MEASUREMENTS OF ULTRA-VIOLET SOLAR RADIATION[1]

By EDISON PETTIT

ABSTRACT

The ultra-violet solar radiometer.—This instrument (Pl. XI*a*) consists of a pair of quartz lenses, one silvered and one gilded, mounted on a rotating disk (Fig. 1) electrically controlled in such a manner that images of the sun in $\lambda\, 0.32$ and $0.5\,\mu$ are made to fall alternately upon the receivers of a compensated thermocouple for consecutive periods of one minute. A complete determination of the ratio of ultra-violet solar radiation at $\lambda\, 0.32\,\mu$ to green radiation at $\lambda\, 0.5\,\mu$ is obtained each four minutes of time, the galvanometer deflections being registered photographically (Fig. 3) together with an hour-angle scale recorded by the control clock (Pl. XI*b*).

Secular variation of the measurements.—The radiometer has been in operation on most of the clear days since June, 1924. Each galvanometer record has been measured, and the logarithms of the ratio ultra-violet to green, plotted against sec z (Fig. 3), furnish a determination of this ratio for the zenith and for no atmosphere for that day. A plot of the monthly means (Fig. 4) shows a considerable correlation with the sun-spot curve, but the amplitude (0.95–1.56) is too great to be explained by variations of solar temperature alone. Since no check observations are available, it is possible that at least a part of this amplitude is due to atmospheric or instrumental effects not understood at present.

Atmospheric and instrumental sources of error.—The effects of the variation of atmospheric ozone on the radiometer measurements were tested experimentally with an ozone tube placed over the radiometer and were found to be negligible. The small variation in atmospheric transparency (Fig. 4) does not seem to show any correspondence to the radiometer-curve. A certain white haze affects the measurements in the afternoon, and, on this account, only morning observations have been used. The transmissions of the metallic films (Fig. 2) seem not to have changed during the seven years they have been in use.

Ultra-violet light from the sky.—By means of a silvered photoelectric cell it was found that the intensity on a horizontal plane of ultra-violet sky light at $\lambda\, 0.32\,\mu$ is about equal to that of direct sunlight when the sun is near the zenith at Pasadena (elevation 845 ft.). The same result was obtained at $\lambda\, 0.31\,\mu$. Change in elevation increases the direct sunlight about as much as the intensity of sky radiation diminishes at this wave-length. Seasonal and weather effects (Fig. 5) studied with an automatic device show that we receive on a horizontal plane about 25 per cent as much radiation of $\lambda\, 0.32\,\mu$ on a cloudy as from sun *plus* sky on a clear day. The least amount observed was 10 per cent, recorded during a rainstorm. We receive about as much on a clear day at the winter solstice as during a cloudy day in midsummer. After the sun reaches an altitude of 6°, the intensity of sky radiation at $\lambda\, 0.32\,\mu$ on a horizontal plane increases proportionally with the solar altitude. The distribution of radiation at $\lambda\, 0.32\,\mu$ over the sky (Fig. 7) is rather uniform, being somewhat greater toward the southern horizon under the sun and less toward the northern horizon. The sudden increase near the sun takes place at greater angular distances on hazy days.

Ultra-violet limit of the spectra of skylight and direct sunlight.—A quartz spectrograph and a concave grating, crossed with a quartz monochromator, were used. In midsummer the ultra-violet limit of skylight is about $\lambda\, 0.296\,\mu$ and of direct sunlight a little less than $\lambda\, 0.290\,\mu$. In midwinter the limits are $\lambda\, 0.298$ and $0.296\,\mu$, respectively. It is believed that it would be difficult to detect the spectrum of the sky much

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 445.

below λ 0.295 μ for a point far from the sun. This argues for a small amount of ozone in the lower atmosphere.

Spectral energy-curve of the sun in the ultra-violet.—This was investigated at the Research Laboratory of the Desert Sanatorium at Tucson with a double arrangement of Bausch and Lomb quartz monochromators (Pl. XII*b*), fed by a siderostat (Pl. XII*a*) with stellite mirror. The thermopile alone was used for wave-lengths greater than about 0.32 μ, while for shorter wave-lengths a quartz photoelectric cell was used in addition to the thermopile. Measurements were made for wave-lengths between λ 0.7 and 0.292 μ. The results show that, outside the atmosphere, the energy-curve (Figs. 10 and 11) has a sudden drop of 35 per cent between λ 0.40 and 0.38 μ and a nearly constant value at about 43 per cent of the maximum between λ 0.38 and 0.325 μ, nearly the entire ultra-violet spectrum. A calibration is given in watts per square meter per hundred angstroms.

Atmospheric ozone at Tucson.—The atmospheric transmissions (Fig. 9) below λ 0.32 μ obtained in the course of the measurement of the solar energy-curve furnish a determination of the atmospheric ozone at Tucson. This is equivalent to a layer 0.18 cm thick at N.T.P.

The well-known eleven-year period of sun-spots strongly suggests that the solar radiation may be a variable quantity. That this variation may be most pronounced in the extreme ultra-violet is to be expected from our experience with non-eclipsing variable stars. Thus the photographic range of brightness of the Cepheid variables is, on the average, 50 per cent greater than the visual range;[1] and the visual range of the long-period variables exceeds that of their total radiation by more than 4 mags.[2] Should the sun be slightly variable, whether owing to a change in temperature, a variable emissivity, or a variable transmission of the outer solar envelope, the range in the ultra-violet radiation would probably be much greater than that in visual or infra-red radiation.

In 1922 C. G. Abbot and his colleagues[3] compared the ordinates of bolometer-curves at several selected wave-lengths recorded at times of high and low solar constant and found that the difference was most pronounced in the extreme ultra-violet, being about 5 per cent at λ 0.32 μ and scaling off practically to zero in the near infra-red. About the same time, G. M. B. Dobson[4] in England, using a photographic method, measured on thirty-four days the solar radiation transmitted by silver films and found a large variation. It occurred to the writer that the defects of the photographic process

[1] Russell, Dugan, and Stewart, *Astronomy*, **2**, 761, 1927.

[2] Pettit and Nicholson, *Mt. Wilson Contr.*, No. 369, p. 486; *Astrophysical Journal*, **68**, 306, 1928.

[3] *Annals of the Astrophysical Observatory, Smithsonian Institution*, **4**, 206, 1922.

[4] *Proceedings of the Royal Society of London*, A, **104**, 252, 1923.

could be avoided by using a thermocouple as the measuring device, and that the uncertainties arising from the atmosphere and the standard of radiation could be eliminated by comparing the deflections produced by sunlight transmitted by silver with those produced by sunlight transmitted by gold. By making the apparatus automatic the number of observations could be increased and a continuous record of sky conditions obtained.

The principle of the apparatus designed to meet these specifications is illustrated in Figure 1. A spindle *A* carries a disk *D*, on which two lens cells are mounted diametrically opposite each other with their centers 6 inches apart. Cell *S* contains a crystal quartz lens and plate, both silvered chemically on their inner surfaces with two coats of silver. Cell *G* contains a similar quartz lens and plate, both coated with gold on their inner surfaces by sputtering. The lenses are of the crossed type, having minimum spherical aberration, and are of 1-inch aperture and 2-inch focal length. The separators fit the surfaces and make practically air-tight contacts. Simple copper diaphragms in contact with the outer surfaces of the plates limit the aperture of the silvered lens to 8.08 mm, and of the gold lens to 9.35 mm. These diaphragms have proved a valuable means of checking the effect of continued exposure of the apparatus to sunlight on the transmissions of the lenses and filters.

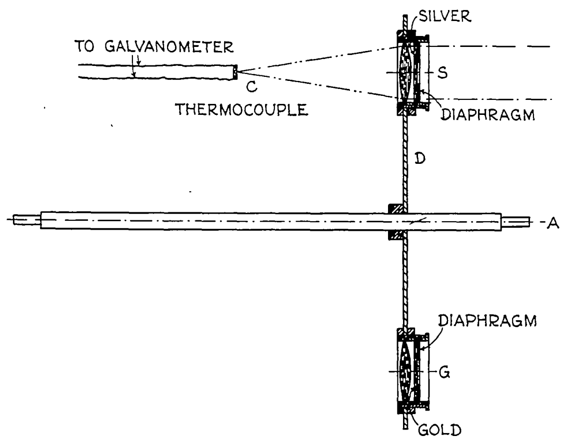


FIG. 1.—Principle of the ultra-violet solar radiometer.

Exposed to the sun, the silvered lens forms a solar image $\frac{1}{2}$ mm in diameter, in ultra-violet light of wave-length 0.32 μ, on one junction of the compensated thermocouple *C*. An escapement attached to the spindle *A*, operated electrically each minute by a contact clock, causes the image to fall first on one, then on the other blackened receiver of the thermocouple, and then permits the disk to rotate a half-revolution and thus interchange the lenses. The process is then repeated with the gilded lens, which transmits green radiation at $\lambda\, 0.50\, \mu$. The galvanometer deflections produced by the thermocouple furnish a complete determination of the ratio of the ultra-violet radiation at $\lambda\, 0.32\, \mu$ to the green radiation at $\lambda\, 0.50\, \mu$ every four minutes of time. The transmissions of the gold and silver films are shown in Figure 2.

Plate XI*a* shows the ultra-violet solar radiometer attached to the 6-inch telescope on Mount Wilson. A brief description of the instrument and some of the results obtained with it have already been given.[1] The thermocouple *T* is of the air-cell type. The cell is of brass weighing about 2 kg and has a copper core provided with four windows, two forward of quartz and two at the rear of glass. The thermocouple mounted within the core is isolated in a small compartment of about 1-cc volume surrounded by thick metal walls and, in the direction of the light-beam, by air compartments. Until this year a vacuum thermocouple and rough galvanometer were used, but these have now been replaced by the air thermocouple just described and a sensitive galvanometer. The motor *M*, working through a friction disk *D*, exerts a continuous torque on the spindle, which is permitted to rotate only when the escapement *E* releases it at intervals of one minute. A cable of wires *C* carries the current from the contact clock to the escapement magnets and also the current from the thermocouple *T* to the galvanometer in the room beneath the telescope. A steel wire *W* runs over the hour-circle of the telescope and over pulleys to the registering device in the room below, where the slide

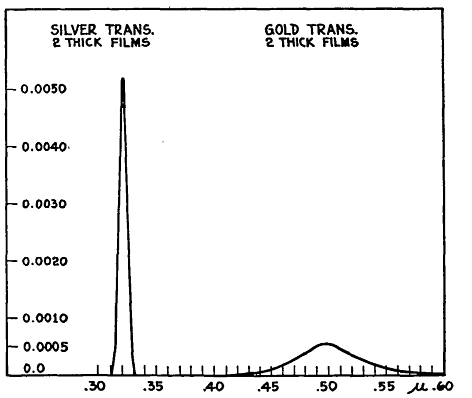
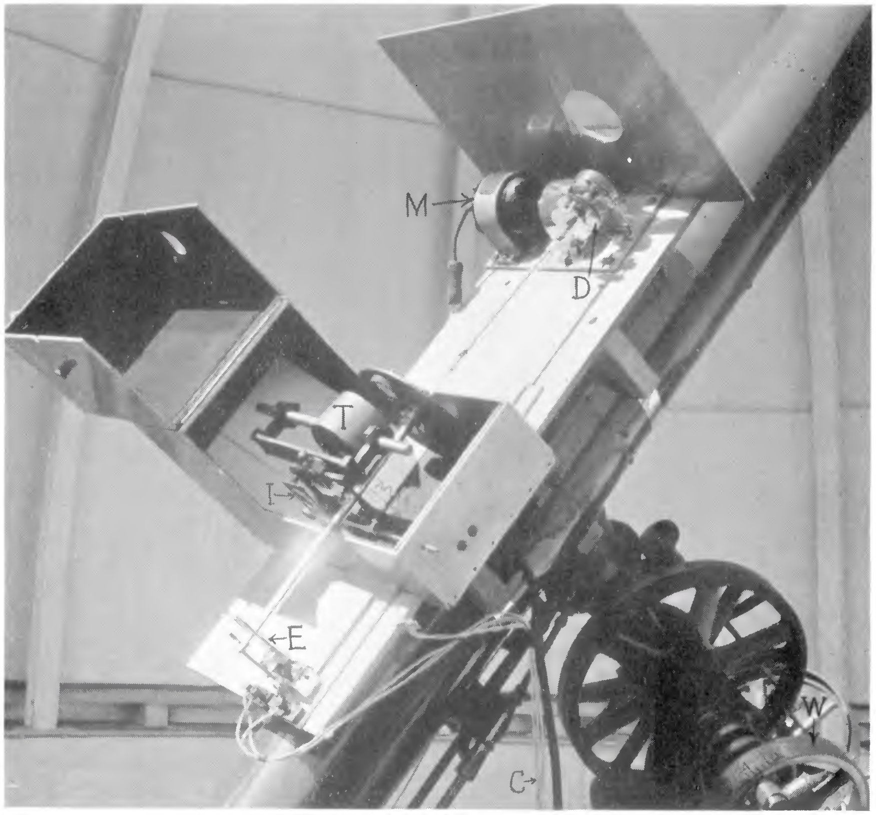


FIG. 2.—Transmissions of the silver and gold films used in the ultra-violet solar radiometer.

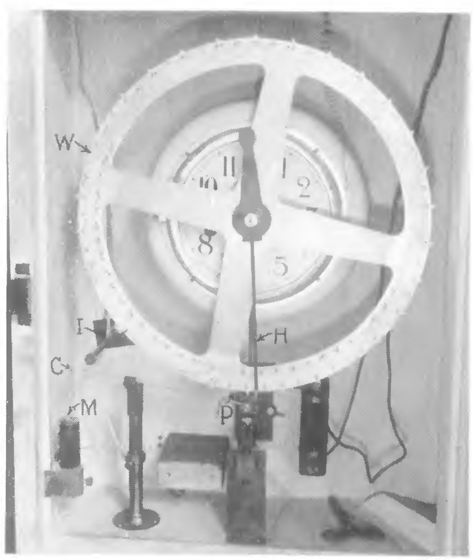
[1] *Publications of the Astronomical Society of the Pacific*, **38**, 26, 1926; *Mt. Wilson Comm.*, No. 98; *Proceedings of the National Academy of Sciences*, **13**, 380, 1927.

PLATE XI

a



b



a) Ultra-Violet Solar Radiometer on Mount Wilson
b) Control Clock

carrying the photographic plate is attached directly to the end of the wire. The motion of the telescope causes the plate to fall at the rate of 27 mm per hour. A record of nine hours (135 determinations of the ratio of ultra-violet to green) can thus be put on an 8×10-inch plate. A motor re-winding automatically maintains driving-clock operation.

ADJUSTMENTS OF THE ULTRA-VIOLET SOLAR RADIOMETER

In the cycle of operations of the escapement, the movement of the image from one junction of the thermocouple to the other in order to give the galvanometer deflection occupies only a fraction of a second, while the interchange of the lenses which follows requires about nine seconds. The controlling clock must therefore give a positive instantaneous contact, followed by one which need not be so positive. To this end the clock illustrated in Plate XI*b* was constructed. The wheel *W* has thirty teeth operating against a pallet *P*, half as long as the space between the teeth. A steel wire contact *C*, which dips into mercury *M* during the minute the pallet is pressed down by a tooth, is released suddenly and remains in open circuit for the following minute. This action operates a double-throw relay which is so wired with the magnets of the radiometer escapement that the interchange of lenses takes place while the clock is depressing the pallet to make contact with the mercury, and the contact is released when the image of the sun moves from one junction to the other. With this arrangement the multiple contacts which sometimes occur at the "make" with the mercury surface do not affect the operation of the lens system. Once each hour a second contact *H* on an adjustable hand makes the circuit with a second mercury cup and lights a small flashlight bulb near the galvanometer. An hour-angle indicator is thus recorded in the form of a straight line crossing the plate at right angles to its motion. A dial on the contact wheel reads the minutes of time from the index *I*, which is a fixed hand set to correct for longitude. An inner dial corrects for equation of time by reference to the contact *H*. The observer then sets the outer dial to read standard time, after which the plate will be automatically flashed with a straight line as the sun passes each hour angle of digital value.

The adjustment of the lenses so that during operation the green and ultra-violet images shall fall alternately in the same place on the thermocouple junctions is important. Since the ultra-violet image is totally invisible, this adjustment is not easy. To accomplish it properly a fluorescent screen is used. The thermocouple is removed and a piece of uranium glass is placed at the focus of the lenses and moved about until a speck of dust centers on the image formed by the gilded lens. The escapement is then operated and the fluorescent image produced by the ultra-violet light from the silvered lens is accurately centered on the dust speck by three radial screws which hold the lens cell in position. Proper relative focusing is accomplished by the same means.

The instrument is pointed on the sun by observing the green image with a simple lens eyepiece *I* (Pl. XI*a*) focused on the thermocouple. The guiding of the instrument may be tested from time to time by checking the position of the green image or by using the image of the sun formed by the telescope on which the radiometer is mounted. After being set on the sun, the hour-circle of the telescope, which has previously been unclamped, is rotated until the plate carriage attached to the steel wire *W* is at the top of its slide. The hour-circle is clamped and the registration of the galvanometer deflections then begins.

MEASUREMENT AND REDUCTION OF THE PLATES

The upper part of Figure 3 illustrates two of the photographic records. The inside rows of dots are produced in each case by the radiation transmitted by silver, $\lambda=0.32\,\mu$, while the outside rows are due to the radiation transmitted by gold, $\lambda=0.50\,\mu$. The heavy lines are hour marks put on by a lamp operated by the contact clock and indicate local time. The numbers at the upper ends of these lines give the local solar time, those below, the hour angle. It will be seen that the ultra-violet light is zero for some time after sunrise and reaches a maximum at noon, while the green radiation has a large value at sunrise and more slowly approaches its maximum at noon.

Measurements of the plates with a suitable comparator[1] give the

[1] *Journal of the Optical Society of America*, **10**, 267, 1925.

galvanometer deflections and eventually the logarithms of the ratio of ultra-violet to green for each four minutes of time. The lower part of Figure 3 shows the graphical solutions for each of the plates. The logarithm of the ratio, ultra-violet to green radiation, is plotted

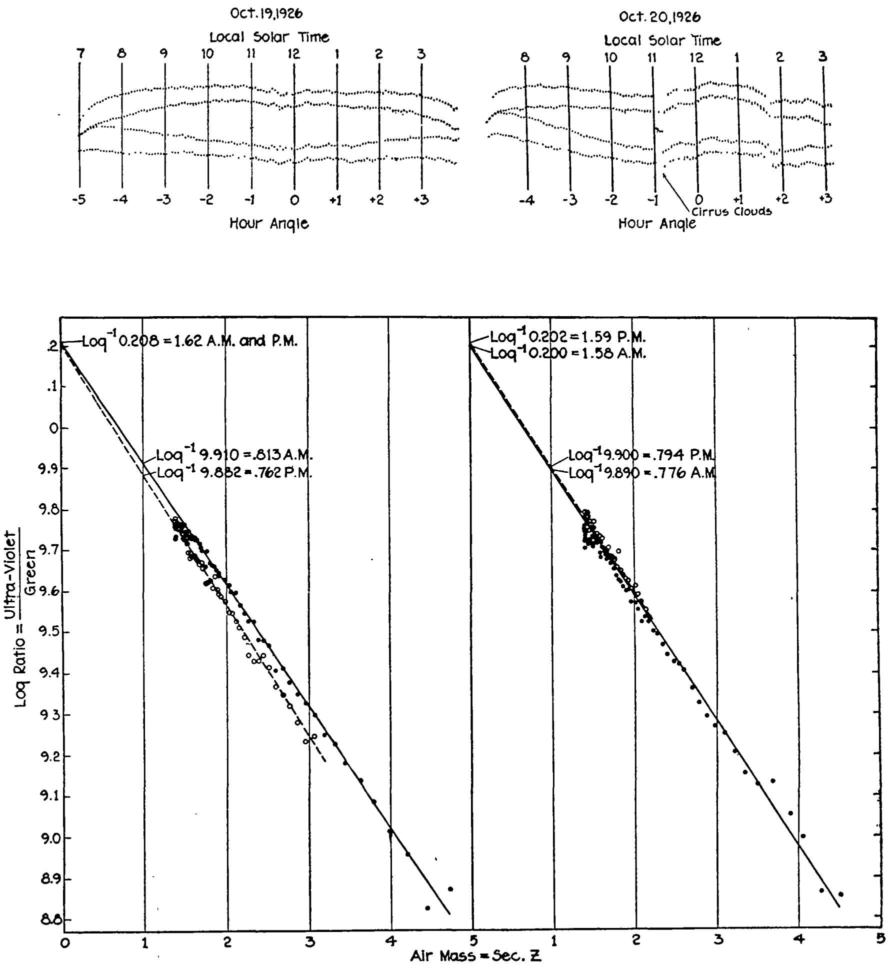


FIG. 3.—Records from the ultra-violet solar radiometer (above) and their graphic solutions (below).

against sec z obtained from the hour angle and a suitable conversion table. This plot defines a straight line from which two values are read, that for the zenith, sec $z=1$, and that for no atmosphere.

The middle curve of Figure 4 shows the march of the monthly means (broken line) and the three-month running averages (full

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line) of the ratio, ultra-violet to green, for the seven years beginning with June, 1924. The arbitrary scale at the left gives these values in units of the average for June, 1924. It will be noted from this curve that the monthly average of the ratio ultra-violet to green solar radiation has varied from 0.95 to 1.57 during the period

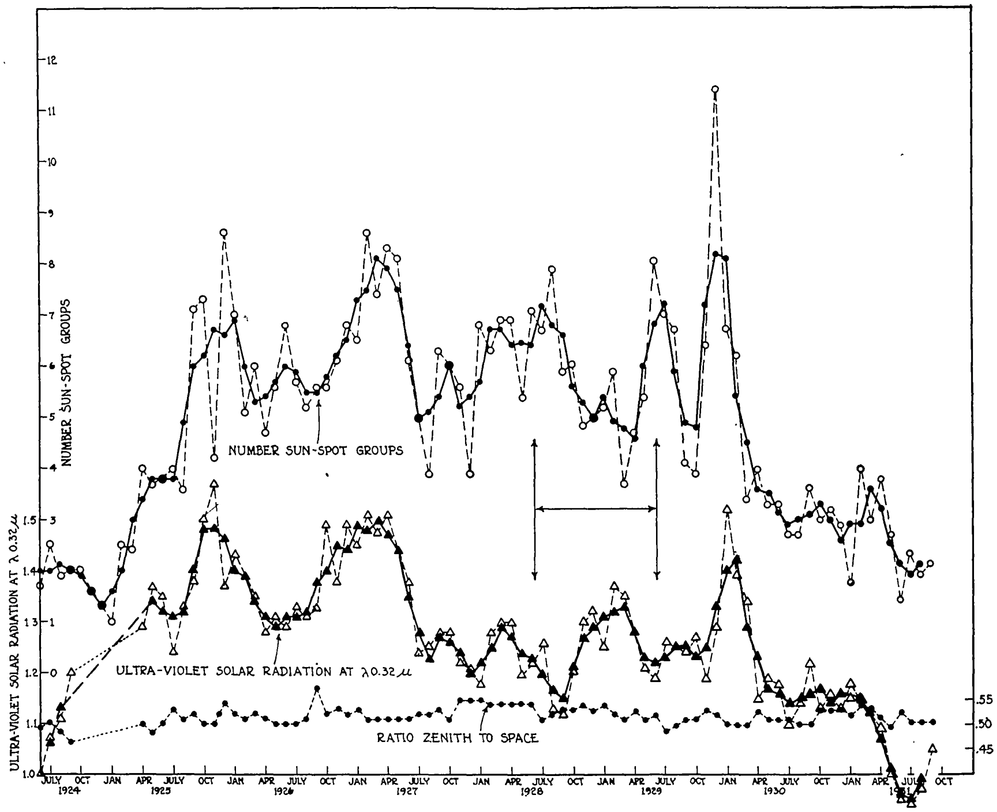


FIG. 4.—Monthly averages (middle curve, broken line) and three-month running averages (full line) of the ratio ultra-violet (λ 0.32 μ) to green (λ 0.5 μ) solar radiation for no atmosphere compared with the average daily counts of sun-spot groups treated similarly (upper curve). Below is the variation of atmospheric transmission at λ 0.32 μ (ratio zenith to space); scale at the right.

of seven years since 1924. On three occasions, namely, November and December, 1925, February and April, 1927, and January, 1930, it surpassed 1.5. It is now back to 1.0, where it stood in the beginning, and at the same point on the descending branch of the sun-spot cycle that it was on the ascending branch in the beginning. The top curve of Figure 4 gives the Mount Wilson monthly averages of the daily number of sun-spot groups treated in similar fashion.[1] Considerable correspondence between the two curves will be noted, but it must be borne in mind that there are no independent checks on these data so much to be desired, such, for example, as another instrument, operated in the Southern Hemisphere. During the year June, 1928, to June, 1929, indicated by the arrows in the figure, the two curves ran exactly counter. No instrumental or atmospheric reason for this is known at this time, but it is significant that plots of the characteristic figures[2] of the calcium and bright hydrogen flocculi show only very slight depressions corresponding to that of the sun-spot curve for this interval. It is clear that no allowable variation in the general surface temperature of the sun will account for the variation in the ratio, ultra-violet to green, shown in Figure 4, since a range of nearly 1000° C is required if the energy-curve behaves like that of a black body. The results suggest a large atmospheric variant like the white haze shortly to be described, which may itself depend on ultra-violet sunlight. The discussion in the following section does not, however, reveal any effect of this sort to account for the phenomenon. On the other hand, the wave-length in which these measurements were made, 0.32 μ, is on a steep slope of the solar energy-curve (Fig. 11), which may be the edge of a variable absorption band in the solar spectrum.

ATMOSPHERIC AND INSTRUMENTAL SOURCES OF ERROR

The work of Dobson and D. N. Harrison[3] has shown that over the continent of Europe the atmospheric ozone varies in a seasonal cycle from a maximum of about 0.33 cm at N.T.P. in April to 0.23 cm in October. Measurements made at Table Mountain, California,[4] distant 24 miles by air-line east-northeast of Mount Wilson, show a range of approximately 0.28–0.21 cm, while in the desert climates of Arizona and South America even smaller values are found.[5]

[1] Published bimonthly by Nicholson in *Publications of the Astronomical Society of the Pacific;* complete monthly averages for the preceding year in the February number.

[2] *Bulletin for Character Figures of Solar Phenomena,* published quarterly by the Federal Observatory in Zürich.

[3] *Proceedings of the Royal Society of London,* A, **110,** 660, 1926.

[4] Dobson, *ibid.,* A, **129,** 411, 1930.

[5] F. E. Fowle, *Smithsonian Miscellaneous Collections,* **81,** No. 11, p. 13, 1929.

To provide a practical test of the question whether any possible fluctuations in the ozone content of our atmosphere might affect the measurements of the ratio of ultra-violet to green, an ozone tube 67 cm long, fitted with quartz windows, was placed in the light-path of the radiometer. Analysis by the usual iodine method showed the amount of ozone to be 1.38 cm at N.T.P., the actual pressure being 29.1 inches *Hg* in Pasadena, where the tube was filled. The ozone content was varied, by use of a pump provided with a gauge, while the sun was crossing the meridian. The experiment began at hour angle -4^{m} and ended at $+36^{m}$, sec z being 1.03–1.04 throughout the interval. The data shown in Table I were obtained with this arrangement on May 26, 1926. A plot of the ozone content against

TABLE I

Pressure	Ozone	Ratio $\frac{\text{Ultra-Violet}}{\text{Green}}$
29.1 in.	1.38 cm	0.610
19.6	0.93	0.731
10.2	0.48	0.897
4.9	0.23	0.955
0.0	0.00	1.000
Air filled	0.00	1.000

the ratio of ultra-violet to green shows that doubling the mean atmospheric ozone content[1] of 0.24 cm reduces the ratio by 5 per cent. Dobson's seasonal range of approximately 0.28–0.21 cm for Table Mountain would produce a variation in the ratio of less than 1 per cent. Since the observed variations of ultra-violet light greatly exceed this amount, it is thought the ozone effect can safely be neglected.

Whether the atmosphere in general affects the measurements may be seen from the bottom curve in Figure 4, which represents the monthly averages of the quotient of the values of the ultra-violet to green ratio for the zenith to no atmosphere. This quotient is the ratio of the atmospheric transmission for λ 0.32 μ to that for λ 0.50 μ, and, since the transmission for λ 0.50 μ is high, about 86 per cent, the curve is essentially a curve of variation of the atmospheric transmission at λ 0.32 μ. The range is from 0.45 to 0.55 and seems

[1] *Proceedings of the Royal Society of London*, A, **129**, 413, 1930.

not to be definitely correlated with the ultra-violet measurements. Ordinary cirrus clouds and haze apparently do not greatly affect the measurements. Indeed, some experimental runs made through such a sky give results nearly equal to the average for the month.

There is, however, a kind of white haze which fills the valley below Mount Wilson and frequently rises over the top by 11:00 A.M. that affects the measures markedly. It is noted especially on very warm days in summer and autumn, and its effect may be seen in the plots of Figure 3, where dots represent morning measurements and open circles afternoon values. The dotted line indicates the solution for the afternoon values. It will be noted that on October 19, 1926, when haze appeared in the afternoon, the values fall below the corresponding results for the morning run, while on October 20, which was free from white haze although some cirrus clouds appeared for a short time, the morning and afternoon values are nearly identical. We have made it a practice to estimate the amount of this haze by holding the thumb at arm's length to cover the sun and estimating the distance from the sun's limb to which the whiteness can be traced. The observer records the result on a scale of 1–5 when he visits the instrument approximately once an hour to examine its adjustments. On account of the prevalence of this white haze, the afternoon runs have not been used in following the variations of ultra-violet solar radiation, and only morning runs were used in the plot in Figure 4.

No tarnish has been observed on the metallic films during the seven years they have been in use without replacement. Their transmissions, determined by direct measurement on a number of occasions spread over this interval, appear to be constant. In making these determinations the cells are taken apart and each film is tested separately. The gold transmission is tested radiometrically and the silver transmission by spectrophotography, by a method already described.[1]

The effect of sunlight on the transmissions of the gold and silver films, and of the quartz lenses and plates, was tested from time to time by removing the copper diaphragms (Fig. 1) and replacing them by diaphragms of twice the aperture, exposing a previously

[1] *Mt. Wilson Contr.*, No. 336; *Astrophysical Journal*, **66**, 43, 1927.

unexposed zone of the lenses and films. This operation has always increased the deflections fourfold, showing that the transmissions of that portion of the optical system exposed by the usual diaphragms has not changed relative to the unexposed portion.

During the first two years of operation a piece of green celluloid[1] was used between the gilded lens and the plate to narrow the gold transmission band. As its density was found to be increasing, this screen was removed on September 23, 1926. The effect of the solarization of this celluloid screen was found both by direct transmission measurements and by substituting a fresh piece of the same celluloid immediately after removal of the solarized piece. Other pieces were exposed to the sun for different intervals (a maximum of two hours at noonday in September) long enough to become denser than the piece removed from the radiometer. The transmissions of these pieces were measured and found to be inversely proportional to the exposure time. The radiometer measures were then collected and corrected by an amount depending on the total number of hours the instrument had been in operation up to the time any given observation was made. The correction factor applied to each value of the ratio of ultra-violet to green varied from 0.998 on May 28, 1924, to 0.600 on September 23, 1926, after a total exposure of 2246 hours. The celluloid was removed from the machine on this date and never replaced.

ULTRA-VIOLET LIGHT FROM THE SKY

The ultra-violet radiation from the sky at $\lambda\, 0.32\, \mu$ was measured with vacuum sodium photoelectric cells constructed by Burt. These cells, made by the process of electrical transfusion through the glass bulb, are essentially spherical soda-glass cells, 70 mm in diameter, with a clear circular aperture of 55 mm. The thin glass readily transmits radiation at $\lambda\, 0.32\, \mu$.[2] The cells were coated with silver, and the deflections were produced by a shutter of thick plate glass, which does not transmit $\lambda\, 0.32\, \mu$, but allows longer wave-lengths to pass through.[3] Thus any pinholes in the film would not affect the observed deflections. The presence of pinholes was tested directly by comparing deflections observed with the glass plate and with a

[1] *Ibid.*, Fig. 4, curve 10. [2] *Ibid.*, Fig. 9, curve 45. [3] *Ibid.*, curve 40.

wooden shutter. No difference was noted, however. The cell was used in series with a 500-ohm galvanometer, a B-battery, and a protecting resistance. That these cells give deflections nearly proportional to the cross-section of the beam entering the circular clear aperture at any angle was tested by mounting them on a turn-table provided with a graduated circle, set 3 m from a lamp, and comparing the galvanometer deflections for various angles of incidence. The deflections when the cell is exposed to radiation from the sky with the plane of the circular window of the cell horizontal are therefore proportional to the intensity on a horizontal plane.

Measurements of the ratio of sky radiation to direct sunlight at $\lambda\ 0.32\,\mu$ in Pasadena show that at this elevation, 845 feet, the intensity of sky radiation on a horizontal plane is equal to that of direct

TABLE II

	Elevation (in Feet)	Sun *plus* Sky	Sky	Sun	Ratio Sky/Sun
Pasadena..............	845	22.0	11	11	1.00
White Man's...........	3400	23.0	9	14	0.55
Mount Wilson..........	5700	23.3	7	16.3	0.43

sunlight when the sun is near the zenith. The sun was shaded off by a black wooden sphere, 4 inches in diameter, held 6 feet from the cell, so that the sky radiation alone was effective. The removal of the wooden sphere gave sky *plus* sun. On October 9, 1928, this ratio for $\lambda\ 0.31\,\mu$ was tested by use of Eastman filter No. 52 and Corning 985B glass, which isolates a narrow band at this wave-length. Although this filter is inefficient, the deflection produced by the sky was 66 mm, and sun *plus* sky, 125 mm, showing that for a zenith distance of 44° the sun and sky contribute equally to a horizontal plane at this wave-length also.

The effect of elevation on the intensity of sun *plus* sky and on the ratio of sky to sun for $\lambda\ 0.32\,\mu$ was tested on June 13, 1928, a very clear day. A silvered cell and portable galvanometer were used, a continuous record being kept in Pasadena by an automatic contrivance shortly to be described. Deflections were taken in Pasadena, elevation 845 feet; at White Man's, on the Mount Wilson trail, elevation 3400 feet; and on Mount Wilson, elevation 5700 feet. Table II shows the measurements.

It appears from this table that at $\lambda\, 0.32\, \mu$ the intensity of sun *plus* sky on a horizontal plane does not vary much with elevation, the decrease in sky radiation being balanced by increased direct sunlight as the elevation increases.

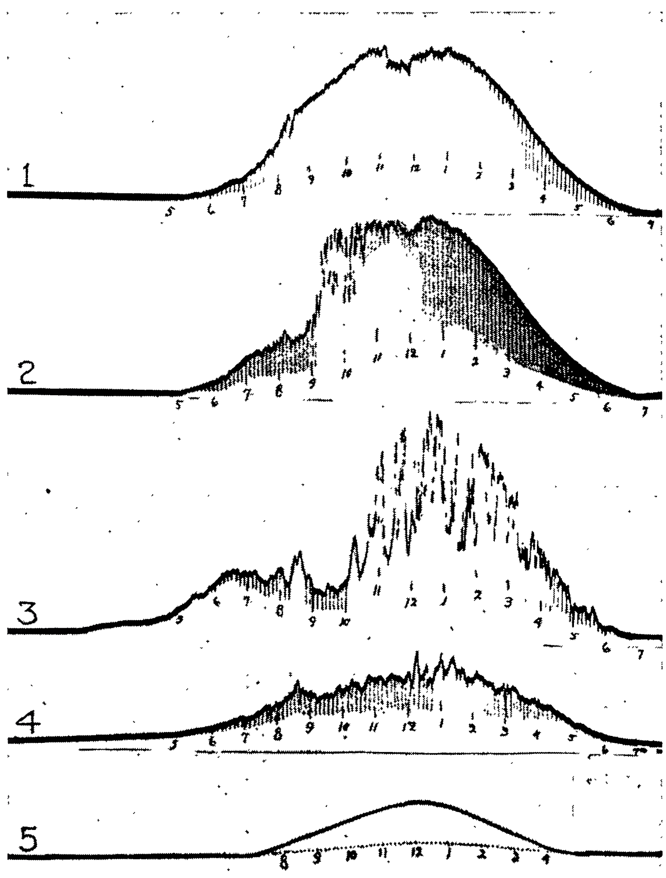


FIG. 5.—Records from the photoelectric radiometer measuring sun *plus* sky on a horizontal plane at $\lambda\, 0.32\, \mu$. Curves 1, 2, 3, 4, very clear to completely overcast days in summer. Curve 5, very clear day in midwinter.

The seasonal and weather effects on sun-*plus*-sky radiation at $\lambda\, 0.32\, \mu$ were studied over a period of eighteen months with a silvered photoelectric cell and a protecting quartz cover mounted in a box with a motor-driven glass shutter. This apparatus was mounted on the roof of the instrument-shop building in Pasadena and the deflections were registered on bromide paper on a rotating drum driven by an eight-day clock. A contact on this clock operated the shutter eight times every hour.

Figure 5 illustrates typical records, the first four taken late in May and the last late in December, 1928. The local solar time is indicated at the base of each curve. Curve 1 shows the diurnal march of the intensity of solar radiation at λ 0.32 μ incident on a horizontal plane for a clear day in early summer. The dip near noon is due to the white haze before mentioned. Curve 2 shows the effects of high fog in the morning followed by a clear afternoon. Number 3 indicates clouds in the morning and passing clouds the rest of the day. Number 4 represents a dark cloudy day such that lights were needed indoors much of the time. Even then the ultra-violet light received was nearly 25 per cent of that for a clear day. Curve 5 shows the seasonal effect of the low December sun. It will be noted that the ultra-violet radiation on a completely cloudy day in summer was as effective as a perfectly clear day in midwinter. Curve 5 also illustrates the effect of wind and rain in removing the white haze that affects the other curves near noon. Measurements were made on a number of dark days, during one of which a thunderstorm passed. The least amount of radiation observed was 10 per cent of that received at the same hour on a clear day.

The march of ultra-violet sky radiation at λ 0.32 μ during the day is illustrated in Figure 6. The ordinates are galvanometer deflections and the abscissae, altitudes of the sun. Until the sun reaches an altitude of about 6°, the amount is small. Thereafter the sky radiation is proportional to the altitude until noon. The afternoon values are higher than those of the morning on account of the additional scattering of cirrus clouds and haze.

The distribution of ultra-violet light at λ 0.32 μ over the sky was measured with a silvered photo-electric cell mounted in a cardboard cylinder, from which a second cylinder projected at right angles to receive the light. The second cylinder was 3 inches in diameter and 20 inches long, blackened inside. The 4-inch wooden ball at 6 feet distance was used to shade the opening in the tube from the sun. The tube was attached to an altazimuth mounting provided with a circle to read angular distance from the sun. The readings were made near noon in the plane of the meridian. The results for several days, under different sky conditions, are plotted in Figure 7, in which the intensities are counted from the graduated circle representing the plane of the meridian. The rapid increase of intensity near the sun begins at greater angular distances on hazy days than on clear days. The intensity toward the southern horizon below the sun is greater than that at an equal distance above (north of) the sun.

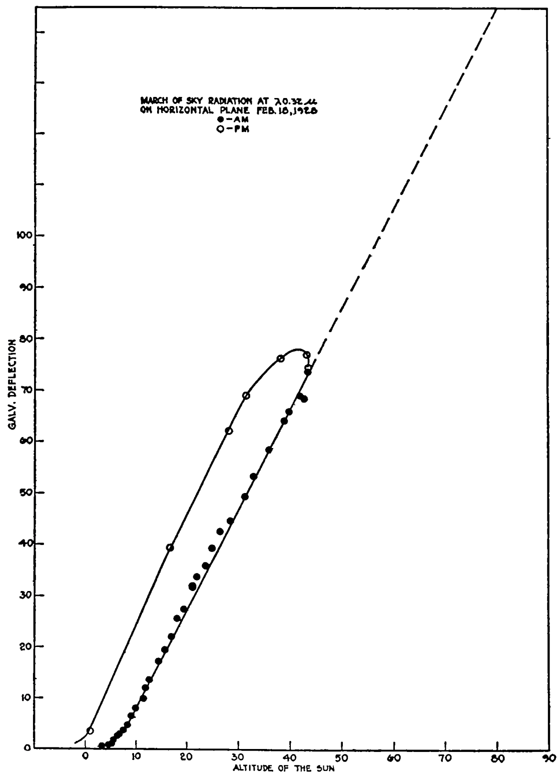
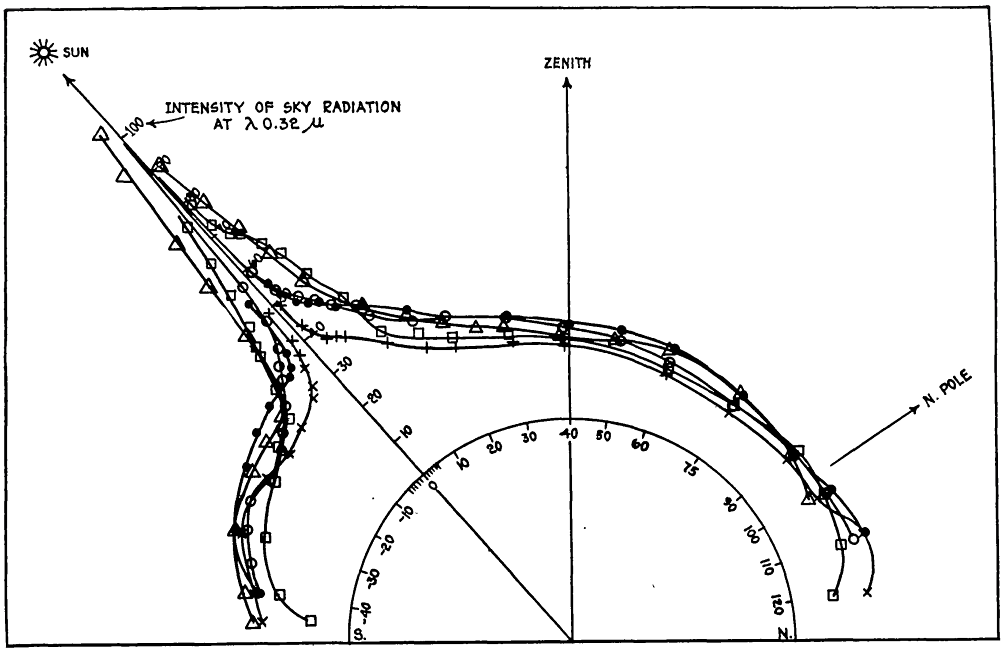


FIG. 6.—March of the sky radiation at λ 0.32 μ on a horizontal plane on a clear day in Pasadena.

THE ULTRA-VIOLET LIMIT OF THE SPECTRUM OF SKYLIGHT AND OF DIRECT SUNLIGHT

It is well known that the ultra-violet limit of the spectrum of direct sunlight photographed with a concave grating or a quartz spectrograph is about λ 0.2975 μ—the violet limit of Rowland's *Table of Wave-Lengths*. Increased exposure brings up only a fogged strip produced by scattered light in the instrument. The most effective way to reduce the fogging is to filter out the longer wave-lengths by using a monochromator in front of the spectrograph with its dispersion along the slit. By means of this crossed spectrograph method Fabry and Buisson[1] have photographed the spectrum of direct sunlight down to $\lambda\, 0.2885\,\mu$. If there is any ozone in the lower atmosphere, it may be questioned whether the sky spectrum would



+ APRIL 5, 1928 SKY VERY CLEAR, WHITENESS 2
● MARCH 21, " SKY CLEAR, WHITENESS 5
O MARCH 30, " SKY CLEAR, WHITENESS 5
□ APRIL 9, " SKY VERY MILKY, CIRRUS CLOUDS JUST VISIBLE, WHITENESS 10, CORONA EXTENDS ALL OVER SKY
△ APRIL 22 " SKY OVERCAST WITH THICK HAZE, SHADOWS EASILY VISIBLE

FIG. 7.—Distribution of radiation at $\lambda\, 0.32\,\mu$ over the sky at noon near the equinox, Pasadena.

reach so far into the violet, since sunlight scattered from the sky must pass through a longer air-path than direct sunlight. In order to study this problem, a Bausch and Lomb quartz monochromator used as a filtering spectroscope was crossed with two spectrographs: (1) a 1-m concave-grating spectrograph and (2) a quartz spectrograph made of the optical parts of the Bausch and Lomb quartz monochromator and designed for use with the 100-inch telescope.

[1] *Astrophysical Journal*, 54, 297, 1921.

The relative speeds of these two arrangements depend on (*a*) the fraction of the sky included by the optical train, (*b*) the dispersion, and (*c*) the spectral efficiency of the instruments. The relative advantages of the two spectrographs are indicated by Table III.

TABLE III

	Fraction of the Sky Effective	Dispersion A per Mm	Spectral Efficiency at λ 0.302 μ
1-m grating..........................	7×10^{-4}	17.4	0.045
Quartz spectrograph..............	5×10^{-3}	61	0.42

The efficiency of the 1-m concave-grating spectrograph, which was ruled with shallow lines giving a bright first order, was measured with a photoelectric cell in combination with the monochromator, the collimator lens of which was diaphragmed down so that the light entering the spectrograph just filled the grating. The ratio of the galvanometer deflections with and without the grating gives the efficiency. The results for several wave-lengths are

λ.............	0.435	0.406	0.366	0.313	0.302	0.254
Efficiency.....	0.054	0.057	0.063	0.049	0.045	0.040

A comparison of the factors given in Table III shows that for $\lambda=0.302\,\mu$ the quartz spectrograph is more than two hundred and fifty times as efficient as the grating spectrograph when used on the sky.

Since the spectral energy decreases indefinitely with decreasing wave-length, the ultra-violet limit must be defined as we observe it. Practically, this limit is determined by continuing the exposure until the fog along the spectrum strip produced by the scattered light in the instrument may easily be seen. The appearance of this fog, which was held at a minimum by maintaining the width of the spectrum (opening of the monochromator slits) at about 0.3 mm, was taken as an index of complete exposure. The minimum wave-length visible on the plates under these conditions is accepted as the ultra-violet limit. The results for the two arrangements of apparatus are given in Tables IV and V. The exposures were made in Pasadena on a point 50° above the northern horizon.

The column labeled "Fog" gives the character of the plate fog as very weak (VW), weak (W), medium (M), strong (S), or very strong (VS).

TABLE IV

ULTRA-VIOLET LIMIT OF SKYLIGHT

1-M GRATING SPECTROGRAPH AND QUARTZ MONOCHROMATOR				QUARTZ SPECTROGRAPH AND MONOCHROMATOR			
Date	Exposure Time	Limit	Fog	Date	Exposure Time	Limit	Fog
		μ				μ	
1928 July 6.......	2h	0.297	VW	1930 June 16, 17..	14h	0.296	S
7.......	5	.296	M	19, 20..	12	.296	S
8.......	5	.295	VW	.21–23..	18	.296	VS
				24, 25..	16	.296	S
Dec. 20.......	6	.301	VW	26.....	7	.295*	M
21.......	6	.301	VW				
1928 Dec. 22 to 1929 Jan. 1..	60	0.298	S	July 5......	10	.296	S
				1931 Jan. 2–8....	42	0.296†	S

* Wide slit. Burned out at λ 0.2967 μ.
† Strong at λ 0.2967 μ. Burned out at λ 0.302 μ.

TABLE V

ULTRA-VIOLET LIMIT OF DIRECT SUNLIGHT; 1-M GRATING SPECTROGRAPH AND QUARTZ MONOCHROMATOR

Date	Exposure Time	Limit	Fog	Remarks
		μ		
1929 June 26......	1h20m	0.290	M	6-inch quartz objective; lines visible to λ 0.291 μ easily
27......	2 0	.290	VW	Easily to λ 0.291 μ; bromine tube and Corning Purple Corex added
July 9......	0 30	.291	W	Narrow spectrograph slit
10......	1 0	.290	W	Very narrow monochromator slit
1929 Jan. 22......	1 0	.297	S	Wide monochromator slit
23......	3 0	.297	VS	Wide monochromator slit
25......	3 0	.296	S	Easily to λ 0.297 μ
26......	3 0	0.297	M	

A comparison of the figures in these tables shows that the ultra-violet limit of the sky spectrum near the summer solstice is about λ 0.296 μ, and that at the winter solstice the exposure required to reach this limit is increased threefold. From a point in the sky far from the sun, it would probably be difficult to detect any sky radiation much below λ 0.295 μ. Further, the ultra-violet limit for the sky spectrum in midsummer is about the same as that for direct sunlight in midwinter.

The work of several observers[1] seems to indicate that the bulk of the atmospheric ozone is localized in a layer at a height of about 50 km above sea-level. Since nearly all the scattered light of the sky comes from far lower elevations, it follows that the screening effect of the ozone would take place before the phenomenon of scattering, thus producing the same result on both sky and direct sunlight. The observations in Tables IV and V, however, show the ultra-violet limit of direct sunlight to be λ 0.290 against λ 0.295 μ for skylight. This argues for a small ozone content in the lower atmosphere.

SPECTRAL ENERGY-CURVE OF THE SUN IN THE ULTRA-VIOLET

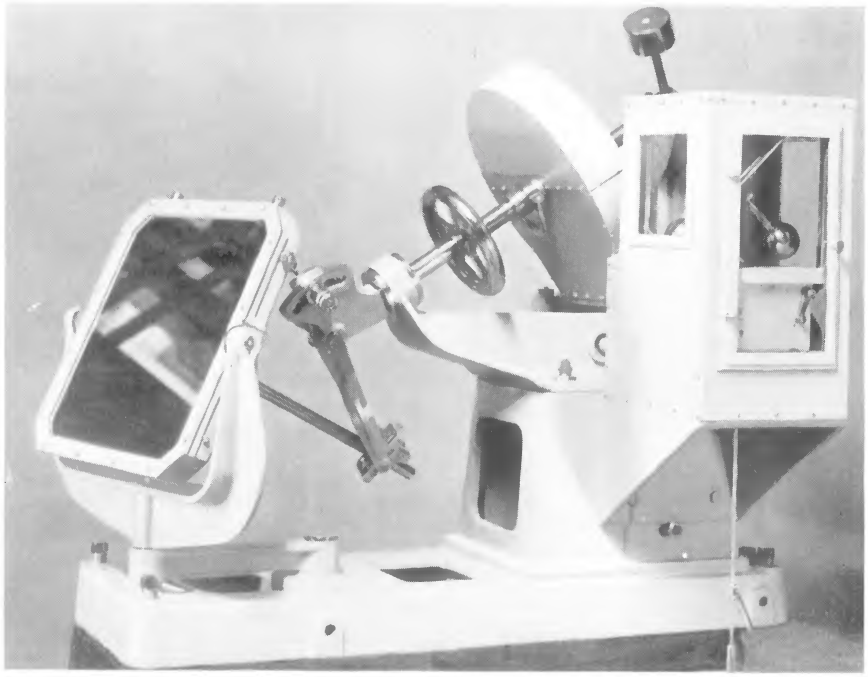
There are three principal methods of determining the spectral energy-curve of the sun by use of the monochromator: (1) keeping both first and second slits at constant width during the measurements and afterward correcting the results for the variable dispersion across the second slit; (2) keeping the first slit at constant width and varying the second slit proportionally to the dispersion, thus eliminating the dispersion corrections necessary in the first method; (3) varying both slits according to the dispersion, thus keeping the purity of the spectrum constant.

The first method is practically that used by the Smithsonian observers in determining the solar energy-curve in the visible and infrared spectrum by the measurement of the ordinates of bolograms. It has the disadvantage, however, that the corrections for dispersion become very large in the ultra-violet, especially if a quartz prism is used, for which the correction factor at λ 0.3 μ is about five times that at the maximum of solar energy at λ 0.5 μ. The method is advantageous in that there is no error due to uncertain action of the

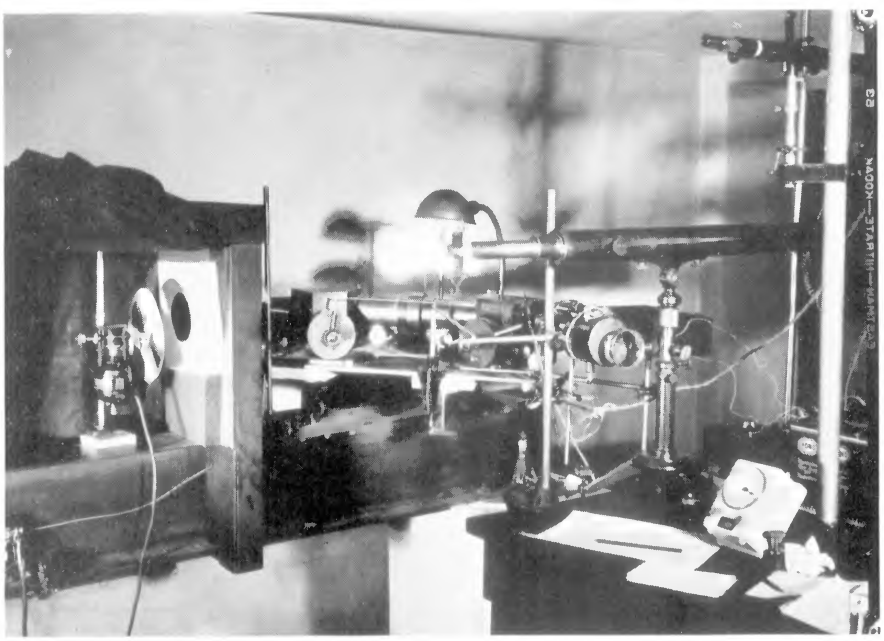
[1] Lambert, Dejardin, and Chalonge, *Bulletin de l'Observatoire de Lyon*, **9**, 45, 1927; Cabannes and Dufay, *Journal de physique*, **8**, 125, 1927; Götz and Dobson, *Proceedings of the Royal Society of London*, A, **120**, 251, 1928.

PLATE XII

a



b



a) 12-INCH STELLITE SIDEROSTAT OF THE DESERT SANATORIUM RESEARCH LABORATORY, TUCSON, ARIZONA

b) DOUBLE BAUSCH AND LOMB QUARTZ MONOCHROMATOR USED WITH THE SIDEROSTAT TO MEASURE THE ULTRA-VIOLET SPECTRAL ENERGY-CURVE OF THE SUN second slit, and, in the hands of Abbot and his colleagues, it has given an accurate determination of the form of the solar energy-curve from the near ultra-violet to the far infra-red.

The second method, principally, and in part the third were adopted by the author for the measurement of the violet slope of the solar energy-curve to the limit of atmospheric transmission, largely because of the much greater deflections resulting from these methods, and also because of the great numbers of Fraunhofer lines, which, with the first method, might lead to scattered results as the dispersion increased. In carrying the measurements into the visible spectrum it was thought that if this overlapping part were fitted to Abbot's curve, the latter would calibrate the measurements.

The spectral energy-curve of integrated sunlight and of light from the center of the solar disk was measured at the Research Laboratory of the Desert Sanatorium of Southern Arizona at Tucson in May, 1931, at the kind invitation of Drs. Davis, Pinner, and Krause. The laboratory is provided with a radiometer built after the pattern of that shown in Plate XI*a* and a Foucault siderostat of the lower arm-drive type with a 12-inch square stellite mirror (Pl. XII*a*). These instruments were designed by the writer for ultra-violet solar investigations and have been described by G. E. Davis.[1] A siderostat is superior to a coelostat or a polar heliostat for this kind of work since the light suffers only one reflection, and, as all metals are poor reflectors in the ultra-violet, the highest efficiency is thus attained with a minimum of uncertainty as to the reflection coefficients. The siderostat used feeds a beam of sunlight into a 12-inch fused-quartz crossed lens of 6-foot focal length, mounted on an I-beam, which also carries the double monochromator attached by dovetail-slides as shown in Plate XII*b*.

This double monochromator consists of two Bausch and Lomb quartz monochromators mounted on a steel plate with a common (middle) straight slit, the two outside slits (entrance and exit slits) being curved. A diagram of the optical system is shown in Figure 8. After leaving the siderostat mirror M, the light passes through the 12-inch quartz lens L and the sector X if the center of the disk is being studied; but if integrated light is used, these are eliminated.

[1] *General Electric Review*, **34**, 98, 1931.

Entering the first slit (curved) S_1, the light passes through the quartz lenses and prism train, consisting of two 30° crystal quartz prisms, of left and right quartz, of monochromator A, then through the straight slit S_2, where the scattered light of monochromator A is eliminated, into the lens and prism train of monochromator B, like that of A, and finally through the curved third (exit) slit S_3. From this slit it passes through the fused-quartz lens L_1 of 3-cm focal

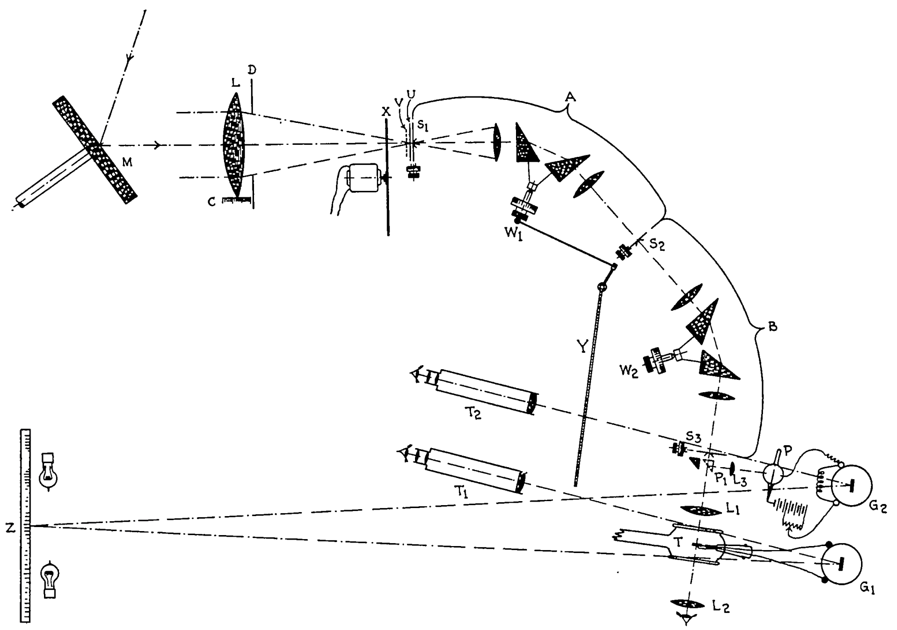


FIG. 8.—Arrangement of the double Bausch and Lomb quartz monochromator for measuring the ultra-violet spectral energy-curve of the sun with the thermopile and photoelectric cell.

length and 25-mm aperture upon one receiver of the vacuum thermopile T. A crystal-quartz prism P_1 may be moved into the beam in order to throw the light into the crystal-quartz lens L_3 of $2\frac{1}{2}$-inch focal length, and thence into the sodium photoelectric cell of quartz, P. To reduce the heating of the first slit S_1 to a minimum, a second wide slit U was used. The deflections were made with a shutter V. When the 12-inch lens, L, was used, a fixed diaphragm D of 20-cm aperture was placed behind it in part of the work, and in another part this diaphragm was attached to the lens. The lens was set for sharp focus upon the first slit S_1 by means of the focusing scale C.

The fixed diaphragm had the advantage that, when the lens was shifted in the direction of this slit, the cone of light limited by the diaphragm D remained constant, and no correction for displacement of this lens was necessary.

ADJUSTMENTS OF THE INSTRUMENT

The slits.—These are opened symmetrically by screws of 1-mm equivalent pitch, with heads divided into tenths. Since most of the measures were made with the first slit set at a fixed opening, this coarse division of the screwhead was sufficient. The second slit, however, was necessarily set at various widths in the spectrum formed by monochromator A to include a constant dispersion, i.e., a constant width in angstrom units. For the measurements on integrated sunlight this slit was always set (save on one occasion) to cover 100 A. For the center of the disk, which was observed with the 12-inch quartz lens, slit widths corresponding to 50 and 100 A were employed. The exit slit S_3 was made a half-division (0.05 mm) wider than S_2. It follows, then, that the second slit S_2 (straight) is the most important, and it was therefore provided with a graduated arc which could be read to one hundredth of a division (0.001 mm).

Slit calibration.—The width of the slit S_2 corresponding to 100 A was determined instrumentally. With this slit opened ten divisions, the lines of the mercury spectrum were shifted from one jaw to the other, the change in wave-length $\Delta\lambda$ being observed on the graduated head of the prism screw. The slit opening in divisions of the head for 100 A of the spectrum at wave-length λ is therefore one-tenth the reciprocal of $\Delta\lambda$ when $\Delta\lambda$ is expressed in μ. The observed values of $\Delta\lambda$ and the width of slit S_2 corresponding to 100 A are given in the second and third columns of Table VI.

Slit proportionality.—The proportionality of the slit opening to the galvanometer deflection was tested at intervals during the work. Narrow slits may be affected by diffraction, and zero errors of the slit screw affect the deflections from narrow slits more than those from wide slits. The monochromator prism screw was set for a flat place in the solar energy-curve or for its maximum (λ 0.5 μ), and readings of the galvanometer for screw settings of slit S_2 ranging from one to ten divisions were observed. If the deflections deviated from simple proportionality to slit width, they were plotted and the resulting smooth curve was used to correct the solar energy measurements.

Wave-length scale.—The zero-point of the wave-length scale on the prism screw-head was checked visually at intervals on the prominent mercury lines. Errors of as much as 20 A were seldom found. The eccentric disks on the screw-nut were adjusted once to bring the

TABLE VI

SLIT WIDTHS S_2 CORRESPONDING TO 100 A, TRANSMISSION OF THE MONOCHROMATOR (T_r), REFLECTING POWER OF STELLITE (R), AND TRANSMISSION OF FUSED QUARTZ (T_R)

λ	Δλ	S_2, 100 A	R	T_r	T_r^2	T_R	T_R^2
μ	μ	div.					
0.697	0.230	0.43	0.66	0.458	0.21	....	....
.623	.160	0.63	.65	....	....	0.938	0.88
.615	.148	0.68	.65	....	....	....	....
.580	.128	0.78	.65	....	....	....	....
.546	.112	0.89	.64	.450	.20	.942	.89
.494	.082	1.22	.64	....	....	....	....
.435	.057	1.75	.62	.442	.20	.944	.89
.406	.045	2.22	.60	.440	.19	.944	.89
.386	.036	2.78	.58	....	....	....	....
.366	.031	3.23	.56	.436	.19	.932	.87
.334	.023	4.35	.53	....	....	.929	.86
.313	.019	5.26	.51	.426	.18	.924	.85
.297	.016	6.25	.50	....	....	.916	.84
.280	.014	7.14	.47	....	....	.900	.81
.270	.012	8.33	.44	.400	.16	.856	.73
.254	.011	9.09	.39	0.380	0.14	.661	.44
0.238	0.010	9.86	0.39	....	....	0.463	0.21

readings of the mercury lines into closer agreement with the known wave-lengths. Throughout the work all the settings were made by turning the screw-head in the direction of decreasing wave-length, which gave the greater wave-lengths the advantage of the greater air masses in determining the atmospheric transmissions for the morning runs.

Illumination of the optical system.—This was tested at intervals during the observing program by setting the wave-length screws for a visual wave-length and testing the illumination of the optical parts with a paper screen. The apparatus proved to be so rigid that no readjustment was required. The place where defective illumination may be most serious in its effect is the thermopile receiver. The receiver was set visually so that the scattered light about it was symmetrical; the thermopile was then moved until maximum deflection was obtained.

Thermopile and photoelectric cell.—The thermopile was of the vacuum type, with four hot and four cold junctions of bismuth against bismuth plus 5 per cent tin, and provided with a window of fused quartz $2\frac{1}{2}$ mm thick. It was connected with a D'Arsonval galvanometer placed 8 m from the scale. The photo-cell was of quartz of the gas-filled sodium type and was used within about 5 volts of the flashing voltage (160 volts). It was put in series with a high-resistance potentiometer, a B-battery, and a second D'Arsonval galvanometer also at 8 m distance from the scale. This galvanometer was of 86 ohms resistance with 100 ohms damping resistance in shunt. The two galvanometers were read by suitable telescopes T_1T_2 (Fig. 8) placed near the monochromator.

TABLE VII

COLOR SENSITIVITY OF THE SODIUM PHOTOELECTRIC CELL

λ	Sensitivity	λ	Sensitivity
μ		μ	
0.546	5	0.313	100
.435	20	.302	87
.406	33	.270	36
.366	55	0.254	27
0.334	93		

The current-sensitivity of the photoelectric cell for various wave-lengths was measured in the mercury spectrum by direct comparison with the thermopile, with the results for a potential within 5 volts of the flashing voltage shown in Table VII. The maximum of sensitivity appears to be near λ 0.32 μ, and it is this property which makes it desirable as an instrument for investigating the solar spectrum in the extreme ultra-violet. The idea was to use the photoelectric cell to extend the measurements made with the thermopile beyond the point near λ 0.30 μ where the deflections dropped to 2 or 3 mm.

Setting the wave-length scale.—After some experiment it was decided to use the galvanometer deflections themselves to indicate accurate settings of the monochromator prism screws W_1W_2. A slow motion consisting of levers (Y, etc., Fig. 8; also Pl. XII) was attached to the prism screw of monochromator A in such a manner that the observer could operate it while looking through either of the galvanometer telescopes. By shifting the lever Y a condition of maximum deflection was reached, which indicated that the two monochromators were set for exactly the same wave-length. The actual wave-length setting was thus made to depend on monochromator B alone.

METHODS OF OBSERVING

The observations consisted, briefly, in determining the intensity of solar energy at different wave-lengths over a constant dispersion at known hour angles. These measures provided at once a determination of the atmospheric coefficients of transmission and of the form of the solar energy-curve.

Since the walls of the dome extend above the siderostat mirror, the observable air mass was limited to 2.9. The coefficients of atmospheric transmission for the longer wave-lengths are therefore not so well determined as might be wished; but the values for the extreme ultra-violet are satisfactory.

Generally speaking, the observing program proceeded approximately as follows. A sheet similar to Table VIII was prepared giving the slit settings for each 100 A between λ 0.4 and 0.33 μ, for greater intervals above λ 0.4 μ, and for each 50 A below λ 0.33 μ. Columns were provided for entering the deflection and hour angle. The wave-length scale and illumination of each optical part, and also the slit zeros, were tested. Two small beams of light taken from the sides of the siderostat mirror produced on cardboard screens in the observing-room and on the wall of the dome images of the sun which were used for guiding. These images were set after the illumination had been tested. When integrated light was being used, a cardboard diaphragm of 4-inch aperture was placed 8 feet from the entrance slit S_1 to limit the sky effective on the monochromator. This slit was customarily set at the one-division opening. These adjustments were maintained throughout the observing program.

The measurements began at the longer wave-lengths, λ 0.6 or

0.7 μ, and proceeded to the ultra-violet limit of the spectrum. For each individual wave-length the following adjustments were required: focusing of four monochromator lenses by setting the focusing heads for the particular wave-length; setting of two prism-box screws, W_1W_2, for the particular wave-length; and setting of the second slit S_2 for the proper opening, as indicated by the observing sheet, and of the third slit S_3 for the same opening plus one half-division to allow for a margin of error. The shutter was then opened, and the slow motion, Y, of the prism screw of monochromator A was moved until maximum deflection was reached. If on closing the shutter the zero was found to have shifted sensibly, a second deflection was read. The hour angle was read directly from a clock having a dial graduated to read in both directions from the noon hour as zero. Observation of the deflection on each wave-length and of the corresponding hour angle proceeded in this manner until the galvanometer deflections had fallen to about 25 mm, which occurred at λ 0.32 μ for large hour angles and at λ 0.31 μ for small ones. From this point on, both photoelectric cell and thermopile were read until the limit of the solar spectrum was reached. The photoelectric cell was adjusted to give a deflection of about 700 mm when the thermopile gave about 30 mm. The efficiency of the monochromator in eliminating scattered light is indicated by the fact that no deflection whatever was observable below λ 0.29 μ with either photo-cell or thermopile, even at noonday.

When the radiation at the center of the disk was measured, the 12-inch quartz lens provided with a 7-inch diaphragm was focused at each wave-length setting of the monochromator. A sector reducing the deflections to one-tenth their undiminished values was used until the point was reached where the photo-cell measurements normally began, when it was removed, thereby increasing the deflections tenfold. An obstruction prevented the focusing of the 12-inch quartz lens for wave-lengths shorter than λ 0.33 μ. About one hour was required to complete a set of observations on the twenty-two wave-lengths observed between λ 0.7 and 0.29 μ, twelve of which were duplicated by the photoelectric cell.

After the apparatus was erected and put in working order, eight clear days were available for the observations. Generally the sky was excellent in the mornings, but by late afternoon on four of these days clouds accompanying distant desert storms made observing conditions poor.

TRANSMISSION COEFFICIENTS AND ATMOSPHERIC OZONE

In reducing the measurements we have to consider (1) the atmospheric transmissions, (2) the reflecting power of the siderostat mirror, (3) the transmission of the monochromator, (4) the transmission of the fused quartz lens L_1 (which projects the image of the exit slit S_3 upon the thermopile receiver), and of the 12-inch lens L (when this was used for the work on the center of the disk). These will be discussed in the order named.

1. *The atmospheric transmissions.*—As already mentioned, the observable air mass was limited to 2.9. The time of starting the observations was therefore limited to an hour angle of approximately $-5^{h}12^{m}$ for the season in which the observations were made. Since a complete set of measurements required an hour, only three or four sets could be obtained while the air mass was changing rapidly. The logarithms of the deflections for each wave-length were plotted against sec z (air mass) obtained from a table with the hour angle and the declination as arguments. A straight line was passed through these points and projected to the axis of air mass 0. The difference in the readings for air masses 1 and 0 is the logarithm of atmospheric transmission. Because of the small range in the air mass, it was thought best to reduce the deflections for a given wave-length for each day with the aid of the mean atmospheric transmission obtained from all the observations at that wave-length on all the days. For this reason the logarithms of the averages of the observed transmissions were plotted against values of $-(u-1)^2/\lambda^4$, which occurs in the right-hand member of Rayleigh's equation of molecular scattering,

$$\log T_r = -\left(\frac{32\pi^3}{3N}\right)\frac{(u-1)^2}{\lambda^4}, \qquad (1)$$

and which depends on both wave-length λ and index of refraction u. This plot (the filled circles and heavy line) is shown in Figure 9. Two additional points (the open circles) at λ 0.32 and 0.5 μ were furnished by the radiometer, which operated at the same time.

If only Rayleigh scattering were involved, we should expect this plot to be a straight line passing through the upper right corner of the diagram. Probably because of scattering by large particles, however, it actually passes below this point, thus indicating that Rayleigh's equation should be modified, as Dobson and Harrison[1] have done, by adding a constant term δ to the right member of equation (1).

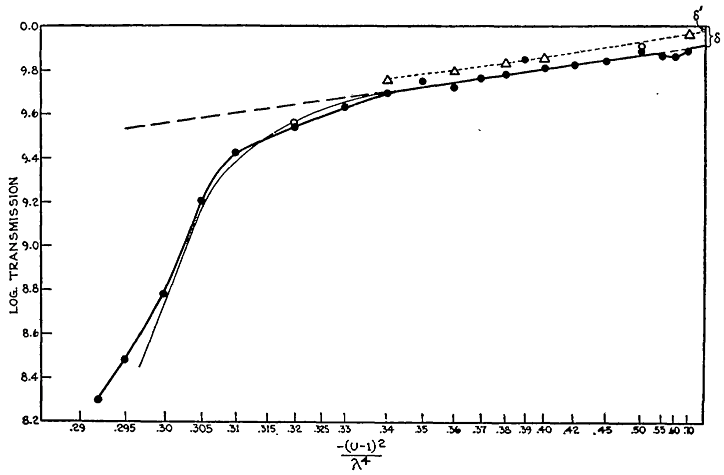


FIG. 9.—Atmospheric transmission (the heavy full line and dots) at Tucson (elevation 760 meters).

It will be noted that the plot is well represented by a straight line above λ 0.34 μ. The rapid fall of the line for wave-lengths less than λ 0.33 μ is due to the Huggins absorption band of ozone. Some indication of the Chappuis band in the orange is seen in the slight hook at the other end of the line.

Atmospheric ozone at Tucson.—We may compute the thickness of the ozone content of the atmosphere at N.T.P., which would account for this deviation of the observed transmissions from the formula of pure scattering with the aid of the coefficients of absorption as given by Fabry and Buisson[2] for 1 cm:

$$\log a = 17.58 - 0.00564\,\lambda\ , \qquad (2)$$

where λ is in angstroms.

[1] *Op. cit.*

[2] *Journal de physique*, **3**, 196, 1913.

If, following Dobson and Harrison,[1] we extend the straight part of the atmospheric transmission-curve in Figure 9 to the violet, as shown in the heavy broken line, we obtain the curve corresponding to an atmosphere free from ozone. The thickness t of the ozone layer at N.T.P. for any λ can then be found from the difference between the ordinates of the dotted line ($\log tr$) and the full (observed) line ($\log tR$) by means of the equation

$$t=\frac{\log tr-\log tR}{a}. \tag{3}$$

From several points on the rapidly changing part of the curve near λ 0.31 μ we find an average of 0.18 cm of ozone. The light line represents the transmission-curve which would be given by this thickness of atmospheric ozone and which probably represents the observed atmospheric transmissions fairly well. Possibly 0.17 or 0.16 cm would be a little better. Dobson's values for ozone at Table Mountain, California, average 0.24 cm, while Fowle's values[2] for Harqua Hala, Arizona, for the years 1921–1924, during which measurements were made at this station on the Chappuis band, average very nearly 0.18 cm, as found by the writer. It follows that the transmissions observed at Tucson are probably reasonable preliminary values. The dotted curve with triangles in Figure 9 represents the values given by Abbot[3] for Mount Wilson, the difference in δ probably being due in part at least to the greater elevation.

2. *Reflecting power of the siderostat mirror.*—On account of the difficulty of manipulating so large a piece of stellite, only a few measurements of the reflecting power of the siderostat mirror were made. The work of Coblentz and Emerson[4] on this subject is so complete that their results were adopted when it was found that their measured reflection coefficients for the mercury lines $\lambda\lambda$ 0.313, 0.366, 0.402, and 0.546 μ were substantially the same as those of the author. The values of the reflecting power, R, of stellite are given in Table VI.

[1] *Op. cit.*

[2] *Op. cit.*, pp. 12–13; see also table on p. 8.

[3] *Ibid.*, **74**, No. 7, p. 21, 1923; see also *Smithsonian Physical Tables* (7th rev. ed., 1921), p. 418.

[4] *Bulletin of the Bureau of Standards*, **14**, 307, 1917, Table 2.

3. *Transmission of the monochromator.*—The intensities of the mercury lines were observed with monochromator A alone, then with A and B together, as shown in Figure 8. The ratios of the deflections observed with A and B together to those observed with A alone are the transmissions of monochromator B. These results agree substantially with the values supplied by Bausch and Lomb. Since the two instruments are identical, the transmission of the whole instrument A and B together is the square of that for B alone. The observed values of the transmissions T_r of A alone and their squares T_r^2 are given in Table VI.

4. *Transmission of fused quartz.*—The fused quartz lens L is approximately $2\frac{1}{2}$ cm thick; L_1 is 1 cm thick at the center, and the window of the thermocouple T, which is also of fused quartz, is $2\frac{1}{2}$ mm thick. To determine the transmissions of fused quartz, a plane-parallel interferometer plate of this substance, 15.3 mm thick, was furnished by King. Light from a mercury arc was collimated between two lenses and the transmission measured in the parallel beam. The results T_R are given in Table VI. Tests were made on the lens L used as a condenser for the mercury arc alternately with a 6-inch crystal quartz lens of the same focal length. The results of this determination were in general the same as those for the plane-parallel piece, but more scattered, probably on account of the difficulty of exact replacement when the lenses were interchanged. When lens L was employed, the square of the measured transmission, T_R^2, was used as a correcting factor. Its values are also included in Table VI.

REDUCTION OF THE MEASUREMENTS

The observations of May 16, 17, 18, and 19 were made on integrated light by the method of constant purity of spectrum (all slits varied); those of May 19 (P.M.), 20, and 23, on integrated light by the method of constant dispersion (second and third slits varied); and those of May 21 and 22, on the center of the solar image by the method of constant dispersion. The measurements of May 23 on integrated light were made with the same slit width (50 A) and slit length (reduced from 10.8 to 4.5 mm) as were used in the measures on the center of the disk. This arrangement decreased the deflections to approximately one-fourth those previously observed for integrated light and perhaps best represents the use of the photoelectric cell. The results of the first run of the morning of May 23 are shown in Table VIII.

The first step in the reduction was to plot the deflections with the photoelectric cell (marked P in the Table) against those obtained

TABLE VIII

MEASURES OF THE SPECTRAL ENERGY OF THE SUN, MAY 23, 1931
(Slit S_2, 50 A wide; slit S_1, 1 div. wide and 4.5 mm long)

λ	S_2	H.A.	Defl.	λ	S_2	H.A.	Defl.
μ	Div.		mm	μ	Div.		mm
0.70.......	0.22	-4^h33^m	64	0.35.......	1.85	-4^h06^m	17
.60.......	0.36	4 30	106	.34.......	2.08	4 00	17
.55.......	0.45	4 28	106	.33.......	2.28	3 52 3 50	540P 14
.50.......	0.58	4 24	99	.325......	2.39	3 47 3 48	530P 13
.45.......	0.81	4 23	91	.32.......	2.50	3 45 3 44	450P 9
.42.......	1.00	4 21	61	.315......	2.63	3 37 3 36	358P 7.5
.40.......	1.10	4 19	54	.31.......	2.78	3 34 3 33	274P 4.5
.39.......	1.28	4 17	46	.305......	2.94	3 31 3 30	170P 2
.38.......	1.39	4 14	25	.30.......	3.12	3 27	84P (0.7)
.37.......	1.50	4 12	25	.295......	3.33	3 25	27P (0.19)
0.36.......	1.60	−4 10	21	0.292......	3.55	−3 23	8P (0.06)

with the thermopile for the same wave-length and to extend to the origin the smooth curve representing them. The thermopile deflections corresponding to those of the photoelectric cell were then read off and smoothed by second differences. The smoothed values appear in the last column of Table VIII, where the last three thermopile deflections, given in parentheses, are computed in this manner from the photoelectric-cell deflections.

The observations of a given day were reduced to the zenith and to no atmosphere by Bouguer's formula, which may be written

$$\left.\begin{aligned}\log d_o &= \log d - \sec z \log Tr ,\\ \log d_z &= \log d_o + \log Tr ,\end{aligned}\right\} \qquad (4)$$

where log d is the average of the logarithms of the observed deflections; d_z and d_o, the corresponding deflections at the zenith and for no atmosphere; Tr, the mean atmospheric transmission obtained as already described; and sec z is the average air mass.

These values of d_o and d_z were then corrected for the instrumental losses described under "Transmission Coefficients and Atmospheric

TABLE IX

ENERGY IN THE SOLAR SPECTRUM AND OBSERVATIONAL CORRECTING FACTORS

λ	Tr_a	$\frac{1}{Tr_a}$	Tr_i	F_1	F_2	F_3	Energy in Arbitrary Units (Deflections in mm)								Energy in 100 A	
							Integrated I		Integrated II		Center		Average		Watts per Square Meter	
							Z	No Atm.	Z	No Atm.	Z	No Atm.	Z	No Atm.	Z	No Atm.
μ																
0.700...	0.79	1.26	1.00	....	1.00	2.22	.....	.....	70.1	88.4	79.3	99.9	74.7	94.2	8.3	10.5
.600...	.79	1.27	0.96	1.83	1.00	1.67	97.7	123.5	115.5	146.8	121.6	154.6	111.6	141.6	12.4	15.7
.550...	.78	1.29	0.94	1.85	1.08	1.57	124.4	160.3	128.3	165.4	129.3	166.5	127.4	164.1	14.2	18.2
.500...	.76	1.31	0.91	1.56	1.13	1.33	.....	.....	137.5	179.9	135.6	177.5	136.6	178.7	15.2	19.9
.450...	.74	1.36	0.87	1.15	1.15	1.15	132.6	180.0	132.6	180.0	132.7	180.0	132.6	180.0	14.7	20.0
.420...	.71	1.41	0.85	....	1.18	1.20	.....	.....	101.0	142.6	107.7	151.9	104.3	147.2	11.6	16.4
.400...	.68	1.47	0.82	0.81	1.19	1.25	99.7	146.8	95.7	140.8	98.6	145.0	98.0	144.2	10.9	16.0
.390...	.66	1.52	0.81	0.76	1.23	1.29	71.1	107.7	68.5	103.7	57.8	87.6	65.8	99.7	7.3	11.1
.380...	.64	1.57	0.79	0.74	1.27	1.36	54.5	85.4	52.6	82.6	51.2	80.2	52.8	82.7	5.9	9.2
.370...	.61	1.64	0.78	0.70	1.32	1.42	52.5	85.8	55.2	90.5	52.5	86.0	53.4	87.4	5.9	9.7
.360...	.58	1.73	0.76	0.63	1.33	1.46	46.9	81.0	52.2	90.3	50.7	87.6	49.9	86.3	5.5	9.6
.350...	.54	1.84	0.74	0.58	1.35	1.50	37.5	68.9	41.8	76.8	45.7	84.2	41.7	76.6	4.6	8.5
.340...	.49	2.02	0.72	0.55	1.37	1.54	36.1	73.1	39.0	78.9	39.6	80.2	38.2	77.4	4.2	8.6
.330...	.43	2.32	0.71	0.54	1.42	1.63	32.1	74.7	34.7	80.6	34.9	80.7	33.9	78.7	3.8	8.7
.325...	.39	2.56	0.69	....	1.45	1.67	.....	.....	31.0	79.6	31.6	80.8	31.3	80.2	3.5	8.9
.320...	.35	2.85	0.68	0.44	1.48	1.73	17.7	49.9	26.5	75.8	20.4	57.8	21.5	61.2	2.4	6.8
.315...	.30	3.29	0.67	....	1.51	1.80	.....	.....	18.9	62.4	14.3	47.1	16.6	54.8	1.8	6.1
.310...	.25	3.97	0.66	0.39	1.54	1.86	6.3	25.1	14.0	55.6	10.3	40.8	10.2	40.5	1.1	4.5
.305...	.17	5.88	0.64	....	1.56	1.91	.....	.....	7.6	44.7	5.1	29.5	6.4	37.1	0.71	4.1
.300...	.07	14.49	0.63	0.38	1.59	1.96	2.2	30.0	4.0	58.7	1.5	21.2	2.6	36.6	0.29	4.1
.295...	.03	30.30	0.61	0.38	1.63	2.05	0.7	19.4	1.3	40.3	0.1	4.4	0.7	21.4	0.08	2.4
0.292...	0.02	50.00	0.59	0.36	1.63	2.06	0.2	9.6	0.5	20.6	0.1	1.1	0.3	10.4	0.03	1.1

Ozone" and, in addition, for certain corrections that apply to the individual days. The measurements made by the method of constant purity of spectrum were reduced to constant dispersion with the aid of the data on the relation of slit width to galvanometer deflection. In some cases a slit-zero correction was also applied. In the case of measurements on the center of the disk, the reciprocal square of the focal length of L was applied to reduce all the measurements to constant angular aperture when the diaphragm was used on the lens.

Table IX shows the results of all the measurements. This table gives the wave-length λ; the atmospheric transmission coefficients Tr_a and their reciprocals $1/Tr_a$ to show the effect of this function as a correcting factor; the instrumental transmission coefficients Tr_i; the complete instrumental correcting factors F_1, F_2, and F_3 applied to the three methods of measurement (constant purity, constant dispersion, and center of the disk); the values of the deflections at the zenith and for no atmosphere, the latter reduced to a mean value of 180 mm at λ 0.45 μ; and, in the last two columns, the average of all these measurements in units of watts per square meter per hundred angstroms.

The results of the measurements are plotted separately in Figure 10, and the average of the three methods in Figure 11. One of the interesting features of these curves is the sudden drop of 35 per cent in the solar energy outside the atmosphere between λ 0.40 and 0.38 μ, and the nearly constant value of the solar energy, about 43 per cent of the maximum, between λ 0.38 and 0.325 μ, which covers nearly the entire ultra-violet spectrum.

The scale on the left is in millimeters of deflection, and on the right, in watts per square meter per hundred angstroms. The latter scale is derived as follows: The energy-curves for no atmosphere are plotted in Figure 10 on a scale to fit Abbot's curve for the longer wave-lengths. Now if Abbot's entire solar energy-curve be plotted to a wave-length scale, where 1 μ is equivalent to 15.2 cm and the maximum of energy is 25.4 cm, the area is found to be 257 cm^2. This area is equivalent to the solar constant, 1.95 cal cm^{-2} min^{-1}, or 1355 watts per square meter. From these data an area 100 A wide by 1.25 cm high was found to be equivalent to 1 watt. A height of 1.25 cm is therefore the unit of watts per square meter per hundred angstroms. It may be seen from the curve that the galvanometer deflections divided by 9 also give the radiation in these units. For the maximum of the curve the rate of emission is 20.3 watts per square meter per hundred angstroms.

We should expect the measures on the center of the disk to show a richer ultra-violet content than those on integrated light, and that these measurements give a result which is about the same as the mean value for the two groups of measures on integrated light is a little puzzling. The Smithsonian work on drift-curves of the sun forms a basis for calculating the energy-curve for the center of the disk. If we divide the solar disk into concentric zones and use the Smithsonian[1] values of the energy at the center of area of each zone

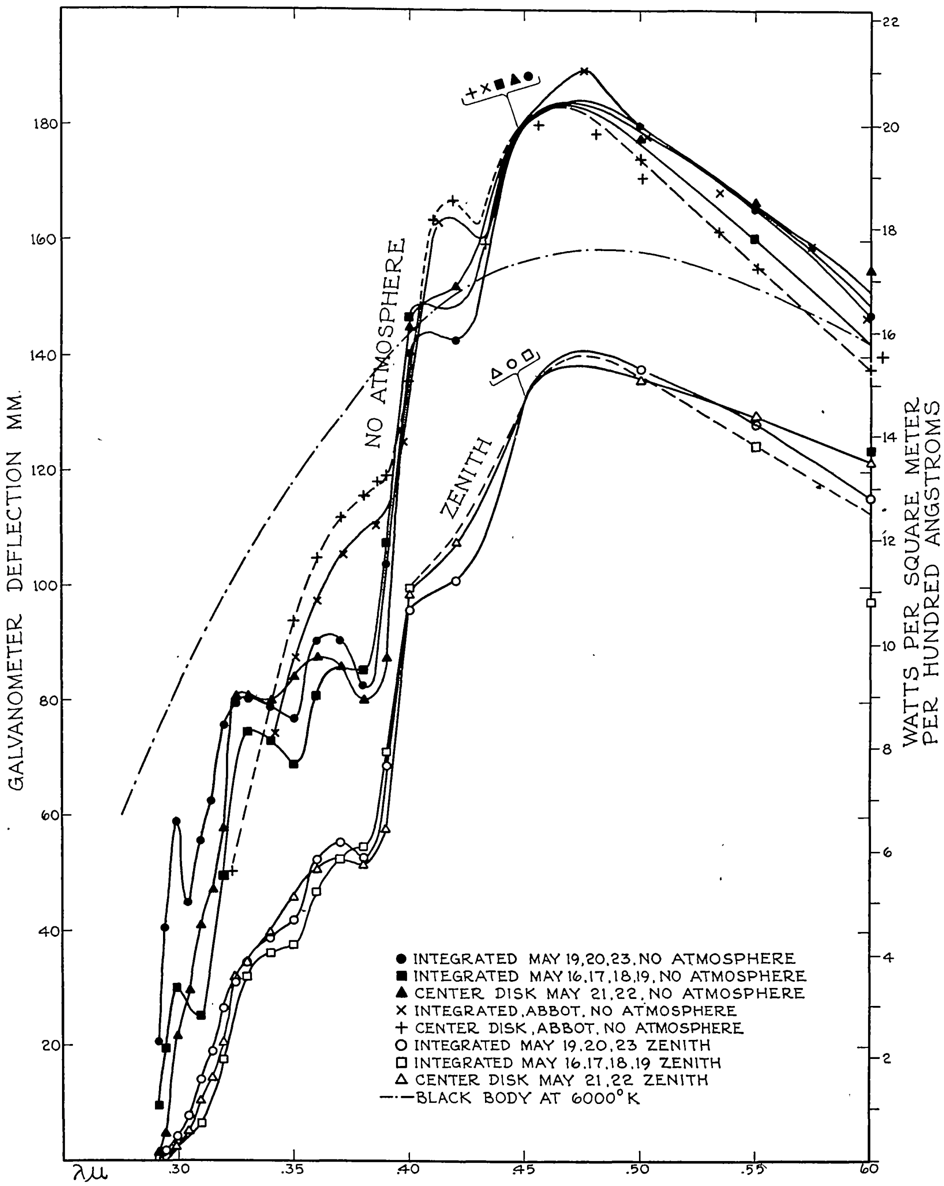


FIG. 10.—Solar energy-curve in the visible and ultra-violet outside the earth's atmosphere and for the sun in the zenith at Tucson.

[1] Abbot, *The Sun* (1926), pp. 106–107.

as weights, we may obtain by summation a series of coefficients by which the energy in integrated light for various wave-lengths must be multiplied in order to give the energy-curve of radiation from the center of the disk. Abbot[1] gives some of these coefficients; others

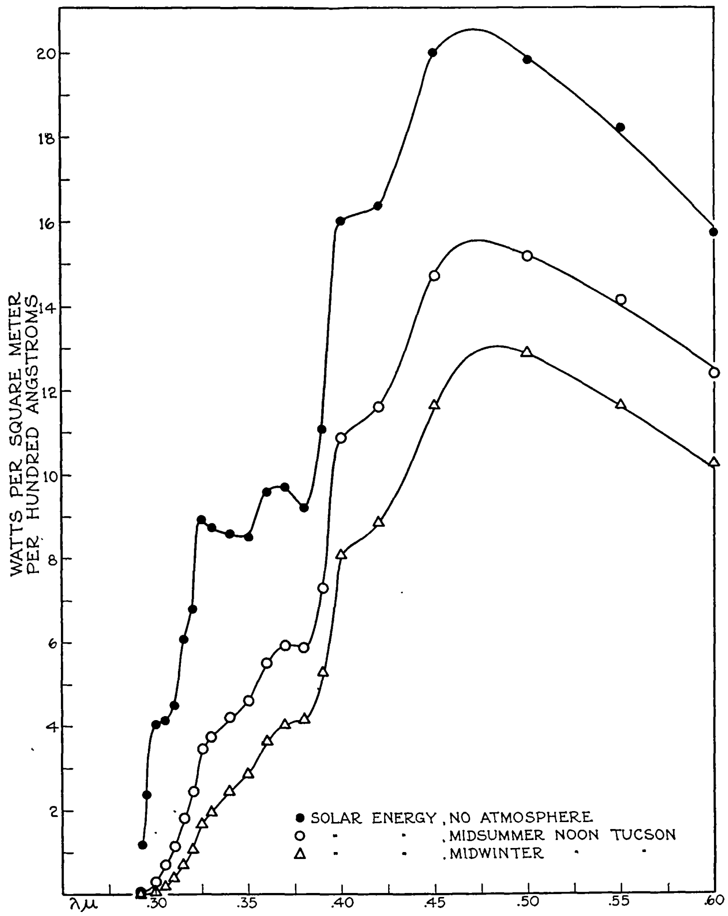


FIG. 11.—Mean curve of solar energy in the visible and ultra-violet, outside the earth's atmosphere and for noonday sun in midsummer and midwinter at Tucson.

have been calculated to obtain the form of the curve in the ultra-violet. Figure 10 shows the results when they are applied to Abbot's curve for integrated solar radiation. The black-body curve for 6000° K has been made to coincide with the solar energy-curve at λ 0.7 μ, because the curve to the red of this wave-length fits the observa-

[1] *Ibid.*, Table VII.

tions of the Smithsonian observers the best. It will be noted that for wave-lengths shorter than λ 0.4 μ the black-body curve lies considerably above the violet slope of the observed curve.

Figure 11 is a plot of the mean values of the solar energy for no atmosphere and for the zenith at Tucson. The zenith-curve is also essentially that for the noonday sun in midsummer. The noonday curve for midwinter at that latitude has been computed from equation (4). These curves are particularly interesting in showing the extremes of the seasonal effect of atmospheric absorption on ultraviolet solar radiation. For example, the energy in the 100 A between λ 0.3 and 0.29 μ at Tucson in midsummer (see col. 16, Table IX, at λ 0.295 μ) is 0.08 watts per square meter; while in midwinter, equation (4) shows that it would fall to only 0.0017 watts, about one-fiftieth part of the energy in midsummer.

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