extensive observational data will be required to give accurate information on the planetary radiation from the *Moon.* The amount of insolation as well as the character of the surface measured will doubtless be factors that strongly influence the energy radiated by our satellite. The 1914 measurements were made on the region near *Mare Crisium* when the sun had attained an altitude of about 70°.

In connection with the planetary measurements this forms an interesting sequence of water cell transmissions which decrease (i. e. the per cent of planetary radiation increases, Table 1) with decrease in thickness and density of the planetary atmospheres; *Jupiter* (68), *Venus* (64), *Saturn* (60), *Mars* (50), and the *Moon* (15). The per cent difference between the water cell transmission of the direct solar radiation and that of the radiation emanating from the planet is a measure of the planetary radiation transmitted by the *Earth's* atmosphere and measuring instruments — see Table 1., and is as follows: *Jupiter* (3), *Venus* (9), *Saturn* (15), *Mars* (30), and the *Moon* (80).

IV. Discussion of Data

In the foregoing pages, data are presented showing that the order of intensity of the planetary radiation, as interpreted from measurement of the total radiation emanating from the planet, which is transmitted through a cell of water, is as follows: *Jupiter* (the least) *Venus*, *Saturn*, *Mars*, and the *Moon* (the greatest). This planetary radiation may consist of (1) the energy re-radiated as the result of heating of the planet, including both the surface and the atmosphere, by solar rays, (2) the energy which may be radiated owing to a high internal planetary temperature, if such a condition exists, and (3) solar radiation which may be selectively reflected from the planet, including the surface and the atmosphere. In order to estimate, if only approximately, the part contributed by each of these sources of long wave length infra red radiation, it is necessary to consider other information on the planets.

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In connection with the following discussion it may be useful to tabulate here certain planetary data.

Planet	Mean distance from *Sun*	Albedo	Diameter	Mass	Density	Intensity of incident solar radiation
	⊕ = 1		⊕ = 1	⊕ = 1	⊕ = 1	$\frac{\text{gm. cals.}}{\text{cm.}^2 \text{ min.}}$
Venus	.723	.59	.972	.82	.89	3.82
Moon	1.000	.073	.273	1/81.5	.61	2
Mars	1.524	.154	.534	1/9 .32	.71	0.86
Jupiter	5.203	.56	10.92	317.7	.24	0.074
Saturn	9.539	.63	9.17	94.8	.13	0.022

Planet	Relative Intensity of incident solar radiation	Relative amount of absorbed solar energy per unit area (normal incidence)	Percentage of planetary radiation measured
Venus	177	72.57	9%
Moon	89	82.50	80
Mars	42	35.53	30
Jupiter	3	1.32	3
Saturn	1	.37	15

The subject of planetary radiation is an intricate one, and it must here be expressly stated that the present paper does not pretend to cover the many questions involved or attempt to deal exhaustively with any of them. The main purpose of this preliminary work was to seek out methods of procedure. The results are of great interest, and an account is given of the measurements as far as they have been carried. Some phases of possible interpretations of the measurements have been discussed in a tentative way.

It is known from the radiant properties of the *Earth's* surface and atmosphere that a correct analysis of the *Earth's* planetary radiation measured from free space would be an intricate problem. Except for practically airless bodies like the *Moon* it is reasonable to suppose that radiometric investigations on the other planets would be of similar character as regards the elements involved. The investigation is all the more complicated if measurements must be made through some intervening medium such as an atmosphere with selective properties. The planetary radiation of the *Earth* is predominantly that of its atmosphere. But our atmosphere is selective to a marked degree as regards emission and absorption of energy in different spectral regions. It is therefore to be expected that the actual mean planetary energy curve of the *Earth* may differ from the energy curve of a perfect radiator or so-called "black body" at the same mean temperature. In such considerations we are met squarely by a number of obvious questions and difficulties involved in the discussion of planetary radiation problems. To know something about the surface conditions we must have a better knowledge of the constitution and properties of the atmospheres. It is

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conceivable that the radiant properties of other planets may be of a character to send out the radiated energy in spectral regions falling within the barriers imposed by the selective absorption of our atmosphere and outside of the limits of transmission of the radiometric apparatus. It would seem highly probable that it will not be possible to determine accurately the total amount of planetary radiation even in the most favorable cases because of the obscuring effects introduced by terrestrial atmospheric absorption of radiation which extends into spectral regions where such absorption is nearly completely constant. For some of the planets the powerful terrestrial water vapor absorption between 4μ and 8μ must deplete a part of the energy but here the case is more hopeful in that this absorption is variable, being dependent to a marked extent upon meteorological conditions, and it is possible that at least a part of the planetary radiation in this region may be directly isolated by carrying out carefully planned observing programs. Furthermore, the extensive research work on atmospheric absorption of radiation in this part of the spectrum should make it possible to apply fairly trustworthy corrections for the depletions, if dependable humidity determinations are made simultaneously with the radiometric measurements.

Planetary Temperatures. In the present state of the radiometric work it is not our purpose to attempt to derive from the measurements actual values for the temperatures of the planets observed, but we have hopes that future observations and discussions may lead to this highly desirable result.

It is difficult to judge as to the possibility of determining actual spectral energy curves of the planets. Further progress in instrumental means may be expected. Our steadily advancing knowledge of the properties of the *Earth's* atmosphere may in time permit fairly trustworthy corrections for general and selective depletions in spectral regions occupied by planetary radiation. Granting that it will be possible to arrive at an approximate knowledge of the distribution of the intensity of radiation in a planet's energy spectrum there is still before the investigator the involved problem of arriving at the connection between planetary radiation and the corresponding temperature of the complex radiating source or sources. As emission from the gaseous and vaporous constituents of planetary atmospheres are involved, the general energy curves of the planets will probably differ one from another, and may deviate to a marked extent from the energy curve of a perfect radiator at the same mean temperature. For bodies having the temperatures one may reasonably assume for the planets the emitted energy has a more uniform and gradually varying distribution of intensity throughout the spectrum than for very hot sources such as the *Sun* where the energy is concentrated in a comparatively narrow spectral band and only a small proportion of the total energy is of greater wave length than 2μ. The comparatively low temperatures of the planets throw a large proportion of the energy into spectral regions where the selective absorption of the *Earth's* atmosphere varies greatly in amount for different wave lengths. These absorptions may for convenience of description be mentioned in the following order: (1) regions

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of the spectrum where the absorption is small, i.e., the transparency high, and practically constant as regards meteorological conditions, such, for example, as the general character of the spectral region between 8.5μ and 13.5μ; (2) spectral regions where the absorption is large and also variable in amount, such as the powerful water vapor absorption bands between 4μ and 8μ which are subject to variability dependent upon meteorological conditions; (3) regions of the spectrum where the absorption is strong but comparatively constant in amount and has little or no certain known dependence upon meteorological conditions, such as the carbon dioxide absorption bands between 3.6μ and 5.4μ, and 13.5μ and 15.5μ. The selective absorption of our atmosphere appears therefore to be an obstacle in planetary energy measurements. In order to isolate the greatest amount of radiation which is influenced by variable factors, such as water vapor absorption, measurements must be carried out according to carefully planned observing programs, utilizing the most favorable conditions. The limitations surrounding the observer will permit him to measure directly only parts of the actual energy curves whether the problem is attacked with the radiometer equipped with suitably devised screens for delimiting the energy measured, or with a highly sensitive spectrobolometer. By applying corrections for depleted regions some approach to actual energy curves may be inferred. An important desideratum at this time is to form some idea, if only in a roughly qualitative way, of the influence of the obscuring factors which probably prevent the detection of, or reduce the intensity of, planetary radiation in certain spectral regions, considered in connection with the present radiometric measurements.

To estimate approximately the influence on the measured planetary energy of the selective action of the *Earth's* atmosphere it would be necessary to know something about the distribution of the radiation in the energy spectrum of the planet, but unfortunately such information is at present lacking. The only means at present available for deriving any assistance in that connection is the employment of the laws of radiation holding for the perfect radiator and such procedure is of course open to question on some points. The auxiliary energy curves are those for the perfect radiator. As elsewhere mentioned the radiant properties of the *Earth* must be chiefly those of its atmosphere. As ABBOT remarks, "Only about one-tenth of the radiation from the solid and liquid surface of the *Earth* escapes directly to space. The atmosphere above 11 kilometers apparently contributes more than half of the radiation of the *Earth* viewed as a planet and prevents half of the radiation of the lower layers from escaping. Nearly the entire output of the radiation of the *Earth* to space, certainly more than three-fourths, arises from the atmosphere and clouds as its source. The 'effective radiating layer,' meaning a layer which if perfectly radiating to space would equal in radiation the actual *Earth* viewed as a planet, may still be thought of as at several kilometers altitude and at a temperature well below freezing."[10]

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[10] *Annals of the Astrophysical Observatory*, Smithsonian Inst. Vol. IV, p. 25.

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The dominant role of the atmosphere has also been emphasized by VERY[11]: "The 'radiant properties of the *Earth*' must of course include those of the atmosphere; but more than this is requisite, because for the largest part of the *Earth*, namely, that included in the tropic and warm temperate zones, most of the radiation which the surface of the *Earth* might emit as its high absolute temperature is prevented by the absorption of the aqueous constituents of the atmosphere. The *Earth* radiates to the air and the air passes the energy along as internal radiation between its particles, and finally as air radiation to space. Thus, in the main, the 'radiant properties of the *Earth*' are those of its atmosphere".

Due to the selective properties of the atmosphere in certain spectral regions it may be assumed that the actual mean planetary energy curve of the *Earth* differs from the theoretical energy curve of the so-called "black body," derived from the calculated mean temperature of the effective radiating layer or surface (To the reader who is not familiar with the subject it is perhaps well to remark that the statement does not refer to a definite atmospheric layer radiating from a given position above the actual solid surface or crust but is a hypothetical radiating layer, as defined in the quotation from ABBOT, in a preceding paragraph). There are, of course, good reasons for extending terrestrial analogies to other planets, though no two planets of the solar system are probably alike as regards their planetary radiation. It is to be expected that different regions of the planetary surfaces, if the area isolated for measurement is not too extensive, will exhibit different characteristics both as to the amount and nature of the radiation sent out.

The true relations existing between the measured planetary radiation and the various factors involved in the energy exchanges of a planet will generally be very complex. For planets which do not radiate appreciable energy on their own account due to internal heat, calculated temperatures by means of the usual procedure, employing STEFAN'S law, should give us a fairly accurate idea of the temperature of the "effective radiating surface." But the meaning of such results are often misinterpreted. It would be well to draw the distinction between the temperature of the hypothetical radiating surface and the actual surface temperature as generally understood in dealing with planetary conditions. For example in the case of the *Earth* the mean temperature of the surface exceeds the mean temperature of the effective radiating layer by about 30°. It can readily be imagined that to unravel from a measured resultant the complex radiation exchanges taking place between the *Earth's* surface and the atmosphere and their joint radiation to space and to find the temperature gradient of our atmosphere would tax the resources of an observer in free space equipped with our present means: and when the investigator is further handicapped by his position at the bottom of an atmospheric ocean which in itself is highly

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[11] *The Radiant Properties of the Earth from the Standpoint of Atmospheric Thermodynamics. P. 75.*

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selective in its behavior towards radiant energy, the problems to be met are of respectable difficulty. The field should be an attractive one to theoretical workers. When one recalls the truly remarkable progress made in recent years in researches on stellar evolution and the internal conditions of the stars one may reasonably expect much to be done on members of the solar system when attention is attracted in that direction.

The theoretical calculations of planetary temperatures should be of service to us in estimating approximately the spectral distribution of the energy sent out by the planet's effective radiating surface and enable us to judge roughly the amount of energy left out of account in the observations. Such estimates must of necessity be uncertain due both to the possible selective properties of the emitting sources and the difficulty of determining the depletion of the actual radiation from the effects of selective absorption of the *Earth's* atmosphere. In the present considerations bearing on the calculation of planetary temperatures it will be assumed that these bodies are neither accumulating nor losing energy — that all the absorbed solar radiation is reradiated. The radiant properties of the earth-like planets would be largely those of their atmospheres and this is probably true to a marked extent for such planets as *Jupiter* and *Saturn* concerning which some astronomers, from various considerations inferred a high internal temperature. Planetary radiation measurements are dealing mostly with the effective radiating surfaces, and analysis of the intricate mechanism of the series of partitionings and transformations of the solar energy taken up by the planet, involving the general and selective processes of reflection transmission, absorption, and reradiation by the surface and atmosphere must at the start be tentative and incomplete. The input part of the problem appears fairly simple, though doubtless we are still lacking full knowledge of the complete effects of solar radiation. If we assume a steady state between the incoming and outgoing streams of energy we may directly find the mean temperature of the planet's effective radiating surface. From this value a mean spectral energy curve may be computed. Though equivalent as regards the integrated total energy, it is to be anticipated that the actual and theoretical energy curves will deviate from each other and have different forms in different parts of the spectrum. It is the business of the observer to find as much as possible of the energy returned by the planet, and it would seem in this early stage of the work that the spectral distribution of the energy would also be desirable in deriving the connection between the measured radiation and the temperature of its source. The difficulties of isolating regions of the energy spectrum of the feeble radiation in low-temperature sources is of course obvious. If the resourcefulness of the theoretical workers should succeed in devising analysis and arriving at interpretations from the measurements of energy in a limited band of the energy spectrum, say, for the spectral region where the *Earth's* atmosphere has a high transparency for long wave radiation, between 8.5μ and 13.5μ it will greatly simplify the arduous labors of the observers.

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In discussions on planetary conditions calculated planetary temperatures are frequently quoted and it is not intended here to belittle the value of such results. But obviously it is unsafe to use such values with the absolute confidence so often shown towards figures derived by calculation. We need not doubt the accuracy of the computations but we have a right to question the hypotheses or assumptions involved when it is a matter of dealing with obscure or imperfectly known factors which enter into the calculations. If it is permissible to apply the laws of radiation to problems of planetary radiation the procedure should not, at the start, carry with it so much an expectation of arriving at trustworthy values for planetary temperatures as for the suggestions the method should give the observer in attacking the problem of securing as great a spectral range of the energy as possible and isolating the maximum amount of energy. The hypothetical energy curves derived from the calculated temperatures may at any rate be a rough guide in some cases as to energy that has not been included in the measurements. Taking into account the more or less well known factors which must influence the results it is evident that even under the most favorable conditions it will be possible to measure directly only a part of the total planetary radiation. Our approach to the true values of the energy must ultimately depend upon the corrections which are applied for the depletions. The subject of the long wave transmission and radiation is one of great difficulty. While much has been done on it some parts are still in an incomplete state and must leave more or less open questions in connection with the analysis and interpretation of the radiometric measurements.

Several investigators have at various times been occupied with the calculation of planetary temperatures, and the most widely quoted are the values derived by Poynting. For bodies like *Venus*, the *Earth*, and *Mars*, the usual procedure employed may perhaps be expected to arrive at approximate values for the mean temperature of the effective radiating surfaces, but as already mentioned, extending such results to the surface of the planet is another matter. If we take the more widely accepted current values for the solar and radiation constants, and the albedo, and carry through the calculation for *Mars*, for example, we arrive at values for the temperature which would seem to be difficult to reconcile with a number of phenomena observed on the planet. These matters are discussed in other parts of the paper.

In his theoretical investigations on radiation in the solar system, assuming that the planets are similar to the *Earth*, Poynting[12] calculated the following temperatures: *Mercury* 196°C, *Venus* 69°, the *Earth* 17°, and *Mars* –38°C. He omitted *Jupiter* and *Saturn* in view of the probability that they radiated heat of their own in considerable proportion. Calculations of this type[13] indicate a lunar temperature of 82°C for the full *Moon*. In his calculations Poynting used a higher value of the solar constant

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[12] Poynting, *Collected Scientific Papers*, p. 304.

[13] Coblentz, *Investig. of Infra-red Spectra*, Pub. No. 97, p. 135, Carnegie Institution of Washington, 1908.

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(2.5 gm cals./cm.^{2} min.) than generally accepted at present and he employed KURLBAUM'S low value for the radiation constant, and the small value of $^1/_{10}$ for the albedo of his "ideal" planet.

Probably the most convincing experimental observations of the range of temperatures of the *Moon* are those of LANGLEY and VERY[14] and later, those of VERY.[15] These measurements indicate inferred effective lunar temperatures ranging from 45°C to over 100°C.

LOWELL'S calculations of the surface temperature of *Mars*[16] gives values much higher than those obtained by POYNTING and others, and they are in agreement with what one would expect from the radiation measurements recorded in the present paper. His calculations, taking into account factors previously neglected, and based on the heat retained, give a mean temperature of 48°F (9°C) for the surface of *Mars*, while another calculation gives a temperature of 22°C. He points out that owing to cloudiness only 60 per cent. of the incident solar radiation is effective in warming the *Earth* while 99 per cent is effective in warming the surface of *Mars*. Observations of *Mars* at later oppositions indicate that its atmosphere is subject to greater obscurations than these estimates but there can be no doubt that the sunward side of the globe of *Mars* is much of the time remarkably free from clouds.

In a recent discussion of climatic conditions on *Mars*, inferred from phenomena generally observed on the planet, PICKERING[17] estimates the mean annual temperature at +20°C as compared with the mean annual temperature of the *Earth* of +59°F (15°C).

SELECTIVE REFLECTION OF SOLAR RADIATION. Investigation of infra-red reflection spectra show that silicates, carbonates and sulphates have the property of selective reflection[18] in the region of the spectrum extending from 6μ to 10μ and the question arose as to the effect this would have upon the solar radiation reflected from a surface like the *Earth* or *Moon*, which is no doubt composed largely of silicates. In the region of selective reflection the radiations that would ordinarily be emitted as a result of warming of the surface by absorption of solar radiation are suppressed. In that paper no estimate could be obtained of the selectively reflected solar radiation of wave lengths 8μ to 10μ which is superposed upon the directly emitted lunar radiation.

More recent consideration of the phenomena does not alter the conclusion that such selective reflection must exist, if the planetary surface contains silicates, carbonates, etc., and in the case of a body with a surface like our *Moon* the effect may be appreciable in amount. For a planet like

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[14] LANGLEY and VERY, *Nat. Acad. Science*, Vols. 3 (1884) and 4 (1887).

[15] VERY, *Astrophys. Jour.*, 8, pp. 199 and 284, 1898; 24, p. 351, 1906.

[16] LOWELL, *Proc. Amer. Acad. Arts and Sciences*, Vol. XLII, No. 25, March 1907. *Phil. Mag.*, (6) 14, p. 161, 1907.

[17] PICKERING, *Pop. Astron.*, 30, p. 410, 1922.

[18] COBLENTZ, Pubs. Nos. 65 and 97, of Carnegie Inst. of Washington.

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the *Earth* with its surface nearly three-fourths water-covered, with the remaining land surface with the greater part covered with soil and vegetation, it is to be expected that the effects of selective reflection, in results dealing with mean values, will be extremely small if not completely suppressed for practical purposes of measurement. From an estimate of the probable maximum magnitude of the selective reflection, and from the calculations of the temperature rise of the planetary surfaces, it appears that for the purpose of the present paper, the planetary radiation may be considered practically free from selectively reflected solar radiation.

The temperatures of the effective radiating surfaces of the planets calculated by the fourth-power law using recent data[19] are considerably lower than POYNTING'S values.

Without some knowledge of the properties of the planetary atmospheres and their temperature gradients calculated values of planetary temperatures must be misleading when interpretations are placed upon them in connection with actual surface planetary conditions. Doubtless the case of *Mars* has suffered the most flagrant abuse in employing such partial results. It may be confidently expected that the radiometric measurements on the planets will stimulate further efforts following LOWELL'S lead of more complete analysis. The phenomena observed on the surfaces of such planets as *Mars* and *Jupiter* would appear to be wholly contradictory to the calculated temperatures. It is however generally conceded that the usual method of calculating temperature is not applicable to *Jupiter* and *Saturn.*

Venus. The radiometric measurements on *Venus* are interesting in that they show only a small percentage of planetary radiation. The planets *Venus* and *Jupiter* have practically the same visual albedo (*Venus* 0.59 and *Jupiter* 0.56, according to RUSSELL). They are subject to great differences of intensity of solar radiation (*Jupiter* : *Venus* = 1: 57.5 approx., at the time of the observations) and both have small planetary radiation, as measured — *Jupiter* 3 per cent and *Venus* 9 per cent. Judging the matter off hand most astronomers would no doubt have anticipated a higher per cent of planetary radiation for both of these bodies, and for different reasons; in one case the reradiation of the large amount of solar radiation absorbed, in the other instance the possible emission of energy due to internal heat. A more complete analysis of the data, allowing for the depletions of energy due to the selective actions of our atmosphere and the measuring instruments, will probably bear out the supposition that both planets have considerably greater planetary radiation than directly measured.

In some respects *Venus* is perhaps the most earth-like of all the planets. Its size, mass, and density do not differ much from those of the *Earth.* JEANS remarks, "Theory would lead us to expect an atmosphere on *Venus* very similar in composition to that on the *Earth.*" We shall not at this

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[19] Radiation constant by COBLENTZ; solar constant by ABBOT; albedos by RUSSELL.

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time undertake a review and discussion of the extensive observational data and the widely different views expressed relative to atmosphere, period of rotation, etc. of the planet. Spectroscopic observations might be expected to give valuable information on the atmosphere, but the method has not yet obtained results which permit of unique interpretations. Careful work on the planet has been carried out by SLIPHER, beginning in 1903 and continued in later years. ST. JOHN and NICHOLSON have recently been occupied with the problem. These observations made with powerful instruments and refined methods, have not brought conclusive evidence as to the composition of the atmosphere, particularly as regards such constituents as water vapor and oxygen which were carefully sought for by the method of velocity-shift, and intensification, compared with the telluric lines of water vapor and oxygen. As in the case of other planets, as for example *Jupiter* and *Saturn*, spectrographic observations of the atmospheres have not yet brought us to the point where anything definite can be said about the constituents of such atmospheres because the depth of penetration of the light analyzed is not known. If the light is returned from comparatively superficial exterior strata the results must be inconclusive as regards the presence or absence of these heavier constituents in the lower strata. We must for the present leave open the question of the composition of the atmosphere of *Venus*. Incidentally it may be mentioned that the investigations of SLIPHER, and ST. JOHN and NICHOLSON, have brought out no evidence of a short period of rotation. This remark is added because it bears immediately on the insolation of the planet's surface and the problem of calculating the mean temperature of the effective radiating surface.

The intensity of the incident solar radiation for *Venus* is almost twice (1.9) that for the *Earth*, and hence one would expect a greater heating of the surface and the lower atmospheric layers of *Venus*, if the solar energy is transmitted and absorbed proportionately to that on the *Earth*. The albedo of *Venus* indicates that about 40 per cent of the incident solar energy is absorbed by the atmosphere and surface. We may assume that for the so-called terrestrial planets no appreciable energy so far as the radiometric measurements are concerned, is sent out due to internal heat, and also, that we are dealing with temperature equilibrium or a steady state — and that all the absorbed solar energy is reradiated. But the altered spectral distribution of the returned energy in the form of planetary radiation may place it in regions where it is masked or rendered more or less inaccessible to direct measurement, due to the selective action of our atmosphere and instruments. For an albedo of .59 the total amount of radiated planetary energy should be approximately 1/10 or 1/5 of the total incident solar energy, or in per cent of the total energy returned by the planet about 15% or 25%, respectively depending on whether it is assumed that the planet has a short day or constantly turns the same hemisphere towards the *Sun*. A plausible explanation of the small amount of planetary radiation measured seems to be that the long wave planetary energy has been ob-

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structed by the selective absorption of the *Earth's* atmosphere in the powerful water vapor bands between 4μ and 8μ, and beyond 14μ. For, if the atmosphere of *Venus* is similar to that of the *Earth,* its planetary radiation will be of wave-lengths 4 to 8μ and longer than 14μ, which would be absorbed by the *Earth's* atmosphere.

While it is intended that calculated temperatures and derived spectral energy curves should be used with due caution in connection with this tentative discussion, a consideration of the matter from this standpoint may be instructive. Taking recent values for the data and employing the fourth-power law the mean temperature of the effective radiating surface comes out 260° and 310° K, for a long and short rotation period, respectively. For a perfect radiator the maxima of the spectral energy curves corresponding to these temperatures would lie near 11μ and 9μ respectively. It may be assumed that a negligible amount of *Venus*' planetary radiation lies at shorter wave lengths than 4μ. The measured energy would therefore be in the interval between 4μ and 12μ. Between 4μ and 8μ occur the powerful selective water vapor absorption bands of the *Earth's* atmosphere. Over much of this region the absorption is nearly complete even with smaller amounts of vapor than generally present in our atmosphere. Much of the planetary energy which may be sent out in this region would therefore suffer heavy depletion, unless the observations happened to be made under exceptionally favorable conditions of small vapor content of the atmosphere. (The hygrometric records taken near the *Earth's* surface at the time of the radiometric measurements we have not deemed trustworthy enough for estimating the amount of vapor in the observational path. It may be stated that the surface conditions were apparently favorable as regards a small vapor content). From the previous considerations one would estimate that the greater part of the present measured planetary radiation for *Venus* is situated in the spectral region between 7.5μ and 12μ, but its distribution in this interval is not determined. Leaving aside for the present the question of a changed form of the energy curve due to selective emission one would estimate for the calculated temperatures given above that a considerable part of the planetary radiation of *Venus* lies outside the spectral interval of effective transmission just mentioned and has escaped detection because of the effects of terrestrial atmospheric absorption.

It cannot now be judged how effectively the present limited observational material may be utilized in temperature investigations on the Planet. *Venus* offers highly interesting possibilities in the way of further observational work. Radiometric measurements should be carried out for restricted regions on different parts of the disk, and also with receivers including the entire surface. It should also be helpful to have accurate photometric measurements of the surface.

Mars. The present radiometric observations bring out the significant fact that, with the exception of the *Moon, Mars* shows the highest percentage (30%) of planetary radiation of any of

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the objects thus far measured. Taking into account the planet's low albedo and the resulting high absorption of the incident solar energy it is obvious that the percentage of planetary radiation actually measured can be only a part of the true planetary radiation, perhaps only in the neighborhood of a half of the long wave energy measurable in free space. This conclusion is based on the spectral energy curve to be expected from the absorbed solar radiation, and the depletion of this energy in its passage through the observer's atmosphere.

For several reasons *Mars* is of unusual interest in connection with these measurements. Physical observations of its surface markings are more complete and extensive than of any other planet. Among the members of the solar system it must, with *Venus*, stand nearest in relationship to the *Earth*, and the observed surface phenomena are more readily interpreted in terms of terrestrial analogies than for *Venus*. Though some matters have been in controversy, there can no longer be any reasonable doubt that many of the observed phenomena on the planet indicate the presence of a fairly extensive atmosphere, and also water vapor and vegetation: (1) the seasonal formation and melting of the polar caps; (2) the formation of temporary obscurations or mists over many areas and particularly those adjacent to the polar regions; (3) seasonal changes in the dark regions which may be reasonably interpreted as the growth and decay of vegetation. It should not here be necessary to go into the fallacies of the arguments which attempt to show that the polar caps are deposits of frozen carbon dioxide. The experimental facts of physics on the properties and behavior of this gas are entirely in conflict with such views, taking into account certain conditions which certainly cannot exist on the planet. Even if the low temperature necessary were granted, our present knowledge of planetary atmospheres would not permit us to assume anything like the pressure needed for the deposition of carbon dioxide. The behavior of the polar caps in forming and dissolving, with their surrounding dark girdle along the border at the time of melting, etc., are in accord with what one should expect from deposits of water vapor in the form of snow, ice, and hoar frost. Records of clouds and obscurations are very extensive, by many eminent observers, going back to the early observations of the planet. It is proper to add that these observations have been variously interpreted, in fact even denied as to their reality. Even if one adopted the very arbitrary procedure of dismissing all of the past observations on clouds and mists as untrustworthy or inconclusive we must meet squarely the significance of the great temporary white area which invaded the *Margaritifer Sinus* region on July 9, of the opposition just past. No reasonable interpretation except a temporary cloud area can explain the observed facts. The formation developed over night. It was intensely brilliant, rivalling the polar caps. (Observations of the brighter terrestrial clouds show reflecting powers approaching 90 per cent). After its discovery it persisted at a maximum brilliancy throughout the last half of the planet's day, being first observed near the Martian

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mid-day. On the following days the brightness fell off rapidly as the area involved increased. Its observed movement and the manner of its dissipation proclaimed it an extended storm area with its accompanying vapor cloud, similar to cloud formations on the *Earth*. The observational data relative to this formation are beyond question owing to the favorable conditions of its presentation. Careful visual examinations were made by several observers, and these observations were fully corroborated by the extensive series of photographs made throughout the period of apparition. We may say, therefore, that *direct* observational evidence establishes with all reasonable certainty the presence of vapor in the atmosphere of *Mars*. Besides, the spectroscopic investigations on *Mars* carried out at this observatory in 1908 and 1914 gave evidence of water vapor in accord with this view.

From our knowledge of the properties and influence of atmospheric water vapor on the *Earth* one may infer something about climatic conditions on *Mars*, and also estimate the possible influence on the radiant properties of the planet resulting from the presence of this constituent in its atmosphere. The smaller value of the surface gravity on *Mars* would of course give a different character to the percentage distribution of the gaseous and vaporous constituents of the planet's atmosphere at different altitudes above the surface than for the *Earth*. Direct evidence as to the great height of Martian clouds have at various times been established by measurements. One might also expect a relatively greater percentage in the atmosphere of *Mars* of such heavy constituents as carbon dioxide. But the greater importance formerly attributed to carbon dioxide by some investigators as a climatic factor has not been corroborated by recent researches, and so far as our present knowledge goes this constituent may be assigned a place of secondary importance, as compared with water vapor, when considered in connection with the spectral range of the present radiometric measurements. If the planetary energy curve of *Mars* could be integrated for longer wave lengths than 13.5μ the influence of carbon dioxide on the observed radiant properties of the planet might possibly be quite appreciable. But the difficulties of disentangling the carbon dioxide emission, if present, of the Martian atmosphere from the corresponding absorption bands in the terrestrial atmosphere appear to be formidable, as the *Earth's* atmosphere contains an amount of carbon dioxide considerably in excess of the amount needed to exercise complete absorption. FOWLE'S researches indicate that one-fortieth part of the amount of this gas actually present in the vertical atmospheric column produces the maximum possible effect. Up to wave lengths as great as 13.5μ we know that in the *Earth's* atmosphere the water vapor absorption bands are dominant as compared with the smaller number and narrower carbon dioxide and ozone bands.

In our present tentative considerations of the radiometric measurements we shall no doubt find it instructive to apply terrestrial analogies to such planets as *Mars* and *Venus*. For all three of

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these bodies we may for the present assume that any appreciable planetary radiation due to internal heat is not present, and that temperature equilibrium exists between the absorbed solar radiation and the energy reradiated. The temperatures of the effective radiating surfaces of these planets are of the same order. But one must be careful to distinguish between these temperatures and the temperatures of the true planetary surfaces at the bottom of the atmosphere. These temperatures of the solid or liquid surfaces are probably dependent upon a number of factors, such as the constitution and radiant properties of the atmospheres, the nature of the true planetary surfaces, the intensity of the incident solar radiation, etc., and it is to be expected that different temperature gradients will be set up between the true surface and the various strata of the atmosphere.

Following the usual procedure of calculating planetary temperatures we find for the *Earth* a mean value for the effective radiating surface about 30° below the observed mean temperature of the surface. It is therefore to be expected that such earthlike planets as *Venus* and *Mars* will also have surface temperatures considerably above the values found for their mean effective radiating surfaces. Doubtless *Mars* with its lesser gravity, rarer and clearer atmosphere, will have an atmospheric temperature gradient somewhat peculiar to itself.

As previously stated, the measured planetary radiation of *Mars* is about 30 per cent, and from the spectral limits of transmission of the radiometric apparatus it is known that this long wave energy lies at wave lengths shorter than 12μ. As to delimiting the spectral distribution of this energy we have at present insufficient observational evidence but we may perhaps infer something as to its location. The powerful selective absorption from moisture in the *Earth's* atmosphere between 4μ and 8μ makes it certain that any planetary radiation in that spectral range, if present, is largely suppressed or obscured. What this depletion may be only future measurements can definitely decide, though we do possess at present a considerable amount of data on water vapor absorption, depending upon local terrestrial meteorological conditions and this suggests the possibility of directly isolating at least some of the planetary radiations in this spectral region. It would be safe to estimate that only a negligible part of the planet's radiated energy lies at shorter wave lengths than 4μ. It is consequently to be inferred that the greater part of the planetary radiation measured in the present observations is of wave lengths between 7.5μ and 12μ. While we may anticipate that the actual spectral energy distribution will not be the same for different regions of the planetary surface and may differ from that of a perfect radiator, in want of more precise information it might be permissible perhaps in a preliminary discussion to indicate approximately the amount of energy left out of account in the measurements, from the derivation of the spectral energy distribution by means of the calculated mean temperature of the effective

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radiating surface and PLANCK'S formula for black body radiation. Actual numerical evaluations and comparisons have not been carried out. However, considerable latitude could be allowed for uncertainties in such estimates and yet leave one on the safe side in concluding that much of the planetary energy from *Mars* has not been included in the present measurements because of its lying in the spectral region of wave lengths longer than 12μ.

The radiant properties of the *Earth* as a planet are largely those of its atmosphere, and the selective actions of this atmosphere play important roles in the transmission, absorption and reradiation of the incoming and outgoing energy streams. The dominant selective properties are attributed to water vapor, carbon dioxide, and ozone. One remarkable property of the *Earth's* atmosphere is its great transparency to radiation in the spectral band between 8–9μ and 13–14μ. In this region there can be only a relatively small emission of energy from the atmosphere itself, if the comparatively narrow absorption bands of carbon dioxide and ozone are left out of account, so that the radiation from the *Earth's* warmed surface or crust, emitted in the spectral band 8–14μ will be transmitted freely to space. If then the composition and properties of the atmosphere of *Mars* resemble those of the *Earth* — except as to density and vertical distribution due to differences of surface gravity — and particularly as regards the great selective absorbing agents water vapor and carbon dioxide, it is to be inferred that the true surface radiation from the planet in the spectral interval between 8.5μ and 13.5μ will be freely transmitted by the Martian atmosphere and will be measurable by an observer at the *Earth's* surface on account of the high transparancy of the *Earth's* atmosphere in the same spectral range.

The water-cell transmissions of the radiations from the southern (50.6%) and the northern (53.1%) hemispheres are higher, i.e., the percentage of planetary radiation is smaller, than the radiations emanating from the equatorial (47.3%) region. This is to be expected from the effect of insolation alone, leaving out of account the modifications of the character of the reradiated energy resulting from atmospheric circulation and the radiation exchanges taking place between the surface and atmosphere. Remarks on atmospheric absorption are added in the following paragraph. At this point in would be well to call attention of the reader to factors which may and probably do, modify the meteorology and the general radiation of *Mars* as compared with the *Earth.* Clouds are much less prevalent on *Mars* and there are no oceans or large free bodies of water with their currents transporting the energy absorbed in certain localities to widely different latitudes where it is reradiated, as in the oceanic circulation of the *Earth.*

At the time of the observations the *Sun* was about two degrees north of the planet's equator so that the insolation for each hemisphere was practically the same. Doubtless some lag in tem-

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peratures occur in each case. The declination of the *Earth* on *Mars* was only about 7° (north) which further simplifies the comparisons. In terms of the Martian seasons it was toward the end of summer or near the autumnal equinox in the northern hemisphere, and near the beginning of spring or shortly before the vernal equinox in the southern hemisphere. One might be led to expect under these circumstances that the water-cell transmissions from the southern and northern hemispheres[20] should be higher than for the radiations emanating from the equatorial regions[21] owing to the small degree of warming of the polar regions, because in these regions the solar radiation traverses a greater air-mass and is incident with greater obliquity upon the Martian surface, and also on account of the depletion of the outgoing reflected and reradiated energy by this same air-mass. From the positions of the *Sun* and *Earth* as viewed from *Mars* one would expect to obtain closely the same transmission for the measured areas of the southern and northern hemispheres, provided the surfaces of these regions are very similar in character and if there are no clouds or other absorptive atmospheric veilings to intercept the reradiated energy. Both the incoming and outgoing energy streams are of course affected by such absorptions and obstructions, but, as in the case of the *Earth,* it is reasonable to suppose that the incident solar energy is transmitted with greater facility than the reradiated long wave energy. These remarks are meant to apply only to average results. Analysis of the radiations from different parts of the surface, isolating smaller areas will doubtless reveal marked differences in the radiation. One may confidently expect to find the effects of diurnal insolation in measurements made of regions on the morning and evening sides of the planet and also for different latitudes when measurements covering different seasons, when the amounts of insolation for the two hemispheres are in stronger contrast than for the present preliminary measures. The differences for the two hemispheres may in the present instance be attributable perhaps largely to the character of the regions measured. The lack of time prevented observations covering different longitudes.

Observations obtained with two thermocouples differing widely in construction, on two dates, are consistent in showing a lower water cell transmission (a higher re-emission) of the thermal radiation from the southern hemisphere than from the northern hemisphere which is on the whole brighter, both visually and photographically, as it is less occupied by dark regions than the southern hemisphere. In the present measurements the receiver over the southern hemisphere covered regions predominantly dark as compared with the areas occupied by the corresponding setting for the northern hemisphere. Taking into consideration the planet's season one might expect, if any-

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[20] These designations mean that the circular radiometer receiver was set centrally on the axis of rotation and tangent to the planetary disc at the pole, including the polar and temporate zones and cutting slightly into the tropical belt. See the diagram.

[21] The radiometer receiver was set centrally on the planetary disc and included only the part of the planetary surface of the tropical belt.

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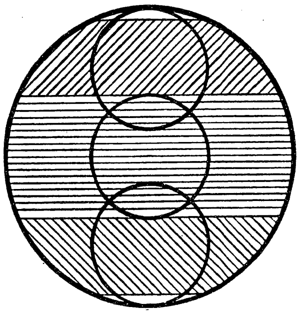
MARS

The results of measurements and other information relative to the regions are here tabulated.

A Southern Hemisphere, (predominance of dark markings)	(a) higher total radiation than N. H. (b) smaller water-cell transmission (50.6%), i. e., proportionately more long-wave radiation than for N. H. (c) lower albedo than N. H., hence greater absorption of solar radiation and therefore probably greater reradiation.
B Northern Hemisphere,	(a) smaller total radiation than S. H. (b) higher water-cell transmission (53.1%), i. e., proportionately less long-wave radiation than S. H. (c) much higher albedo generally than S. H.; reflection of radiation may be largely non-selective from polar cap and extensive cloud areas; loss of transmitted solar radiation through trapping of reradiated long-wave radiation, by clouds and mist.
C Equatorial Belt	(a) higher total radiation than S. H. or N. H. (b) smaller water-cell transmission (47.3%) than S. H. or N. H., i. e., proportionately more long-wave radiation than S. H. or N. H. (c) albedo: for these longitudes of the planet, there is a preponderance of dark markings but they include also a considerable portion of bright areas.

Total Radiation (June 18)	
S. H.	7.1
Eq. Belt	8.2
N. H.	5.4

(arbitrary units)



Water-Cell Transmission	
S. H.	50.6%
Eq. Belt	47.3%
N. H.	53.1%

thing, the northern hemisphere to be slightly warmer at the time of the observations both from the advantage of greater insolation and also from a possible seasonal lag in the march of the surface temperature. The northern hemisphere was of course on the descending branch and the southern hemisphere on the ascending branch of seasonal temperature curves. From the observations one might offer as a possible interpretation that the darker southern hemisphere emits more of the long wave radiation than does the northern hemisphere. Further observations will, however, be

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required to settle definitely that point as doubtless several factors are involved, such as the insolation, meteorological conditions on the planet, and the surface character of the regions observed. Just at the time of the measurements the northern polar regions and the adjacent parts of the temperate regions showed (as fully brought out by subsequent examinations and comparisons) striking evidence of the approaching autumn in the very rapid increase (especially on June 16 and 17 — corresponding dates of the Martian year Sept. 19) in the size of the north polar cap and the extensive area of cloud formations over the neighboring outlying regions. For the part of the radiometer receiver covering the bright area just mentioned one would expect a higher general reflection by the white surface of the polar cap and clouds, and also a diminished outgoing transmission by them of any long wave radiation resulting from the incident solar radiation which has passed through the mist and clouds to the surface.

Jupiter. Transmission measurements of *Jupiter** show no appreciable long wave energy, or planetary radiation. The water cell transmission (Average = 68 per cent) is, within errors of measurement, closely the same as for the *Sun*, — about 69.6 per cent. From the previous discussions of the observations of *Venus* and *Mars* it will be evident that we may not conclude from the apparent absence of planetary radiation that *Jupiter* does not radiate long wave energy, but that the observations indicate that the temperature of the planet is lower than for *Venus*, the *Earth*, and *Mars*. At first sight it may be somewhat puzzling to find that *Saturn*, a much more distant planet which absorbs per unit surface only about one-fourth as much solar energy, shows a measured planetary radiation of about 15 per cent. These observed facts are doubtless significant as regards the physical conditions of the two planets. If for the moment we leave out of account in our preliminary discussion any radiation due to internal heat and suppose temperature equilibrium established with absorbed solar radiation the resulting low temperature would necessarily give a more uniform spectral distribution of the reradiated energy. For example, if an observer in free space measured with perfectly non-selective instruments a planet at the distance of *Venus* and also its exact counterpart placed at the distance of *Jupiter*, the percentage of planetary radiation should be the same. But an observer at the surface of the *Earth*, can only directly measure the energy selectively transmitted by his instruments and the atmosphere. The planet in the position of *Venus* would on account of its higher temperature throw most of its energy in a comparatively concentrated spectral range, whereas the feeble planetary radiation from the same planet at the distance of *Jupiter* would vary more uniformly over a much greater part of the spectral range of the reradiated energy. The selective actions of our atmosphere and instruments would introduce relatively different amounts of depletion. If the albedo of the planet should be about the same as for *Venus*

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* The planetary radiation is so small that in the Bureau paper (*B.S. Sci. Paper* No. 460) no value was assigned to the measurements.

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or *Jupiter* the temperature, for a steady state due to absorbed solar radiation, would throw much of the reradiated energy into the spectral region between 4μ and 8μ where serious depletion by the strong water vapor bands would take place and the loss would be a large proportion of the total energy as well as of the part effectively transmitted between 7.5μ and 12μ. In the second case, with the planet at the distance of *Jupiter*, the theoretical energy curve would indicate that much of the planetary radiation must be thrown into regions of strong selective absorption of the atmosphere and also beyond the transmission range of the instrument, so that the part effectively transmitted by the atmosphere and instrument (7.5μ — 12μ) would be only a small fraction of the total energy emitted by the low temperature source. If the absorbed solar radiation alone played the dominant rôle in the planetary radiation from *Jupiter* it should therefore not be surprising that the radiometric results are of the character actually found. The theoretical mean temperature of the effective radiating surface of *Jupiter*, if maintained by absorbed solar energy would be not far from 100° Abs. or about −175° C. The energy curve corresponding to such a temperature indicates what a small proportion of this relatively feeble energy falls within the region effectively transmitted to the thermocouple receiver. Unless very precise measurements could be made the small difference between the actual transmission values for the *Sun* and planet might not stand out clearly. The preceding remarks are based on the assumptions that we are dealing with a perfect radiator and that the reradiated energy arises wholly from absorbed solar radiation. It is to be expected that the problem is much more complicated. We may reasonably assume that the planet's atmosphere possesses properties of selective absorption and emission as in the case of our own atmosphere. The radiation exchanges may occur in spectral regions which are largely inaccessible for practical purposes of measurement. The views widely held that the planet may have a comparatively high internal temperature seems reasonable enough as inferred from the various observed surface phenomena. But to many, evidence of this kind is not conclusive. The present measures do not directly support the hypotheses of a high temperature, as high say, as for the *Earth* or *Venus*, but it may well be and probably is much higher than the theoretical temperature based only on that maintained by the absorption of solar energy. It is difficult to understand how a temperature of the effective radiating surface of the order of 300° Abs. could have failed to give some evidence of appreciable infra-red radiation in the measurements. Any assumption of energy so selectively emitted that the depletions by our atmosphere and observing instruments should wholly mask the planetary radiation for such a temperature appears to be too arbitrary.

Spectrum photographs of *Jupiter* and *Saturn* are very similar, and one might infer from this that the constitutions of their atmospheres are similar. But it may not be permissible to conclude

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from the available spectroscopic data that the composition or radiant properties of these atmospheres are alike, or even similar in some important respects. It is not yet known to what depths the spectroscopically examined light has penetrated; the examination may be quite superficial. The spectral range of the radiation examined spectroscopically includes practically only the visual region. While it is true that the greater part of the incident solar energy lies in this region, it is to be expected that important atmospheric bands should lie at longer wave lengths. As in the case of the *Earth's* atmosphere, doubtless other planetary atmospheres possess properties of selective absorption but such characteristics may differ widely for different planets. More definite information relative to certain important data on planetary atmospheres may be expected to greatly aid in the interpretation of the energy measurements, and we must not yet attempt to interpret too definitely the radiant properties of the planets by extrapolating measurements on limited regions of the spectral energy distribution. In the present state of our knowledge we cannot conclude that *Jupiter* does not actually send out considerable amount of planetary radiation. The enormous and rapid variations in the surface detail observed both visually and photographically at once testifies to the presence of energy and it would not be in keeping with our experience in connection with material systems to assume that radiant energy is not sent out. Of course radiation takes place, at all temperatures above absolute zero. Certainly the forty per cent of the absorbed incident solar energy must be reradiated but how much from internal heat we do not at present know. Even if it is assumed that the planet has a considerably higher temperature than would result from absorbed solar energy, say between 150° or 200° Abs., for the effective radiating surface, the resulting spectral energy curve (for a perfect radiator) would have so large a proportion of its energy outside of the spectral interval directly accessible to measurement that very accurate transmission measurements by the radiometer or bolometer will be needed to isolate the actual planetary energy falling upon the receiver.

Saturn. Of the measured total radiation from the ball of *Saturn* from 12 to 15 per cent is long wave length planetary radiation. In view of the almost total absence of planetary radiation from *Jupiter* the case of *Saturn* is interesting. Various considerations, such as the similarity of the spectra, the character of the surface phenomena as recorded by visual and photographic observations, the amount of solar energy absorbed, etc., might lead one to expect that radiometrically these two planets would have shown a greater similarity than actually found. The radiometric results are doubtless significant in their bearings on the internal states of these planets and the constitution of their atmospheres. From absorbed solar energy alone, if it were possible to integrate practically the entire spectral range of the planetary radiation curve of *Saturn*, one should have about the percentage value actually found for the planetary radiation. There seems to be no

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escape from the conclusion that we are here dealing with radiation due to the planet's internal heat. For *Saturn* the temperature of equilibrium with the absorbed solar energy is very low — less than 100° K. A comparison of the black body energy curve for this temperature with the terrestrial atmospheric absorption of low temperature radiation shows at once that it would be possible to measure directly only a very small fraction of the total planetary radiation due to solar influence in this case. We may expect to find that the planets will show selective radiation, with the development of more refined instruments and methods of observation, but we shall not here attempt to bridge a difficulty by calling to our aid an assumption of a high selective emission of the absorbed solar energy in the comparatively narrow band of the energy spectrum accessible to measurement. A part of the radiation due to the internal heat is probably transmitted directly by the planet's atmosphere but most of it doubtless leaves the planet after very complex radiation exchanges in the atmosphere. The spectral transmission limits of the measuring instruments tell us that the observed energy must practically all lie in a region of wave lengths shorter than 12μ, but its actual spectral distribution is not known at present, and this may be a matter of some importance in the information it may give on the temperatures of the emitting source or sources.

Calculation of the temperature of the effective radiating surface of *Saturn*, due to absorbed solar energy alone, by the fourth-power law, employing recent values for the required observational data, gives the low value of about 70°C absolute. From examination of the table giving the values of the intensities of the incident solar energy and the albedo it is seen that *Saturn* absorbs only about one-third of the solar energy absorbed by *Jupiter*, average values per unit surface, normal incidence. For the computed temperature the energy emission is very feeble and the spectral energy curve is of course, very flat, so that only a very small fraction of the total radiation would fall within the spectral band transmitted effectively by the *Earth's* atmosphere and measuring instruments. In the present state of the investigation the most plausible interpretation of the results of the measurements seems to be that energy emitted by *Saturn* on its own account has been observed.

It is not meant to carry too far the comparison of energy curves of the perfect radiator in planetary problems. The radiated energy curves of the planets may deviate to a marked extent from black body energy curves as regards the character of the actual spectral distribution. All that any of the comparisons imply in the present discussion is that the total energy returned by the planet due to absorbed solar energy should be equivalent to the black body radiation of the effective radiating surface for its computed temperature, leaving out of account radiation due to possible internal heat. The eminently selective properties of gases and vapors warn us that working

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hypothesis based on the assumption of the perfect radiator must be used with caution, since the atmospheric envelopes of the planets must play such important parts in the actual radiation they send out. For average or mean values one would expect theoretical and actual results to be approximately in agreement, but on the other hand isolated regions might deviate to a marked extent.

In observations of *Saturn*, as well as the other planets, the importance of extending as far as possible the spectral range of the measuring apparatus should be desirable, and also means for delimiting the energy in different spectral regions. Subsidiary investigations to supplement the radiometric work are urgently needed.

The Moon. As already stated, the water cell transmission of the radiation from the *Moon* is low (15 per cent) indicating a large temperature rise of the lunar surface, due to heating by solar radiation. Furthermore, this superficial radiation is estimated at 80°C to more than 100°C after prolonged insolation. By comparison of the planetary radiation from the *Moon*, and from *Mars*, it appears that the temperature rise of *Mars* is considerable, from 10°C to 20°C.

V. SUPPLEMENTAL DISCUSSION

The problem of the radiation from a planet and its surrounding atmosphere is exceedingly complex and no attempt is made at this time to enter into a full discussion of the numerous subsidiary questions involved.

As previously explained, the present observations were carried out principally with the idea of making a beginning on a program of more systematic work in radiation measurements on the planets. Unavoidably the data are incomplete on account of lack of time for making more extensive measurements, and also because certain auxiliary observational means were not available at the time.

The observational work and the discussions are preliminary, and in the meantime it may be useful to amplify certain statements in preceding parts of the paper. For example, planetary radiation might have been defined and discussed in greater generality but the practical limitations imposed upon the observer will probably in most cases largely confine measurements to the spectral band between 7 and 14μ. Hence even though a planet may be radiating all wave lengths extending from 3 to 100μ only the wave lengths extending from 7 to 14μ will generally be transmitted by the *Earth's* atmosphere. The limit was set at 12μ for planetary radiation owing to the fact that the fluorite window (2 mm in thickness) of the vacuum thermopile is opaque to radiations of wave lengths greater than 12.5μ. By using a rock salt or sylvite window the additional planetary radia-

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tion of wave lengths extending from 12 to 14μ would be observable, and hence the transmission data might be relatively different from those given in Table 1.

Until trustworthy spectral energy curves of planetary radiation can be determined it may not be possible to estimate accurately what proportion of the planetary radiation is absorbed by the terrestrial atmosphere. Hence, the statement that the water cell transmission is a measure of planetary radiation must remain indefinite, and the values assigned to the various planets are not completely comparable. For example, the value (80) given for the *Moon* may represent practically all the planetary radiation emitted. On the other hand, the value (9) assigned to *Venus* may represent only 10 per cent of the total planetary radiation of all wave lengths emitted; the remaining 90 per cent being of wave lengths which are absorbed by the *Earth's* atmosphere.

A discussion of the radiative equilibrium of the planets has not been attempted. It is generally assumed that the planetary temperatures have reached a steady state. It is also generally assumed that all bodies above the absolute zero of temperature emit thermal radiation. The fact that but little planetary radiation was observed from *Venus* simply means the apparent absence of radiation of wave lengths from 7 to 12μ. But nothing is known at present of its emission of radiation of wave lengths 4 to 7μ, and of wave lengths greater than 12μ which is absorbed by our atmosphere and instruments.

ABBOTT (in his book on the *Sun* and in other papers) shows that but little of the nocturnal radiation from the *Earth's* surface escapes directly into space, and that the *Earth's* effective radiating layer may be regarded as situated in the atmosphere, consisting chiefly of layers of water vapor at an elevation of several miles, and at an average effective temperature of about —10 C. It is generally supposed that KIRCHHOFF'S law of emission and absorption holds. Hence, at this low temperature the water vapor emission will be predominantly of wave lengths greater than 14μ with a less intense emission of radiation of wave lengths 4 to 7μ. An observer, using the herein described water cell apparatus on a planet similar to the *Earth,* might therefore conclude that practically all the planetary radiation (the nocturnal radiation of wave lengths 7 to 12μ, emitted by the *Earth's* surface) is trapped by the *Earth's* atmosphere. Furthermore, he would not observe the radiation emitted by the water vapor of the *Earth's* atmosphere, because it is absorbed by the water vapor in the atmosphere of the planet he used as an observing station, if one considers mean value effects. If the observer, however, selected his station with special care as regards the transparency and dryness of his atmosphere he should probably be able to detect radiation from the water vapor in the other planet's atmosphere and also from the solid surface over its

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warm and arid regions — through the great atmospheric spectral band 8 to 14μ which would readily transmit the surface planetary radiation.

It is not unreasonable to suppose that there may be a similar effective radiating layer in the atmosphere of *Venus*, the temperature of which will no doubt be higher than that assigned to the *Earth*. The nocturnal radiation from the surface of *Venus* (like that of the *Earth*) will be small, as observed. The radiation emitted by the water-vapor in the atmosphere of *Venus* will be absorbed by the *Earth's* atmosphere and the planetary radiation is low, as observed. No doubt there are other explanations to account for the absence of planetary radiation from *Venus*, but this one seems to account for the unexpected observation of practically no radiation of wave lengths 7 to 12μ.

If the temperature of the effective radiating layer of the *Earth's* atmosphere is low (–10°C) as estimated by ABBOT, it may be assumed that, if *Jupiter* has a similar effective radiating layer, its temperature will be still lower, owing to the greater solar distance. Hence, the atmospheric radiation will be mainly of wave lengths greater than 15μ which are absorbed by the *Earth's* atmosphere. The statement that the radiation emanating from the interior of *Jupiter* is completely trapped refers of course to the observable spectral region of 7 to 12μ.

From these considerations it does not appear inconsistent with the theory of radiative equilibrium and planetary temperatures to find practically no emission of thermal radiation of wave lengths 7 to 12μ from the planets which have thick, dense atmospheres. It simply means that, owing to terrestrial atmospheric absorption, we cannot observe the radiation emitted by these planets.

In conclusion, it is relevant to emphasize that this paper presents the results of a search for a means of investigating the radiation (particularly from the interior) of a planet. These results show that for planets having dense atmospheres, the secrets within will to a great extent remain hidden. On the other hand, in a planet like *Mars*, a way has been shown for studying the radiation from different parts of the surface. The observation of accurate quantitative data must await the future.

VI SUMMARY

The present investigation was undertaken for the purpose of obtaining measurements of the thermal radiation emitted from a planet as a result of warming of its surface by exposure to solar radiation, including heat radiated by virtue of a possible high internal temperature of the

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planet itself, and also selectively reflected solar radiation of long wave lengths. It is shown that the latter is probably small and negligible in comparison with the radiation emitted as a result of heating by solar radiation.

By comparing the transmission of the direct solar radiation through a 1-cm. cell of water, with the transmission of the radiation emanating from the planet, a measurement is obtained of the intensity of the planetary radiation, in as far as it is transmitted by the *Earth's* atmosphere and the radiometric apparatus.

Radiometric measurements were made on *Venus*, *Mars*, *Jupiter*, *Saturn* and the *Sun*, and in cases where similar measurements had been made at Mt. Hamilton, Calif., in 1914, the data were found in good agreement.

The radiometric measurements of the water cell transmissions of the radiations from *Jupiter* and from the *Sun* were practically the same. A direct interpretation of the results may not be obvious. It cannot mean the absence of long wave radiation from the planet but probably does indicate the energy reradiated as the result of absorption of solar energy and the emission of radiation due to possible internal heat is of such wave length and spectral distribution as not to be transmitted to the radiometer receiver on account of terrestrial atmospheric absorption and the limits of transmission of the radiometric apparatus. It is therefore to be inferred that the mean temperature of *Jupiter's* effective radiating surface must be considerably lower than for any of the so-called terrestrial planets.

The intensity of the planetary radiation increases with decrease in the density of the surrounding atmosphere and (as interpreted from the water cell transmission) in per cent of the total radiation is as follows: *Jupiter* (3), *Venus* (9), *Saturn* (15), *Mars* (30) and the *Moon* (80).

The intensity of the planetary radiation from the northern hemisphere of *Mars* was found to be less than from the southern hemisphere. This might be expected for the present measures in view of the preponderance of dark markings in the southern hemisphere as compared with the northern, and perhaps also in part to the observed increase in cloudiness of the north polar regions at this time.

Flagstaff, Arizona. January, 1923.

VII APPENDIX — CONCERNING STELLAR TEMPERATURES

BY W. W. COBLENTZ

During the past summer at the invitation of the Lowell Observatory to carry out radiometric measurements on the planets, the writer was given a further opportunity to continue his investigations of 1921, relating to instruments and methods of radiometry, as applied to the measurements

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of stellar and planetary radiation. It is one thing to attempt to develop stellar radiometric apparatus as a part of a general investigation of instruments and methods of radiometry, and it is quite another thing to have placed at one's disposal a large reflecting telescope to try out such apparatus under favorable sky conditions. It is therefore with a grateful feeling that the writer of this part of the paper records here his acknowledgements to the Lowell Observatory for financing this research, and for the numerous courtesies shown him.

A description of the spectral radiometer has been given in connection with the radiometric measurements of the planets and reference is made to that part of the paper for an account of the methods of observation and recent improvements and developments of the apparatus.

As mentioned in the part of the paper dealing with the radiometric measurements of the planets, the method of determining the spectral energy distribution of stars was worked out early in 1919. Since then the device has been given a thorough trial and found to fulfil all the claims made for it. By means of the transmission screens it was possible to obtain for the first time an insight into the radiation intensities in the complete spectrum of a star.

In this connection it is of interest to point out that the results obtained in mapping the spectral energy distribution of a star by means of a spectrobolometer may be essentially different from those obtained by the use of transmission screens. For, as may be seen from inspection of photographs of stellar spectra, the spectrum of a star consists of a bright continuous background superposed upon a series of absorption (and in some cases bright emission) lines. Hence, unless a very large dispersion can be used, the spectrobolometer will merely cover wider regions of the spectrum containing bright and dark bands. The spectral transmission screen does practically the same thing, in the sense that it integrates the energy present in a certain spectral region (without indicating the amount lost in the spectral absorption lines) and has the advantage of utilizing perhaps 40 per cent of the total intensity of the incident radiations which is lost by employing a spectroscope.

From this it is evident after exhausting the possibilities with the spectrobolometer, the spectral transmission screen method should become a valuable adjunct in extending the spectral radiation intensity investigations to stars which are too faint to measure with the spectrobolometer.

Furthermore, after exhausting the possibilities with the spectral transmission screen method there still remains the photographic plate for determining the spectral energy distribution of the very faint blue and yellow stars, which (as first demonstrated by the writer in 1914, by measurements through the water cell, on bright stars of the same spectral class) have practically all their

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radiations of wave lengths situated in that part of the spectrum to which the photographic plate is sensitive.

It may be added that if this fact had been known to astronomers, instead of plotting the densities of the photographs of stellar spectra, they could have determined the spectral energy distribution of blue and yellow stars photographically, long ago, by simply calibrating the spectral sensitivity of their plates in terms of the spectral energy distribution of some standard source.

Herewith is given the spectral energy distribution and the temperature of the *Sun*, as determined by means of a series of transmission screens placed in front of the stellar radiometer. The data obtained verify previous measurements indicating stellar temperatures ranging from 3000° K for red, class M stars, to 12,000°K for blue, class B stars.

In a previous paper,[23] data are given on the spectral energy distribution and the temperature of 16 stars as determined by means of a series of transmission screens placed in front of a vacuum thermocouple, as described and illustrated in a foregoing part of the present paper.

Not being equipped at that time for making radiometric measurements on the *Sun*, the effective temperature of which is known with some degree of accuracy, and hence could be used as a standard, an estimate of the effective temperature of a star was obtained by two methods. The first method consisted in making all corrections to the observations, excepting those for atmospheric absorption, and comparing them with the calculated values, using a solar type star (α *Aurigae*, Class Go) as a standard. This seemed permissible, in view of the fact that the observed temperature (6000°K) of α *Aurigae* was found to be in close agreement with that assigned to the *Sun*. The stellar temperatures estimated in this manner are given in column 4, Table 4. The results of the present investigation show that this assumption was satisfactory.

The second method consisted in applying all corrections to the observations, including the one for atmospheric absorption, and comparing the results with the calculated values. Applying factors for atmospheric absorption introduces great irregularities in the observed spectral radiation components. This no doubt is owing partly to selective emission of the star, and partly to the use of improper transmission factors, which, because of lack of time could not be determined directly.

The temperature of a star, as estimated from the spectral energy components outside of the atmosphere, extends over a wide range, the average value of which is in good agreement with that obtained by the first method. (See column 4 of Table 4).

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[23] COBLENTZ, *Bur. Standards Sci. Paper* No. 438; 1922.

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As mentioned in a preceding caption (II), for the present investigation a special thermocouple was provided for measuring the spectral radiation components from the *Sun.* The solar radiation data are given in Table 5, in which column 1 gives the spectral range, and columns 2 and 4 give the spectral radiation components (A.M. and P.M.) of the *Sun,* (also of α *Aurigae,* Column 6) corrected for all losses except atmospheric absorption. The corresponding temperatures are given in columns 3, 5 and 7.

For the purposes of the present investigation, the agreement between the observed temperatures of α *Aurigae* and the *Sun* is satisfactory and the scale of temperatures given in Table 4, remains as previously published.

It is interesting to note that less than 1 per cent of the total solar radiation measured is of wave-lengths greater than 4μ. This is in agreement with measurements made by the Smithsonian Astrophysical Observatory showing that practically no solar radiation of wave-lengths greater than 4μ is transmitted by the *Earth's* atmosphere. This fact makes it possible to study planetary radiation by means of transmission screens as described in the foregoing part of this paper.

These data are interesting in showing a close agreement between the spectral radiation components of the *Sun* and α *Aurigae* in the visible spectrum (0.43μ to 0.6μ) which is in agreement with the visual and photographic observations. However, in the ultra-violet the radiation component of α *Aurigae* is less, — and in the infra-red it is greater than that of the *Sun.*

These radiometric observations, showing that the solar radiation, in the region of short wave-lengths, is greater than that of *Capella* are in agreement with what is known from direct comparisons of their spectra, which show that dwarf stars are bluer than giant stars of the same spectral type.

In conclusion a few comments are appropriate concerning the relative size of the galvanometer deflections as observed with the 36-inch Crossley reflector and with the 40-inch Lowell reflector. The latter has a diagonal mirror which probably renders the two mirrors of not markedly different effective apertures.

For the 1921 observations the galvanometer coils were in series-parallel giving a resistance of 20 ohms as compared with 5 ohms in 1914. Hence a galvanometer sensitivity of $i = 1 \times 10^{-10}$ ampere was really only $i = 2 \times 10^{-10}$ ampere when compared with the observations of 1914. This reduced galvanometer sensitivity was compensated for by using the double deflection (by exposing both thermo-junctions to the star) and the resultant galvanometer deflections of 1921 for a given star are practically the same as those observed in 1914.

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Table 4. — Stellar Temperatures

Star	Class	Coblentz		Wilsing, Scheiner & Münch	Nordmann and LeMorvan	Nordmann	Saha
		Calculated °K	Class G0 as Standard °K	°K	°K	°K	°K
ε Orionis	B0	13,000 to 14,000	13,000	.....	.....	.....	18,000
β Orionis	B8p	10,000 to 12,000	10,000	.....	.....	.....	.....
α Lyrae	A0	8,000 to 10,000	8,000	9,400	.....	12,200	.....
α Canis Majoris	A0	8,000 to 11,000	8,000	.....	.....	.....	12,000
α Cygni	A2	8,000 to 10,000	9,000	9,400	.....	.....	.....
α Aquilae	A5	7,000 to 9,000	8,000	8,100	.....	.....	.....
α Canis Minoris	F5	5,500 to 7,500	6,000	7,200	.....	.....	.....
α Aurigae	G0	5,300 to 6,500	6,000	7,100	.....	.....	7,000
α Bootis	K0	3,500 to 4,500	4,000	3,700	.....	.....	.....
β Geminorum	K0	4,500 to 7,000	5,500	4,900	.....	.....	.....
α Tauri	K5	2,800 to 4,500	3,500	3,500	3,600	3,500	.....
α Orionis	Ma	2,800 to 3,300	3,000	3,000	.....	.....	5,000
α Scorpii	Map	2,500 to 3,200	3,000	.....	.....	.....	.....

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Table 4. — Stellar Temperatures (*Continued*)

Star	Class	Coblentz		Wilsing, Soheiner & Münch	Nordmann and LeMorvan	Nordmann	Saha
		Calculated °K	Class Go as Standard °K	°K	°K	°K	°K
β Andromedae	Ma	3,500 to 4,500	4,000	3,200	4,300	3,700	.....
μ Geminorum	Ma	2,500 to 3,300	3,500	3,100	3,200	.....	.....
β Pegasi	Mb	2,500 to 3,200	3,000	2,800	.....	.....	.....
Sun	Go	.....	5,800* to 6,200	.....	.....	5,320	.....

* Coblentz, Recalculated from Abbot & Fowle, *Jour. Opt. Soc. Amer.*, 5, p. 272; 1921.

Table 5. — Spectral Radiation Component of the *Sun* and of α *Aurigae* in Per Cent of the Total

Spectral range μ = 0.001 mm	SUN				α AURIGAE	
	A. M.		P. M.			
	Spectral radiation component	Temperature °K	Spectral radiation component	Temperature °K	Spectral radiation component	Temperature °K
0.30μ to 0.43μ	25.0%	5670	35.6%	5750	18.4%	5000?
0.43μ to 0.60μ	22.1	6500	19.0	5760	18.2	5800
0.60μ to 1.40μ	31.8	5860	35.0	5050?	30.6	6000
1.40μ to 4.10μ	20.6	6060	20.1	6140	26.4	5200?
4.10μ to 10.00μ	0.5	....	0.8	....	6.4	....
Average		6000 °K		5900 °K		5900 °K