

# RECENT MEASUREMENTS OF STELLAR AND PLANETARY RADIATION<sup>1</sup>

By W. W. COBLENTZ

## CONTENTS

I. PHOTOELECTRIC PHOTOMETRY, II. STELLAR AND PLANETARY RADIOMETRY: 1. Reflecting telescopes; 2. Galvanometers and magnetic shielding; 3. Bolometers; 4. Thermocouples; 5. Stellar spectroradiometry; 6. Stellar spectral energy distribution by means of transmission screens; 7. Stellar radiation intensities; 8. Variable stars; 9. Stellar temperatures; 10. Planetary radiation measurements; 11. Bibliography.

In a previous report,<sup>2</sup> a summary and bibliography were given of measurements of thermal radiation from stars prior to 1920. The bibliography to the present report is given at the end of this paper.

I. PHOTOELECTRIC PHOTOMETRY: As indicated in the preceding report, the potassium hydride photoelectric cell is a useful instrument for photometering celestial objects, such as for example, variable stars.

Stebbins,<sup>1, 2</sup> after many trials has succeeded in developing a potassium photoelectric cell of fused quartz, which is much more sensitive than the selenium photometer previously used, thereby enabling him to study sixth-magnitude stars with a 12 in. telescope.

With this devise, Stebbins<sup>1</sup> was able to show that the variability in brightness of a certain star is not caused by eclipsing, but that the variation is caused by a change in the ellipsoidal shape of the components, resulting from their mutual attraction.

<sup>1</sup> Section of 1922 Report of Standards Committee on Spectroradiometry, W. W. Coblentz, Chairman.

<sup>2</sup> Coblentz, Jour. Opt. Soc. Amer., 5, p. 269 (see p. 276); 1921.

In a recent photoelectric study of the variability of Algol Stebbins<sup>3</sup> found new results showing an effect due to the ellipsoidal shape of the components of the system.

Rosenberg<sup>4</sup> describes a stellar photometer consisting of a photoelectric cell and amplifying tubes. Measurements are given on several stars and planets.

II. STELLAR AND PLANETARY RADIOMETRY: Under this caption are described recent developments in nonselective stellar radiometers as well as recent measurements of the radiation from stars and planets.

1. *Reflecting Telescopes*.—Recent press dispatches tell of generous gifts of a 6 ft. reflector to be used primarily by students in a certain college in the state of Ohio, and of a 10 ft. reflector to be located in the state of Washington.

The gifts seem to be made through local pride for the hometown without consideration of the number of clear nights that will be available for observation and without thought of attainment of the maximum usefulness.

The needs of stellar radiometry are reflecting mirrors 15 or more feet in diameter, situated in a dry cloudless climate, such as obtains in Arizona and California. Some years ago, the writer had the temerity to inquire into the feasibility of constructing such a mirror by piling up a number of sheets of polished plate glass, and bringing them to the annealing temperature, when they will coalesce. By placing them in a suitable mold, they will sag to the proper curvature, so that in the polishing there will be no cutting through of the first layer.

The production of a large disk of glass by this method would obviate the difficulty of obtaining a sufficient amount of molten glass for casting in one piece, which is homogeneous and free from local imperfections. From a discussion of the matter with a large-scale plate-glass producer, it appears that the suggestion of building up a glass disk from polished, selected sheets of plate glass may not be as foolish as it appears on first thought.

2. *Galvanometers and magnetic shielding*.—For stellar radiometry Abbott,<sup>7</sup> proposes to use a 2-coil galvanometer, in magnetic

shielding, instead of the 16-coil instrument heretofore employed in his solar radiation work.

The use of a 2-coil non-astatic galvanometer is, of course, not new, similar instruments having been used by duBois and Rubens.<sup>10</sup> Modern conditions require so much magnetic shielding that the astatic magnet system is relatively unimportant. In his improved type of iron-clad Thomson galvanometer (in a vacuum) with the coils imbedded in blocks of soft iron and with an inner laminated shield of transformer iron, Coblentz,<sup>12</sup>,<sup>6</sup> found that the old type of 4-coil galvanometer with its astatic magnet system can be displaced by a 2-coil galvanometer with a single set of magnets, reducing the weight of the suspension by one-half and thus practically doubling the sensitivity.

The use of an inner shield of laminated transformer iron separated by equal thicknesses of paper has recently been described by Wente.<sup>14</sup> In the interest of historical accuracy, it is relevant to add that Esmarch,<sup>13</sup> used shields consisting of fine iron wire wound upon cardboard instead of transformer iron as one would infer from the above quoted paper.<sup>14</sup>

The writer has tried the laminated shields, lightly wound (hence small air spaces between the lamina) without the intervening cardboard, and with the intervening spaces uniformly separated by cardboard, and has found no marked difference in the shielding efficiency. A considerable quantity of the metal close to the galvanometer, with the top of the laminated iron cylinder covered with a laminated lid seems most effective. In this connection, it is interesting to recall that from his theoretical calculations, of magnetic shielding, Rücker,<sup>11</sup> concluded that, under certain conditions, the resultant magnetic shielding obtained by the best use of a given quantity of material can be still further improved by filling up the spaces between the shells with additional material.

3. *Bolometers*.—From his theoretical studies, Abbot<sup>8</sup> concludes that contrary to the conclusions arrived at by him in determining the best dimensions for a solar vacuum bolometer, the most effective stellar vacuum bolometer must be exceedingly thin, say 0.0005 mm in thickness (length 8 mm, width 0.12 mm).

Material of this thickness or even thinner, has been extensively used in black body spectral energy measurements. Owing to its small heat capacity, it is easily disturbed by air currents and hence must be used in a vacuum when refined measurements are attempted.

In view of the feeble intensity of the stellar radiation, it is evident that receivers of low heat capacity should be used. It seems to have been overlooked by users of bolometers that there is considerable loss of heat radiation from the rear side of a bolometer receiver, even when it is unblackened. By placing a second bolometer receiver directly back of the front one, Coblentz<sup>9</sup> found that the radiation sensitivity was greatly increased (amounting to 50 per cent in receivers which were blackened on both sides).

Johansen<sup>15</sup> has shown experimentally that heat conduction from the ends of a platinum bolometer strip (0.001 mm in thickness) greatly reduces the radiation sensitivity, extending out 3 to 4 mm from the electrodes. Coblentz and Emerson<sup>16</sup> using a platinum bolometer from one-half to one-third of this thickness, found appreciable heat conduction and hence loss in thermal radiation sensitivity extending 1.5 to 2 mm back from the ends of the bolometer receiver. From this and from Abbot's<sup>8</sup> calculations, it appears that a bolometer receiver for stellar radiometry cannot be made much less than 5 to 6 mm in length without loss in radiation sensitivity by heat conduction to the electrodes.

4. *Thermocouples*.—In a recent study<sup>17</sup> of thermocouple material to be used instead of a bolometer for stellar radiometry, it was found that the radiation sensitivity was closely proportional to the thermoelectric power (which was to be expected) but there was no great gain in sensitivity from reduction in thermal conduction by reduction of the heat capacity of the material as compared with that previously employed.<sup>5</sup> The chief gain was in quickness of action and hence increased accuracy of observation.

The height of the spectrum of a star is only a small fraction of a millimeter. Hence, by placing the connecting wires of the thermocouple vertical, so as to coincide with the spectral image of the entrance slit of the spectroradiometer, it seems that the

thermocouple could advantageously replace the spectro-bolometer, in view of the fact that the latter is heated by the battery current, which renders the galvanometer reading unsteady. For measuring the radiation from small areas, as for example the dark spots on Mars, the (vacuum) thermocouple seems more suitable than the (linear) bolometer.

5. *Stellar Spectroradiometry*.—The hundreds of photographs of stellar spectra, obtained by astronomers, show dark absorption lines and bands (also in some cases, bright emission lines) of hydrogen, helium, etc. From this, it is evident that a smooth spectral energy curve, without deep indentations, cannot be obtained. Our inferences as to the probable spectral energy distribution and inferred effective temperatures must therefore be obtained by smoothing over the depressions in the observed spectral energy curve. Then assuming that the stellar envelope radiates like a gray or black body, the effective temperature may be calculated.

Equipped with a spectroscope attached to a powerful telescope and the above mentioned improvements in radiometers, Abbot and Aldrich<sup>8</sup> expect to obtain the spectral energy curves of stars. Indeed, recent press dispatches announce this as now an accomplished fact. They find the effective temperature of a blue star (Betelgeux) to be 10 000°, confirming the observations of Coblenz,<sup>17</sup> which is to be expected in view of the fact the transmission screen method employed by the latter simply integrates wider regions of the spectrum in a single measurement.

While the discussion of stellar spectroradiometry has been mainly in connection with the determination of spectral energy curves, it should not be overlooked that the device may prove useful in mapping the spectral emission and absorption lines and bands of stars, in the infra-red spectrum to which the photographic plate is not sensitive. Spectroscopists will no doubt find use for any information pertaining to the wave-lengths and intensities of the bright and dark lines in this part of the infra-red spectrum.

6. *Stellar Spectral Energy Distribution by Means of Transmission Screens*.—At best a spectroscope is an inefficient device (Abbot,<sup>8</sup> *loc. cit.*, p. 59, places the loss at the slit jaws at 40 per cent) for

utilizing the incoming stellar radiation, and recently Coblentz<sup>17</sup> determined the feasibility of obtaining the spectral energy distribution of a star by means of a series of transmission screens, placed in front of a vacuum thermocouple which was used as the radiometer.

Screens were selected which, either singly or in combination, had a uniformly high transmission over a fairly narrow region of the spectrum, terminating abruptly in complete opacity in the rest of the spectrum. By proceeding in this manner, the observations required no correction other than that for surface reflection, which amounts to about 9 per cent for the two surfaces of the screen. Corrections were made for absorption by the telescope mirrors; also for atmospheric absorption, using the spectral transmission factors for the sun, as observed by Abbot and Fowle.

By means of these screens (of red and yellow glass, quartz and water) 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 telescope mirrors) at  $0.3\mu$  to  $0.43\mu$ ;  $0.43\mu$  to  $0.60\mu$ ;  $0.60\mu$  to  $1.4\mu$ ;  $1.4\mu$  to  $4.1\mu$ ; and  $4.1\mu$  to  $10\mu$ .

By this novel means the distribution of energy in the spectra of 16 stars was determined, thus obtaining for the first time an insight into the radiation intensities in the complete spectrum of a star. From press dispatches, it appears that Abbot's recent spectrobolometric measurements verify the results obtained by Coblentz which is to be expected in view of the similarity of the principles involved.

This method may be open to criticism in view of the fact that it integrates the energy present in a certain spectral region and hence does not indicate the amount lost in the spectral absorption lines. The same criticism is true also of the direct spectroradiometric method which is no doubt limited to a few of the brightest stars, and if the dispersion is small, cannot properly evaluate the spectral intensities. Hence, the transmission screen method should prove useful in supplementing the spectroradiometric measurements, on fainter stars not measurable by the latter method. By integrating the spectrobolometric energy

curves, a relation ought to be obtainable with the data observed with the transmission screens and in this way a comparison obtained of the spectral energy distribution of bright and faint stars of the same spectral class.

The measurements made by Coblentz<sup>5</sup> with the water screen show that, in blue and yellow stars, practically all the energy lies in that part of the spectrum to which the photographic plate is sensitive. Hence, since the effect on the photographic plate is cumulative, and the time for exposure is relatively unlimited, the spectral energy distribution of many weak stars and nebulae can be mapped, which will not be possible by any other methods known to us at the present day. Indeed such a beginning has been made by Plaskett.<sup>19</sup> But the measurements made through the water cell show that, if astronomers had known it, they could have used the photographic method long ago for determining the spectral energy distributions of blue and yellow stars. For this purpose, the photographic plate must, of course, be standardized by exposing it to the spectrum of a source of known spectral energy distribution as was done, for example by Ives and Coblentz<sup>24</sup> in determining the spectral energy distribution in the light of the firefly.

7. *Stellar Radiations Intensities*.—The thermocouple measurements of the total radiation from stars, made by Coblentz,<sup>5, 17</sup> in 1914, at Mt. Hamilton, Calif., (Lick Observatory, altitude 4000 ft.) were verified in 1921 at Flagstaff, Ariz. (Lowell Observatory, altitude 7250 ft.), showing that the early-type (Class M) red stars are losing heat 3 to 4 times as fast as the more dense, but hotter late-type (class B, A) blue stars. The least dense, class M, stars must therefore be losing heat by radiation, in which conduction does not contribute very materially in maintaining the surface at a given temperature.

In the dense stars the shape of the spectral energy curve, and hence our inferences of the effective temperature is determined by the spectral emissivity of the surface; while in the less dense stars the radiation emanates from great depths.

The water cell measurements open up a new line of thought on stellar evolution, showing, as already stated, that red stars are

losing heat 4 times as fast as blue stars. From present theories, it appears that, in the Giant, red-star stage of evolution, a star may be rising in temperature, while it is decreasing in temperature on its return to the Dwarf (red star) stage.

A question of interest is whether, when the star is passing through the high temperature, blue, class B, A-stage of development (and is losing heat one-fourth as fast as when it is in the red, class M-stage) the interval of time of transition is relatively much longer (say 3 to 4 times longer) than when the star is in the low temperature, red, class M, N stage of evolution.

8. *Variable Stars*.—When the vacuum thermocouple and water cell were first used successfully,<sup>5</sup> in separating the infra-red from the visible radiation from stars, the usefulness of this device was apparent in studying the heat from double stars and from planets.

Recent reports from the Mt. Wilson Observatory, where Pettit and Nicholson<sup>18</sup> are using the 100 inch reflector, show that the vacuum thermocouple and water cell are rapidly becoming useful for routine study of variable stars of long period. However, from the viewpoint of the physicist it would seem preferable to tabulate the water-cell absorption in per cent of the total radiation received instead of in difference of stellar magnitude as given by these observers (or give both). For example it seems simpler to state that the water cell absorbs 25 per cent of the total radiation from Vega than to state that the water cell absorption, in difference of magnitude, is 0.3. The field of stellar radiometry is practically new and the adoption of a simple nomenclature and a simple tabulation of data should be begun now.

The water cell, having the property of absorbing the invisible infra-red rays, which are emitted by stars of low luminosity, will be a useful device for studying double stars, like Sirius, which have companions of low luminosity, and in searching for double stars which many have dark companions. This will form a new field of investigation.

9. *Stellar Temperatures*.—Data on the spectral energy distribution and temperature of stars as related to that of a black body are very meager. They are the results practically of the spectrophotometric measurements of Wilsing,<sup>20</sup> and of Nordmann,<sup>21</sup> and



the spectral energy curves determined photographically by Plaskett,<sup>19</sup> all of which relate to the visible spectrum. From the data obtained on the radiation intensities in the visible spectrum, these experimenters have obtained estimates of stellar temperatures of 3000° for red stars to 25 000° or even higher for blue stars.

The temperature measurements of Wilsing, Scheiner and Münch<sup>20</sup> of various stars of class B (blue) vary from 7000° to 15 000° K; class A, from 8000° to 12 000° K; class F from 5000° to 8000° K; class G, (solar type) from 4000° to 7000° K; and class M (red) 3000° to 3500° K.

By means of his transmission screen device, Coblentz<sup>17</sup> found that, in the class B and class A (blue) stars, the maximum radiation intensity lies in the ultra-violet ( $0.3\mu$  to  $0.4\mu$ ) while in the cooler, class K and M (red) stars, the maximum emission lies at  $0.7\mu$  to  $0.9\mu$  in the infra-red. From this it appears that the black body temperature (i.e., the temperature which a black body would have to attain in order to emit a similar relative spectral energy distribution) varies from 3000° K for red, class M, stars to 10 000° for blue, class B, stars.

This estimate of the effective temperature of a star was obtained by comparing the observed spectral radiation components with the calculated values for a black body at various temperatures.

In Table 1, are assembled various determinations of the effective stellar temperatures by Nordmann,<sup>22</sup> and by Nordmann and le Morvan,<sup>21</sup> also by Wilsing, Scheiner, and Münch,<sup>20</sup> and calculated values by Saha<sup>23</sup> on the basis of ionization theory.

While it is to be expected that the various methods must give different results, it is interesting to find a rather close agreement in the estimated stellar temperatures. The agreement is especially close for stars of classes G, K, and M, that is, stars having a low temperature.

10. *Planetary Radiation Measurements.*—By planetary radiation is meant the emission of thermal radiation from a planet as a result of warming of its surface by exposure to solar radiation, including heat that may be radiated by virtue of a possible high internal temperature of the planet itself.

TABLE 1.—*Stellar Temperatures*

Star	Class	Coblentz	Wilsing, Scheiner & Munch	Nord- mann & Morvan	Nord- mann	Saha
		°K	°K	°K	°K	°K
$\epsilon$ Orionis.....	Bo	13 000	.....	.....	.....	18 000
$\beta$ Orionis.....	B8p	10 000	.....	.....	.....	.....
$\alpha$ Lyrae.....	Ao	8 000	9 400	.....	12 200	.....
$\alpha$ Canis Majoris....	Ao	7 000	.....	.....	.....	12 000
$\alpha$ Cygnii.....	A2	8 000	9 400	.....	.....	.....
$\alpha$ Aquilae.....	A5	8 000	8 100	.....	.....	.....
$\alpha$ Canis Minoris....	F5	6 000	7 200	.....	.....	.....
$\alpha$ Aurigae.....	Go	6 000	7 100	.....	.....	7 000
$\alpha$ Boötis.....	Ko	4 000	3 700	.....	.....	.....
$\beta$ Geminorum.....	Ko	5 500	4 900	.....	.....	.....
$\alpha$ Tauri.....	K5	3 500	3 500	3 600	3 500	.....
$\alpha$ Orionis.....	Ma	3 000	3 000	.....	.....	5 000
$\alpha$ Scorpii.....	Ma <sub>p</sub>	3 000	.....	.....	.....	.....
$\beta$ Andromedae.....	Ma	4 000	3 200	4 300	3 700	.....
$\mu$ Geminorum.....	Ma	3 500	3 100	3 200	.....	.....
$\beta$ Pagasi.....	Mb	3 000	2 800	.....	.....	.....
Sun.....	Go	$\left\{ \begin{array}{l} 5\,800^a \\ \text{to} \\ 6\,200 \end{array} \right.$	.....	.....	5 320	.....

<sup>a</sup> Recalculated from Abbot & Fowle, Jour. Opt. Soc. Amer., 5, p. 272; 1921.

The temperature of the surface, due to absorbed solar radiation and due to internal heat, at most, is probably not much higher than several hundred degrees centigrade and hence the reradiated energy will be predominately of long wave-lengths,— $7\mu$  to  $12\mu$ . Hence by means of a 1 cm. water cell interposed in the path of the total radiation emanating from the planet, this long-wave-length radiation can be separated from the reflected solar radiation, and in this manner a measurement obtained of the planetary energy radiated. If there is planetary radiation then the water cell transmission will be less than that of the direct solar radiation.

During the past June, (1922) the writer made further measurements (at the Lowell Observatory) of the thermal radiation emitted by the major planets.

By comparing the transmission of the direct solar radiation, through a water cell, with the transmission of the radiation emanating from the planet, a measurement was obtained of the intensity of the planetary radiation.

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 water cell transmissions of the radiations from Jupiter and from the Sun were practically the same, indicating (1) that the outer atmosphere of Jupiter does not become heated (either by the Sun's rays or by internal radiation) and emit long-wave-length infra-red radiation and (2) that any radiation emanating from its interior is entirely trapped by surrounding atmosphere. Hence, we cannot determine the internal condition of Jupiter.

The intensity of the planetary radiation increases with decrease in the density of the surrounding atmosphere and, as interpreted from the water cell transmission, is as follows: Jupiter (0), Venus (5), 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 is to be expected in view of the observed cloudiness over the northern hemisphere which is approaching the winter season, and hence is at a lower superficial temperature.

The radiometric measurements on Mars are of especial interest in view of the question as to its temperature, etc. Lowell's<sup>26</sup> calculations of the surface temperature of Mars give values much higher than those obtained by Poynting,<sup>25</sup> who obtained a value of  $-38^{\circ}$  C.

The calculations of Lowell, based on the heat retained, give a mean temperature of  $9^{\circ}$  C for the surface of Mars; while another calculation gives a temperature of  $22^{\circ}$  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. Other meteorological data of interest are that on Mars, water boils at  $44^{\circ}$  C; that the amount of air

per unit surface is 177 mm ( $2/9$  the earth's) and that the density of the air at the surface is 63 mm ( $1/12$  the earth's).

In a recent discussion of climatic conditions on Mars, Pickering<sup>27</sup> inferred from phenomena generally observed on the planet, estimates the mean annual temperature at  $+20^{\circ}$  F as compared with the mean annual temperature of the earth of  $+59^{\circ}$  F ( $15^{\circ}$  C). At night, the Martian temperature is below  $32^{\circ}$  F ( $0^{\circ}$  C) and at noon it is perhaps 60 to  $70^{\circ}$  F ( $15^{\circ}$  to  $20^{\circ}$  C). These estimates are arrived at from the appearance and disappearance of snow and frost during the course of the Martian day, and from the fact that snow is never seen on the equator at Martian noon.

The writer's radiometric measurements are in agreement with the calculations of Lowell, and with the arguments set forth by Pickering, showing a considerable rise in temperature of the surface of Mars.

Probably the most convincing experimental observations of the range of temperature of the moon are those of Langley and Very<sup>28</sup> and later, those of Very.<sup>29</sup> These measurements indicate inferred effective lunar temperature ranging from  $45^{\circ}$  C to over  $100^{\circ}$  C. The calculated value<sup>30</sup> using recent data on the solar constant, indicate a lunar temperature of  $82^{\circ}$  C.

When we consider that 30 per cent of the total radiation emanating from Mars is of planetary origin, as compared with 80 per cent from the moon, and that all the evidence shows that the lunar surface becomes appreciably warmed it appears that there is also a considerable temperature rise (10 to  $25^{\circ}$  C.) of the surface of Mars as calculated by Lowell. So whether or not we accept the view that vegetation can exist on Mars, the radiometric measurements confirm other meteorological data, showing that at Martian noon the snow is melted, which could not happen if the temperature were  $-39^{\circ}$  C as some have calculated.

As for the views held by some, of the possibility of vegetation growing on Mars, much depends upon whether we think of palm trees growing in our tropics, or the mosses and lichens which thrive on the apparently bare piles of volcanic cinders of Arizona and under our Arctic snows.

In conclusion, it may be noted that there is a divergence of opinion as to the spectral character and the intensity of the solar radiation, the "solar constant," outside of our own atmosphere. The unexpected observation of a considerable heating of the surface of Mars, raises the question whether the calculations of planetary temperatures are in error, or whether the solar radiation intensity (the "solar constant") outside our atmosphere is higher than the present accepted value.

BUREAU OF STANDARDS,  
WASHINGTON, D. C.

## II. BIBLIOGRAPHY

### II. *Photoelectric Photometry.*

1. Stebbins, *Astrophys. Jour.*, *51*, p. 218; 1920.
2. Stebbins, *Astrophys. Jour.*, *51*, p. 193; 1920.
3. Stebbins, *Astrophys. Jour.*, *53*, p. 105; 1921.
4. Rosenberg, *Die Naturwissenschaften*, *9*, p. 359; 1921.

### III. *Stellar and Planetary Radiometry.*

5. Coblentz, *Bull. Bur. Standards* *11*, p. 613; 1915 and Lick Observatory (Stellar Radiometry)
6. Coblentz, *B. S. Bull.* *13*, p. 442; 1916. *14*, p. 519; 1918. (Galvanometers)
7. Abbot, *Annals Astrophys Obs.*, *4*, p. 60; 1922 (Galvanometers).
8. Abbot, *Annals Astrophys Obs.*, *4*, p. 64, (Bolometers).
9. Coblentz, *B. S. Bull.* *14*, p. 532; 1918 (Multiple Bolometer) (Magnetic Shielding).
10. duBois & Rubens, *Electrotech. Zeit.*, *15*, p. 321; 1894.
11. Rücker, *Phil. Mag.*, (5) *37*, p. 95; 1894.
12. Coblentz, *B. S. Bull.*, *9*, p. 60; 1911.
13. Esmarch, *Ann. der Phys.* (4), *39*, p. 1540; 1912.
14. Wentz, *Phys. Rev.*, (2) *16*, p. 137; 1920.
15. Johansen, *Ann. der Phys.* (4), *33*, p. 517; 1910 (Bolometers).
16. Coblentz & Emerson, *B. S. Bull.* *12*, p. 503; 1916 (Bolometers).
17. Coblentz, *B. S. Sci. Paper* *17*, p. 725; 1922 (Thermocouples, Stellar temperatures.)
18. Pettit & Nicholson, *Pub. Astron. Soc. Pacific* *34*, p. 181; 1922.
19. Plaskett, *Monthly Notices, R.A.S.* *80*, p. 771; 1920.
20. Wilsing, Scheiner & Münch, *Pub. Astrophys Obs.*, Potsdam, *24*, No. 74; 1920.
21. Nordmann & Le Morvan, *Compt. Rend.*, *173*, p. 72; 1921.
22. Nordmann, *Compt. Rend.*, *149*, p. 1038; 1909.
23. Saha, *Proc. Roy. Soc., London (A)* *99*, p. 135; 1921.
24. Ives & Coblentz, *B. S. Bull.*, *6*, p. 321; 1910.
25. Poynting, *Phil. Trans. Roy. Soc.* *202A*, 525; 1903. *Jahrbuch der Radioaktivität*, *2*, p. 42; 1905.

26. Lowell, *Phil. Mag.*, (6) *14*, p. 161; 1907.
27. Pickering, *Pop. Astron.*, *30*, p. 410, 1922.
28. Langley & Very, *Nat. Acad. Science*, *3*, (1884) and *4* (1887).
29. Very, *Astrophys. Jour.*, *8*, pp. 199 and 284, 1898; *24*, p. 351, 1906.
30. Coblentz, *Pub. 97*, (p. 135, 1908) of the Carnegie Institution of Washington.