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THE PHOTOELECTRIC PHOTOMETER OF THE LICK OBSERVATORY AND SOME RESULTS OBTAINED WITH IT

INTRODUCTION

After the work of Elster and Geitel¹ and others had shown that the photo-electric cell could be used as an accurate light-measuring instrument, astronomers were quick to adopt such cells for use in stellar photometry. The pioneers were Guthnick and Prager² at the Berlin-Babelsberg Observatory and Rosenberg³ at Tübingen. The work was taken up first in this country by Stebbins and Kunz⁴ at the University of Illinois. More recently, A. F. and F. A. Lindemann⁵ have published a description of their photometer at Sidmouth, England. At a number of other observatories plans are being made for the installing of this type of instrument.

Weather conditions at Mt. Hamilton are such as to encourage the undertaking of photo-electric photometry here. In summer we generally have many consecutive weeks when no clouds appear and the transparency of the sky remains nearly constant. At that time, also, the humidity is very low, remaining below 10 per cent for days at a time. Under these conditions electric instruments are easy to operate, for one need not contend with those leakage effects which can become troublesome in damp weather.

Encouraged by the success attained elsewhere, I undertook to install a photo-electric photometer at this observatory. From its inception the project received the enthusiastic support of Director Campbell, who took a keen interest in every phase of the work and ungrudgingly devoted to its completion the resources of the observatory. The funds used were in part those given by Mrs. Phoebe A. Hearst for another purpose, but applied with her permission to the building of this instrument. Mrs. Hearst's grant was supplemented by

money from the observatory maintenance fund. Dr. Dershem of the Physics Department of the University kindly agreed to accept direction of the preliminary work which was done at Berkeley. Having assisted Professor Stebbins for some time, Dr. Dershem was well informed as to the problems in this field, and he generously put at my disposal the results of his experience. I am glad of this opportunity to acknowledge my indebtedness to him for his unfailing kindness and for the careful attention which he gave to the work done under his direction.

The first sketches for the photometer were made by the writer. These plans were modified and greatly improved by Mr. M. A. Silva, Chief Mechanician of the observatory, who made the working drawings and constructed the instrument, except the electrometer section. Special credit is due Mr. Silva for the exercise of great care and skill in this work; he spared no pains to make the photometer efficient in every way, keeping specially in mind considerations of the observer's convenience. The satisfactory performance of the instrument has amply justified the pains taken in its construction. Thanks for valuable advice and assistance are due also to other members of the Lick Observatory staff, to other members of the Physics Department (particularly Professor E. P. Lewis and Mr. Chas. T. Dozier), to Mr. Wm. H. Taylor then of the U. S. Bureau of Standards, and to Dr. Harlow Shapley.

In what follows, many processes are described and facts mentioned which are in no sense new; they are given here for the sake of completeness and with the hope that they may be useful to others who plan to undertake work of this nature.

SOME REQUIREMENTS OF THE DESIGN

Limitations as to Weight, Rigidity, and Rotation.

Some of the primary limitations for the photometer were dictated by the character of the 12-inch (30.5 cm.) telescope; this telescope has an old-style mounting and

¹ *Phys. Zeitsch.* **11**, 212, 1910; **12**, 609, 1911; **13**, 739, 1912.
Wied. Ann. **48**, 625, 1893.

² *Veröffent. Sternwarte Berlin-Babelsberg*, **1**, part 1, 1914;
2, part 3, 1918.

³ *V. J. S. der A. G.*, **48**, 210, 1913.

⁴ *Ap. Jour.* **39**, 484, 1914.
Pop. Astron. **22**, 631, 1914.

⁵ *M. N. of R. A. S.*, **79**, 343, 1919.

a small driving clock, and in general is not adapted to carrying a heavy auxiliary instrument. For this reason it was necessary to keep down the weight of the photometer. At the same time, rigidity is required lest on account of flexure the incident light fall upon slightly different parts of the cell, according to the position of the object observed; since the hydride surface varies in sensitiveness from point to point, it is obvious that such a variation in the position of the beam will produce errors, even though the danger be lessened by having the beam out of focus when it strikes the cell. Another requirement is that there be means for rotating the photometer about the axis of the telescope. The Lick Observatory 12-inch refractor is not equipped with a rotatable tail-piece, and so the means of rotating must be provided in the photometer.

Electrometer. Depth of Focus, Magnification and Rigidity. Because of the war it was not possible to follow the original plan of purchasing a string electrometer, preferably of the Lutz⁶ design. It was necessary, therefore, to undertake the construction of such an instrument. With the approval of Professor E. P. Lewis, the Physics Department of the University kindly agreed to make it in their Department shop, and Dr. Dershem consented to supervise the work, which was carried out by the Chief Mechanician, Mr. W. R. Stamper. The construction of the instrument was facilitated through the kindness of Professor Stebbins, who let us have the design for an electrometer made for him by the Gaertner Company. Using this design as a guide, Mr. Stamper drew new plans into which he incorporated his own ideas and several changes suggested by Dr. Dershem and the writer. It was especially desired to make the microscope more rigid, in order to eliminate those minute motions which sometimes cause zero-shifts. (See next paragraph.) Also it was desired to increase the magnification of the thread but at the same time to have an increased depth of focus; other observers have been annoyed by the fact that the thread, as it crosses the field of view, sometimes sways back and forth in the line of sight, thus getting out of focus and rendering the measures difficult. Depth of focus can be obtained by using a low-power objective; increased magnification, by an unusually large tube-length. But it is undesirable to make the microscope very long because rigidity would be sacrificed and the chances increased of striking the microscope accidentally while observing. Director Campbell suggested that the difficulty be circumvented by attaining the longer tube-length with a prism system. Accordingly a 2-prism microscope was designed which has an actual length of 132 mm. and an optical path equivalent of 380 mm. in air; the magnification of the thread is 350 diameters. With the above design there is suffi-

cient depth of focus so that the instrument has not given any trouble in that respect. The optical performance of the microscope is good, despite the fact that the objective is designed for a much shorter tube-length.

Precautions Against Zero-shift. One of the corrections which must be applied to measures with an electrometer of this kind is for shift of the zero point. Suppose that, when grounded, the thread is at scale division x . Then the drift of the thread is watched through A divisions, and is observed to have a drift of A divisions in B seconds. If the thread is now grounded again and does not come back to x but to $x + \Delta x$, the rate $\frac{A \text{ divisions}}{B \text{ seconds}}$ must be corrected by the amount $\frac{\Delta x \text{ divisions}}{B \text{ seconds}}$. This zero-shift can be traced to several causes. One is friction in the bearings of the gimbals supporting the electrometer; such friction prevents the electrometer from always coming promptly to the vertical position. Another cause is lack of rigidity of the microscope; a very slight "creeping" could produce a large apparent motion of the zero-point, and when the observer accidentally brushes against the microscope the effect is at once evident if the microscope has any "play." A third cause is imperfection in the temperature compensation. On this account the tension of the thread changes, and this is accompanied by a change in the zero-point. The zero reading depends upon the tension of the thread for this reason: the string is not perfectly straight even when at zero-point, because it is grounded to the center of the knife battery and therefore never at exactly zero potential.

In designing the present instrument special effort was made to eliminate as far as possible the effects mentioned above. Friction in the gimbals was combatted by providing these with ball-bearings. Rigidity of the electrometer microscope is increased by making the tube short and fastening it with numerous strong screws. The problem in computing the temperature compensation was to find what proportions must be adopted for the amber, brass and other materials of the suspension so that its expansion would approximately equal that of the brass housing. Since different samples of amber vary widely in their characteristics, it was necessary to know the coefficient of expansion of the particular piece employed. Mr. C. G. Peters of the U. S. Bureau of Standards very kindly took the necessary measures by an accurate interferometer method. He found that the increase in length in μ per centimeter from 0°C to any temperature t is

$$\Delta L = .4910 t + .00159 t^2$$

The mean coefficient of expansion is

$$\text{C.E. } 0^\circ \text{ to } 25^\circ = 45.2 \times 10^{-6}$$

$$\text{C.E. } 0^\circ \text{ to } 100^\circ = 57.2 \times 10^{-6}$$

⁶ *Phys. Zeitschr.* 13, 954, 1912.

By a comparison of several tables, values were adopted for the probable coefficients of expansion for the various other materials in the suspension under the conditions to be anticipated in practical use of the instrument. The following dimensions were determined:

From top to bottom,

Amber	13.5 mm.
Brass	22
Silver	10
Platinum	75
Silver	10
Brass	20
Amber	10
Nickel-steel	6
Brass	64
} or { 50	
} or { 20	

The pairs of values give the range of proportions in the temperature compensation; 6 and 64 when the clamp is at the bottom, 50 and 20 when it is at the top. The exact position for the clamp was found later by experiment.

Sectored Disks. It has been frequently pointed out that the accuracy of photo-electric measures is decreased if the two light sources to be compared differ too much in brightness. When one is observing stars it is advisable to reduce the brighter one artificially to within one-half magnitude of the fainter; an even closer equality is to be desired. For this purpose Guthnick and Prager have employed objective diaphragms; the University of Illinois observers, neutral-tinted shade-glasses near the focus. Each of these methods is subject to disadvantages. With the first, it is necessary to have a cumbersome apparatus at the objective for the changing of the diaphragms, and it is not convenient to have a large number of diaphragms. Shade glasses at the focus can be readily changed, but one cannot often obtain exactly the desired amount of absorption. Moreover, no glass can be found which is really neutral.

It was with a view to avoiding such difficulties that plans were made to employ a rotating sectored-disk in the present instrument. There is the great advantage that sectors can be cut so as to reduce the brighter of two objects to almost *exact* equality with the fainter, and thus a variation of either object can be readily detected. The plan was adopted with hesitation because of the fear that the vibration of the disk and driving motor would affect the electrometer thread. Accordingly, a preliminary test was made, using a motor with an eccentric weight on the shaft to produce excessive vibration. It was found that, except at the instant of starting, there was no visible effect on the readings.

Grounding Key. The most frequent operation in the course of observing is the opening or closing of the grounding key. It is therefore important that there be a simple and convenient mechanism for performing this

operation. A special advantage is secured if the observer can use the same motion whether opening the key or closing it. Moreover, the mechanism must be positive and make a good contact, but it must work without jarring.

DESCRIPTION OF THE PHOTOMETER AND ITS ACCESSORIES

General Plan. The general plan of the photometer is best perceived from Figure 1, where the instrument is shown on the telescope ready for use.⁷ The most conspicuous features are the supporting frame-work, the motor-box *a*, the cell-box *b*, the gimbals *c*, the electrometer *d* and the steadying weights *e*. Comparison with the yard-stick (0.914 meters) on the pier shows the dimensions of the various parts.

Except in the electrometer (which is of brass), aluminum was employed to a large extent, in order to make the weight of the instrument as small as possible; in the picture it is easy to distinguish the aluminum parts because they appear bright in contrast with the other portions. The weight of the photometer as a whole is 99½ pounds (45.1 kilograms).

Top Section. At the top of the supporting frame-work is a circular brass casting called the top plate, which fits over the base plate of the telescope. The top plate is attached to the telescope by 4 studs passing through the lugs *f*. Four steel tubes extend down from the top plate and end in an aluminum casting *g* which is similar in shape to the brass one above. Between the centers of the two plates passes a thin-walled brass tube *h*. This section is really an extension of the telescope rather than a part of the photometer.

Mechanism for Rotation. Under the casting *g* fits another, *i*, which is much like it. These two plates, together with a small brass plate (see Figure 3, *j*) and four clamping screws *k*, constitute the essential parts of the mechanism by which the photometer is rotated. The relations of the parts are shown in Figure 2, which diagrammatically represents a cross-section of the mechanism. From the brass plate *j* there project upward 4 studs, which pass through the plate *g*. To rotate the photometer, one slackens the clamping screws, grasps the lower rods *l* and turns the instrument upon the bearing surfaces *m, m*. This construction gives great rigidity because of the wide bearing surface. The knobs *k* have large knurled heads and fine-pitch threads.

Diaphragms. The focal plane of the refractor is about 42 cm. below the base plate. In the focal plane is placed a diaphragm to limit the field and to screen away the light of the sky or of objects near the star under observation. Likewise in the photometry of

⁷ Except that in Figure 1 the conduit between cell-box and electrometer is not covered with the rubber sheath which is necessary in practice.

surfaces, diaphragms are obviously necessary. For convenience, three diaphragms are provided; their apertures are respectively $1/16$, $1/8$ and $1/4$ inch (1.6, 3.2, and 6.4 mm.) in diameter. The 6.4 mm. diaphragm remains always in place in the optical axis; the other two are cut in thin strips of brass which can be moved in or out by operating the small knobs n , Figure 1.

Setting Eyepiece. For setting purposes, means must be provided for viewing the diaphragm, together with the object whose light may be focussed there. In Figure 1, o is the diagonal eyepiece used for setting. It is supported by another tube p within which it is moved back and forth by a rack and pinion. The eyepiece is frequently used for the purpose of shutting external light away from the cell-box. When the prism is in the tube q (Figure 3), all light coming through the telescope is totally reflected out through o .

Motor, Sectored-Disks, and Safety Switch. Immediately above the diaphragm is the position for the sectored disks. The relative positions of disk, motor and diaphragm can be seen best in Figure 3. This picture shows how the motor is pulled out and supported when the disk is to be changed. The clamping nut r , which holds the disk, can be readily loosened with the fingers. s is the handle which is grasped in pulling out the motor; it serves also in opening or securely closing the motor-box, by operating the locking-pin t . It is of interest to note the shape of the edges of the motor-box. This light-tight form of construction is used wherever necessary throughout the instrument.

In order to lessen vibration, the speed of the motor was regulated to about 1000 R.P.M. by means of resistance coils. A number of other precautions were taken to diminish the vibration: the motor was fastened down upon pads of felt; care was taken to see that the bearings were properly fitted, and special oil-cups were provided; the disks were carefully balanced, equal sectors being cut from exactly opposite sides.

u (Figure 1) is the switch for the motor, and v is a safety switch. Suppose the observer turns off the current at u , thus stopping the disk in order to let through the uninterrupted light of a star. He then grasps the knob w (Figure 3) and pushes it upward until the leather disk x (Figure 4) is in contact with the nut r . By turning w the sectored disk is turned until the open part comes opposite the diaphragm. Then a catch clicks into a small depression in the disk. Figure 4 (1), is a diagrammatic cross-section showing the relative positions of the various parts. Figure 4 (2), is a diagrammatic view from above; in dotted lines is shown the position of the catch when it is turned up horizontally out of the way of the disk. Damage might be done if the motor were started in rotation while the catch was still holding the disk; hence the safety switch v . It is seen from Figure 4 that the catch is directly connected

with v . When the catch is turned down to engage in the disk, v is "Off." When the catch is turned up away from the disk, v is "On." Thus the motor cannot be started unless the catch is out. I have found, however, that when using sectors of large aperture (viz., $1/4$, $1/2$ or 1 mag.) it is seldom necessary to use the catch. Having finished a group of readings on the brighter star, I stop the motor by turning the switch u and rack in the setting eyepiece. By the time the latter operation is finished, the disk has come to rest. A glance into the eyepiece shows whether the occulting portion of the disk is in front of the diaphragm. If so, the knob w is turned until the star again flashes into view. With a moonlit sky, it is not necessary to keep the telescope on the previously observed star while setting the disk; the sky background is plainly visible in the eyepiece unless the disk happens to be in the way.

Focussing Mechanism. It would be very convenient if the photometer were attached to a tail piece of the telescope which could be moved up and down in the optical axis, thus focussing the photometer as a whole. Since the Lick 12-inch refractor is not thus equipped, other means of focussing must be adopted. For setting purposes it is essential that one be able to bring both star and diaphragm to focus in the eyepiece. Also, one sometimes (when working with a small diaphragm) wishes to put it out of the visual focus by a definite amount, so as to make sure that all the violet light is admitted. At the same time it is desirable that the relative positions of diaphragm, eyepiece and disk be kept always the same. A plan was considered for making the whole photometer (including cell-box and electrometer) move together with the motor-box. But that plan was discarded in favor of the simpler and easier one of moving motor-box alone. The mechanism for focussing is the familiar one frequently employed in astronomical instruments. The tube which projects upward from the motor-box is provided with an external thread; this thread engages in the internal thread of a collar to which is attached the focussing wheel, Figure 3, y . The collar is suspended from the casting i (Fig. 1) just above in such a way that it can rotate freely. Turning the focussing wheel causes the upper tube of the motor-box to travel up into the collar or down out of it, according to the direction of rotation.

The Cell-Box and Its Contents. The cell-box is made mostly of aluminum. The front and back sides consist of sliding doors which are instantly removable and afford easy access to the box. In Figure 3 the box is shown with both doors removed; the ends have been taken off, too, for this picture; z , z are tubes cast into the frame-work. Through each tube passes one of the supporting rods l (Fig. 1). The latter have long threads so that the box can be moved vertically if desired. Since the cell-box and motor-box are movable separ-

ately the tube connecting them must be made to fit that condition. This is accomplished by using telescoping tubes at *A*. There is an advantage in making the cell-box readily detachable, because it not infrequently happens that one wishes to work with cell-box and electrometer alone. It is necessary merely to give several turns to the lowest section of the tube *A*, thus unscrewing tube from cell-box, and then to take off the four nuts *B*.

In Figure 3 is shown the quartz photo-electric cell *C*. It is necessary that the cell be supported in such a way that its position can be changed readily in any or all of the three coördinates; hence the system of rods and clamps, whose relations are obvious from the picture. A rigid bar connects the two uprights so that there is no danger of possibly moving the one upright more than the other and thus throwing a strain upon the cell. But since the uprights must be movable independently so as to increase or decrease the distance between them⁸ the connecting bar is made of two parts which telescope.

To the cathode of the cell is attached a fine platinum wire which passes down through the bottom of the cell-box and through a flexible conduit until it joins the thread of the electrometer. Means must be provided for touching this connection so as to discharge the electrometer thread or to charge it to a known potential. *E* is the standard supporting the contact point, which appears in the picture as a small round dot. Between the brass standard *E* and the contact point there is an insulating disk of amber. *F* is the arm which moves up to make contact. Both of the contact points are tipped with platinum. Figure 5 shows the mechanism by which the grounding key is operated. *G* is a string pulled by the observer. Each time the string pulls down the arm from which it is suspended, the ratchet wheel *H* advances by one notch ($=1/8$ of a revolution). *H* is rigidly connected to the same axis as the cam wheel *I*; when *H* advances $1/8$ revolution, *I* also advances $1/8$ revolution. Thus the finger *J* successively falls into one of the depressions or rises upon one of the blades of the cam wheel. *J* is connected to the rod *K* and its motion causes *K* to rotate slightly. To the middle of *K* is connected an arm (see Figure 3, *F*). As *K* rotates back and forth, the arm *F* successively comes down to touch the contact point and moves back about 4 cm. from contact. For Figure 5 the photo-electric cell has been displaced to the right from its usual position in order not to obstruct the view of the grounding mechanism.

Two wires (one to the grounding key and the other to the anode of the cell) enter the cell-box through the tube *M* (Figure 3). This same aperture admits dry air; the dry-air tube *N* joins an extension of *M* not visible

⁸ For instance, such an adjustment would be necessary in order to exchange the cell shown here for one of different size.

in the picture. *O* is a thin piece of optical glass which seals the box nearly air-tight. This glass is mounted in such a way that it can be readily removed if necessary.

Gimbals and Flexible Conduit. Figure 3 shows the gimbal rings *c* which are necessary in order that the electrometer may hang always vertical. The gimbals are provided throughout with ball-bearings as a precaution against zero-shift.

Q is a flexible coil spring which conducts the platinum lead between cell-box and electrometer. In practice this conduit is kept covered with a rubber sheath to keep out dust and moisture. But while these pictures were being taken the sheath was removed in order to show clearly the construction of the conduit. Inside the spring, at intervals of about four cms., there are amber disks which support and insulate the platinum wire. Each amber piece is mounted in a metal cell which has an external thread of the same pitch as the spring; by means of a special driver these cells were screwed along the spring to the proper places.

Electrometer. Since the electrometer is of standard type and the main features are well known, it is not necessary here to give more than a brief description of the instrument. It consists essentially of a fine platinum wire (called generally the "thread") which is stretched vertically and parallel to two equidistant knife edges. One of these knives is charged positively, the other negatively, and the suspension is connected to ground. If the ground connection is broken the thread is free to pick up a charge and it will drift toward one knife or the other according to the sign of the charge acquired. There are means for changing the tension of the suspension by minute amounts, for adjusting the knife-edges to parallelism, for moving each knife in or out by small distances, and for adjusting the microscope.

In Figures 6 and 7 are exhibited the various parts mentioned above. For Figure 6 the outside case of the electrometer has been removed, and the slide drawn up. In Figure 7 half of the case is pulled back and the side of the microscope is removed to disclose the optical system. *R* is the bracket which supports the microscope objective; *S* is the handle of the screw for focussing the objective by sliding the bracket *R*. In Figure 6 the nose of the objective can be seen behind the knife-edges. *T, T* are total-reflection prisms; they are mounted on brackets which can be slid backward or forward on smooth, dove-tail ways. The scale of the microscope is in the common focal plane of objective and eyepiece. *U* is an electric lamp for illuminating the thread and the scale; *V* (Fig. 6) is the ground-glass window which admits the illumination; *W* is the capstan-headed screw which is turned in order to change the tension on the suspension. *X, X* are the micrometer heads which are turned to move the knives

in and out; Y , Y are adjusting screws for setting the knives vertical and parallel. Z (Fig. 7) is a clamp for the microscope; the latter can be moved slightly in the horizontal direction (cf. p. 109) when this clamp (and some other screws) are loosened. α (Fig. 6) is a tube containing metallic sodium, for keeping the inside of the electrometer dry; β (Fig. 7) is a tube for admitting dry air; but in practice this tube is kept closed and sodium alone is used.

The whole electrometer is covered with a jacket made of half-inch felt, the purpose of which is to protect the instrument from temperature changes; δ (Fig. 1) and η (Fig. 7) are corresponding caps in the felt jacket and in the metal case. Both caps can be turned back without disturbing the rest of the jacket and case, thus affording easy access to the micrometer head, X (Fig. 6). Similarly, the felt cap θ (Fig. 1) and the door λ (Fig. 7) can be opened to provide access to the capstan screw W . μ is a handle which is grasped for unscrewing the weight-rod from the bottom of the electrometer. ξ is the clamp of the temperature compensation; changing the position of this clamp alters the proportions of brass and nickel-steel in the suspension (cf. p. 109). The Wollaston wire at present in the suspension is .0015 mm. in diameter. Unexpected difficulties were encountered while putting in this suspension and experiment showed that the trouble was due to faulty methods of etching off the silver. The procedure which was finally adopted is given below for the benefit of other persons who may encounter similar difficulties.

The wire is cut to the proper length and the ends are soldered into two small brass pieces. By means of these end pieces, the wire is held straight in the clamp. Now beeswax is spread carefully over clamp, brass end-pieces, and a little of the wire at each end. All liquids are gently and slowly siphoned into and out of the vessel containing the wire. Distilled water is used in all solutions. First mix a solution consisting of nitric acid about 12 parts, water 100 parts, sodium nitrite 1 part; allow the wire to remain in this solution until it is seen that the silver has mostly been dissolved, then wash with a strong solution of potassium dichromate; wash next with a 50 per cent solution of ammonia, and lastly with distilled water.

The paragraph above embodies not only my own experiments but also the conclusions which the staff and the mechanics of the Physics Department have arrived at more recently in the course of putting the suspension into their new electrometer. In preparing the suspension for the Lick Observatory electrometer, no use was made of potassium dichromate or of sodium nitrite; but there are advantages in the more lengthy process recommended here.

A description of the electrometer is not complete without special acknowledgement to Mr. W. R.

Stamper for the excellence of his work on this instrument. It has proved to be highly satisfactory in every respect.

Sensitivity Switch. Mention has been made above of the fact that the sensitivity of the electrometer thread is measured by charging it to a known potential and noting the resulting deflection. In Figure 7, Φ is the sensitivity switch. The lowest of the three terminals is connected to the grounding key in the cell-box. Of the upper terminals, one is connected to ground and the other to the positive pole of the sensitivity cell.

Batteries. As has been mentioned above, the potentials for the photo-electric cell and the electrometer are furnished by dry-batteries. The kind used are the small three-cell units used in flashlights. These batteries are placed end to end and the successive terminals soldered together. Two different methods have been employed for preserving the batteries. One method is to place them in a shallow box, solder the terminals and then pour in melted paraffine sufficient to cover all but the terminals. The other method is to shellac the batteries, place them in a glass-lined box, and separate each from its neighbor by interposing strips of glass. These two methods appear to be about equally efficient. With the second one there is the advantage that it is not necessary to solder the connections, a tightly twisted wire being sufficient. Moreover, in the second method it is easy to remove a battery which has "gone bad" and to replace it with a new one.

Dry-Air System. Compressed air from a storage tank escapes slowly through a valve, bubbles through a U-tube containing sulphuric acid and from there is conveyed by rubber tubing to the cell-box.

Photo-Electric Cell. The fundamental necessity in work of this kind is to have a good photo-electric cell; it should be as sensitive as possible, give photo-currents strictly proportional to the light-intensity (at least within the range used) and be free from large or inconstant dark-currents. Professor Jakob Kunz has described⁹ his methods of constructing cells which in general fulfill these requirements, though there is wide divergence in the performance of different cells even if made at the same time under apparently identical conditions. If the material of the cell-wall be fused quartz, dark-currents are greatly diminished. Also, quartz cells are more sensitive than those made of glass. Professor Kunz kindly supplied both a quartz and a glass cell for use in this photometer. Each is argon-filled and has a sensitive surface of potassium-hydride.

Stop-Watch. All measures with the electrometer consist in noting the time required for the thread to traverse a given number of scale divisions. For this purpose a stop-watch is employed. Other observers

⁹ *Phys. Rev.* 7, 62, 1916.

have found it a problem to obtain a watch which will stand up under constant use. I have experienced no difficulty in that respect. The watch used is a "17 jewel Standard," made by the Standard Watch Co., New York; it has given excellent service for more than a year.

TESTS AND ADJUSTMENTS

Characteristic Curves of the Photo-Electric Cells. Before a photo-electric cell can be used, its characteristic curve must be determined. The illumination is kept constant while the potential across the cell is varied; the rate of charging changes at first slowly, then more rapidly until the "danger point" is reached. Beyond this point the voltage cannot be increased for fear of

TABLE I
COMPARISON OF CHARACTERISTIC CURVES
(points read from smooth curves)

Volts on Cell	Rate of Charging $\left(\frac{\text{volts}}{\text{sec}}\right)$			
	G I	G II	Q	Q/G II
0	.00	.00	.00	
5	.01	.00	.005	
10	.01	.005	.010	2.0
15	.02	.005	.010	2.0
20	.02	.005	.010	2.0
25	.02	.005	.010	2.0
30	.02	.005	.015	3.0
35	.03	.010	.020	2.0
40	.04	.010	.020	2.0
45	.04	.010	.025	2.5
50	.04	.010	.025	2.5
55	.04	.010	.030	3.0
60	.05	.015	.035	2.3
65	.05	.015	.040	2.7
70	.05	.020	.045	2.2
75	.06	.020	.050	2.5
80	.07	.020	.060	3.0
85	.08	.025	.070	2.8
90	.09	.030	.075	2.5
95	.10	.040	.080	2.1
100	.11	.045	.095	2.1
105	.13	.050	.105	2.1
110	.14	.065	.120	1.8
115	.16	.080	.140	1.8
120	.18	.095	.165	1.7
125	.20	.115	.195	1.7
130	.22	.140	.240	1.7
135	.24	.160	.290	1.8
140	.26	.190	.340	1.8
145	.29	.230	.400	1.7
150	.31	.265	.455	1.7
155	.35	.315	.515	1.6
160	.38	.390	.590	1.5
165	.43	.470	.670	1.4
170	.50	.580	.785	1.4
175	.58	.700	1.000	1.4
180	.67	.825	1.280	1.6
185	.79	.970	1.770	1.8
190	1.00	1.250	2.080	1.7
195	1.24	1.860	2.330	1.3
200	1.82	2.990		

Mean, 2.2

"flashing" the cell. A safe rule is to stop when the addition of 4 volts doubles the rate of charging. In the work described below, the two cells belonging to the observatory are designated as G II and Q—the former being the glass, the latter, the quartz cell. Besides these there was at hand a glass cell belonging to the Physics Department, which is designated as G I.

First, characteristic curves were derived for each of the three cells; the results are given in Table I and Figure 8. In each case the illumination was about equivalent to that of an object of -4.1 magnitude (i.e. about 110 times a first-magnitude star) as seen through the 12-inch telescope. It is seen from Figure 8

Fig. 8. Characteristic curves of 3 potassium-argon cells.

- G I. Glass cell I. (belonging to the Physics Dept. of the U. of C.).
 — G II. Glass cell II. (belonging to the Lick Observatory).
 — Q Quartz cell (belonging to the Lick Observatory).

that, except for the highest voltages, the curves for G II and Q are similar in shape, the ordinate of Q being almost constantly two times that of G II. But G I has a curve markedly differing in shape from the other two. All three cells were made by Professor Kunz and are of practically identical pattern; but G I is about four years older than the others.

Comparison of the characteristic curves for G II and Q exhibits the superiority of the quartz cell, which for any given voltage is about twice as sensitive as G II. Moreover the glass cell has reached the danger point at about 195 volts, while an increased voltage (with consequent increase in sensitiveness) can safely be applied to Q. A further important advantage of the quartz cell is that the dark-current is vanishingly small, while for the glass cell there is a large dark-current. I therefore decided to discontinue the tests of the glass cell.

A further study of the quartz cell was next made, to determine the characteristic curves under different degrees of illumination. Although I found no published account of a similar investigation, I expected that

changing the amount of incident light (say, reducing it one-half) would merely result in multiplying each ordinate by the same factor. The two curves would thus have similar shape although in the second case a slightly higher voltage could be applied before the danger point was reached. These expectations (except, of course, the latter) were not fulfilled, as can be seen by an examination of Figures 9 and 10. In the second part of Table II is given a comparison of the several curves. It is

Fig. 9. Characteristic curves of quartz cell under various illuminations.

- I. Light equivalent to a star of *minus* 4.1 magnitude, as viewed through the 12-inch refractor.
- III. Light equivalent to a star of *minus* 1.7 magnitude.
- V. Light equivalent to a star of *plus* 3.0 magnitude.

evident that the curves cannot be fitted together by applying any simple factors.

Figures 9 and 10 are significant in their relation to the question of what voltage should be applied when the cell is used for stellar photometry. Obviously, the voltage can be much greater for the fainter stars. The following rule has been adopted: for observing stars of third magnitude and fainter, put 300 to 310 volts across the cell; for stars of 1.0 magnitude and fainter, 240 to 260 volts; for stars brighter than 1.0 magnitude, 200 volts or less.

In studying this subject further, it will be of interest to see whether similar results are found for the glass cell, and to use an even wider range of intensities for the quartz cell. With the latter it seems likely that characteristic curves with illuminations equivalent to fifth or sixth magnitude stars would indicate the advisability of using potentials higher than 310 volts in observing these fainter stars.

Illumination-Current Proportionality. It is a very important matter to determine what are the qualities of a cell in regard to illumination-current proportionality; its value and convenience as a photometric instrument are greatly increased if it shows strict linear propor-

tionality. Different experimenters¹⁰ have found various results. Elster and Geitel made measures with their cells over a wide range of intensities and concluded that the relation is strictly linear. Guthnick and Prager¹¹ found that two Elster and Geitel cells (one of sodium, the other of rubidium) showed linear proportionality

Fig. 10. Characteristic curves of the quartz cell under various illuminations. (Drawn with large vertical scale in order to show accurately the lower part of each curve.)

- I. Light equivalent to a star of *minus* 4.1 magnitude, as viewed through the 12-inch refractor.
- III. Light equivalent to a star of *minus* 1.7 magnitude.
- V. Light equivalent to a star of *plus* 3.0 magnitude.

through a range of $2\frac{1}{2}$ magnitudes. Kunz¹² used a number of methods to test the cells made by him. He concluded that if the incident illumination is weak the cells show linear proportionality, and that they are therefore sufficiently accurate for stellar photometry. He found, however, that for large illuminations (greater

¹⁰ Griffith, *Phil. Mag.* (6) **14**, 297, 1907.

Elster and Geitel, *Phys. Zeitschr.* **14**, 741, 1913.

Ives, *Ap. Jour.* **39**, 428, 1914; **43**, 9, 1916.

¹¹ *Veröffent. Berlin-Babelsberg*, **1**, part 1, p. 18.

¹² *Ap. Jour.* **45**, 69, 1916.

than are obtained from stars) there are deviations from a straight line. Coblenz¹³ after investigating about a dozen photo-electric cells, concludes that "if the deflections method is to be used,—the proportionality test should be made upon every cell—even when the maker's tests indicate that the cell functions in direct proportionality."

In the physics laboratory at Berkeley, a few measures were made of the cell G I, using a galvanometer to measure the current; the illumination was varied by an adjustable sector-disk, also by altering the distance between lamp and cell. G I was found to show strict linear proportionality within a range of intensities from about 1 to 0.04 candle-meters.

The proportionality of the quartz cell was tested at the observatory. The cell-box and the electrometer were set up at the end of a long gallery; upon a table, which could be wheeled back and forth along a track, was set a small lamp which was fed by current from a storage battery and this lamp was enclosed so that reflection from the walls of the gallery would not produce erroneous effects at the cell. In order to guard against errors which would result from a progressive change in the lamp or in the sensitiveness of the cell, I generally varied the distance in no regular way but

¹³ *Sci. Papers Bur. of Stand.* No. 319, 1918.

moved the light back and forth so that a particular part of the curve was observed at different times in the course of one series of measures. After finishing one series, I varied the intensity of the lamp by changing the current and then took another series of measures with the same procedure. The smallest distance used was 58 inches (1.5 meters) and the greatest was 457 inches (11.6 meters).

Table III contains the results of the investigation. The separate values are given in order of increasing light intensity. The first column gives the value of $1/D^2$. For convenience in making the table, the values of $1/D^2$ throughout are multiplied by 10^5 . For instance in the case of the first tabulated value, the distance was 456.8 inches and the logarithm of $1/D^2$ is 4.6806—10.

If the points of Table III (exclusive of those enclosed in brackets) are plotted with $1/D^2$ as abscissae and volts/sec. as ordinates, they are found to define accurately a series of straight lines passing through the origin. The slope of the particular line depends upon the intensity of the light, since varying the absolute brightness of the lamp in a certain ratio has the effect of changing the vertical scale by that same amount. Thus on September 19 the light for the third series was 2.43 times as bright as that for the first series. Since on the three dates all conditions of observing were the

TABLE II
CHARACTERISTIC CURVES OF QUARTZ CELL UNDER VARIOUS ILLUMINATIONS

Volts on cell	Rate of charging ($\frac{\text{volts}}{\text{sec.}}$) (points read from smooth curves)					Ratios				
	I	II	III	IV	V	I/II	I/III	II/III	III/V	IV/V
0					.000					
10	.009		.002		.000		4.5			
20	.013		.003		.000		4.3			
30	.017		.004		.000	4.5	4.2			
40	.023		.004		.000		5.8			
50	.029		.006		.000		4.8			
60	.038		.007		.000		5.4			
70	.047		.009		.001		5.2		9.0	
80	.060		.011		.002		5.5		5.5	
90	.076		.014		.002		5.4		7.0	
100	.097		.018		.002		5.4		9.0	
110	.122		.024		.002		5.1		12.0	
120	.172		.030		.003		5.7		10.0	
130	.252		.037		.003		6.8		12.3	
140	.324		.047		.004		6.9		11.8	
150	.410		.061		.004		6.7		15.2	
160	.580	.122	.078		.005	4.8	7.4	1.6	15.6	
170	.780	.152	.106		.005	5.1	7.4	1.5	21.2	
180	1.270	.191	.139		.006	6.6	9.1	1.4	23.2	
190	2.075	.250	.192		.007	8.3	10.8	1.3	29.4	
200		.400	.280		.008			1.4	35.0	
210			.396		.009				44.0	
220			.510		.010				51.0	
230			.675		.013				51.9	
240			.920	.028	.015				61.3	1.9
250			1.245	.031	.018				69.2	1.7
260				.035	.023					1.5
270				.041	.029					1.4
280				.052	.036					1.4
290										

same and the same potentials were maintained at the anode, it is reasonable to assume that the sensitiveness of the cell was practically the same for all the measures in the table and that one may safely compare any two series of points. Thus it is seen that the brightest light used was for the third series of September 19; and this was about 490 times as intense as the faintest light, which was that for the second series on September 23.

The straight line relation does not hold, however, when the rate of charging becomes relatively very large;

this is seen by examination of the points included in brackets. The deviation is marked and always in the same direction, namely; the increase in the current is too rapid in proportion to the increase in $1/D^2$. Within the limits of illumination where the cell was observed to show linear proportionality, the maximum rate of charging was 1.54 volts per second. This is about what is produced by a star of 0.8 magnitude when the cell is mounted in the photometer on the 12-inch refractor, with 300 volts at the anode. The minimum rate was

TABLE III
MEASURES FOR DETERMINING THE ILLUMINATION-CURRENT
RELATION FOR THE QUARTZ CELL

Relative intensity 1/D ²	Rate of charging volts/sec	Relative intensity 1/D ²	Rate of charging volts/sec	Relative intensity 1/D ²	Rate of charging volts/sec	Relative intensity 1/D ²	Rate of charging volts/sec
1920 September 19		1920 September 19—(Cont.)		1920 September 23—(Cont.)		1920 September 27—(Cont.)	
1st series		5th series		5th series		2nd series	
.48	0.090	.37	0.037	2.28	0.050	.86	0.120
.60	.110	.49	.038	2.36	.060	.90	.130
.82	.160	.56	.047	2.67	.060	1.04	.130
1.21	.241	.65	.045	2.70	.060	1.21	.160
1.99	.405	.78	.071	3.09	.070	1.39	.180
		.92	.092	3.61	.080	1.61	.211
2nd series		1.10	.116	4.96	.110	1.85	.241
3.85	.691	1.29	.130	6.03	.130	2.11	.271
4.21	.735					2.25	.291
{ 8.53	1.682 }	1920 September 23		1920 September 27		2.40	.323
						2.73	.356
						3.31	.435
3rd series		1st series		1st series		3.73	.488
.37	.180	17.09	0.030			4.08	.539
.41	.200	20.55	.035			4.44	.575
.52	.241	23.13	.040	.87	0.140	4.53	.599
.56	.261	25.20	.044	1.06	.155	4.74	.616
.58	.279	30.25	.050	1.22	.161	4.86	.646
.68	.331			1.38	.180	5.08	.675
.78	.380	2nd series		1.59	.239		
.86	.337	19.98	0.019	1.80	.270	3rd series	
.98	.479	20.85	.021	2.02	.300	2.91	0.345
1.14	.519	23.49	.023	2.26	.339	3.43	.398
1.34	.616	26.66	.028	2.64	.396	4.02	.477
1.55	.764	29.47	.034	3.04	.458	4.46	.536
1.89	.958	3rd series		3.43	.514	4.94	.584
{ 2.37	1.208 }	3.85	0.709	3.82	.589	5.35	.640
		4.20	.797	4.19	.644	5.74	.672
		4.60	.867	4.36	.663	6.13	.728
		4.94	.949	4.53	.684	6.72	.794
		5.27	1.048	4.77	.773	7.18	.856
{ 5.55	1.110 }	5.55	1.110	5.05	.823	7.94	.932
		5.76	1.258	5.33	.906	8.15	.967
				5.43	1.005	8.98	1.082
				5.59	1.080	9.71	1.215
				5.72	1.154	10.52	1.386
{ 5.83	1.189 }			5.83	1.189	11.08	1.610
		4th series					
		0.83	.180				
		1.06	.220				
		1.37	.272				
1.67	.329						
1.91	.367						
2.32	.441						
2.75	.536						
3.13	.583						
3.52	.662						
3.85	.734						

0.019 volts/sec., about what is produced by a 6th magnitude star under the same conditions. It is evident, therefore, that when the incident light is of the same order as that found ordinarily in stellar photometry, the photo-currents are proportional to the illumination over a wide range. The deviations from this rule for lights brighter than a star of 0.8 magnitude need give no concern in the case of the present photometer, because in practice one always cuts down the light of such bright objects by means of a sectored disk. The conclusion stated here is in agreement with that of Kunz,¹⁴ and the deviation for large intensities is in the same direction as was observed by him.

Adjustment of the Electrometer. The first step in adjusting the electrometer was to set the knives parallel by means of the screws provided for this purpose. Then the clamping screws for the microscope were loosened and the latter was moved slightly until the thread appeared in the field of view near the zero division, following which the clamping screws were securely tightened again.

Fig. 11. Curves showing the variation of the Electrometer field as the distance between the knives is changed.

The next step was to set the knives at such a distance apart that the field between them was uniform over the space included in the microscope field. For testing the electrostatic field one varies by minute known amounts, the potential on the thread, and notes how many scale divisions of deflection result from applying each potential. A potentiometer circuit used with a storage battery furnished the small potentials required. When the results are plotted with deflections as abscissae and applied potentials as ordinates, the curve should be a straight line if the field is uniform. In Figure 11 are given a few of the curves. In each case the potential between the knives was 80 volts, but the tightness of the thread was varied so as to bring the curves a convenient distance apart. With each curve is given the distance between the knives. It is seen that as the distance increases the field becomes more

uniform. As a consequence of these tests the rule was adopted that $8\frac{1}{2}$ mm. between the knives should be the minimum distance, and the usual distance is 9 to 12 mm.

It was necessary to determine by experiment the best position for the temperature compensation clamp. The method employed for changing the temperature was to pump hot or cold air into the outer case of the electrometer. The electrometer was wrapped heavily in flannel to minimize losses by radiation; a thermometer was put inside the case in such a way that it could be withdrawn readily for reading. As the temperature changed the sensitivity of the thread was read at frequent intervals. The sensitivity changes were rapid at first, but became less as the electrometer approached a uniform temperature. At last a steady condition was reached, when the entering air no longer changed the temperature, and the sensitivity remained constant. Next the temperature was changed again (by making the incident air colder or warmer) until another steady condition was reached. The first experiment gave as equilibrium positions:

Temperature 18 deg. C, Sens. 65.0 div./volt

22	50.5
24	44.0
23	44.8
27	25.5

The clamp of the compensation was about 11.9 mm. from the top of its range.

From the above figures it is seen that with increasing temperature the suspension expands by too small an amount. Accordingly the proportion of brass was increased by moving the clamp down 13 mm. and the experiments were repeated. This time the temperature-sensitivity curve observed between 19 degrees and 30 degrees C. was found to be nearly horizontal, and so the compensation clamp was not moved further. In practice the temperature compensation has functioned satisfactorily.

Other Adjustments. When the photometer was first put on the telescope, difficulty was experienced with dark-currents and leakage effects. These factors did not cause any difficulty during the dry season, but when the humidity is high they are sometimes present to a considerable amount.¹⁵ Evidently, then, they are due to the accumulation of moisture upon some of the surfaces. Plans have been considered for making the cell-box more nearly air-tight, and for improving the method of drying the air.

For a while trouble was experienced with contact potentials at the grounding key and the sensitivity

¹⁵ It should be added that always after light has fallen on the cell there will be a residual dark-current which gradually fades away. One test showed that, with 245 volts across the cell, the dark-current 30 seconds after exposure to a 4.0 magnitude star was about 2 per cent. of the star effect, or equivalent to that produced by an 8.2 magnitude star.

¹⁴ *Ap. Jour.* 45, 75, 1917.

switch. The trouble persisted in spite of repeated scrubbing of the contact points with "non-beverage grain alcohol." Then chemically pure alcohol was employed with the result of removing the contact P. D.

PROCEDURE IN OBSERVING

Preliminary. Precautions must be taken to insure that the photometer has settled down to a steady condition before one begins observing. For one thing, if the sensitivity of the electrometer thread is changing rapidly during the measures, an amount of uncertainty is introduced and there will be large zero-shifts. The change of sensitivity is rapid for some time after the electrometer lamp is lighted. This is due to the fact that the lamp heats the electrometer slightly, causing an expansion of the parts, and a steady condition is not reached for some time. For this reason the observer lights the electrometer lamp an hour or more before beginning the observations, and he opens the dome for a similar reason.

About one-half hour before observations are begun the potentials are applied to the electrometer knives and to the photo-electric cell. The potentials fluctuate slightly at first and do not steady down until 15 minutes or more after the connections are made.

It is necessary to illuminate the cell for several minutes before beginning to take measures; otherwise it is found that the first measures are inaccurate. One begins at twilight to allow enough skylight to fall on the cell so that an effect is produced which is about equivalent to that of a third magnitude star. The amount of skylight is controlled by the position of the diagonal eyepiece; as the skylight fades, a larger and larger aperture is opened. The above is the procedure if one is to begin observing as soon as the sky is free from daylight. If one begins later in the night, a star is used for the purpose. The preliminary illumination need not last more than half an hour and generally not longer than 15 or 20 minutes. The observer takes test measures, beginning soon after the illumination is applied. At first the rate obtained is too small, sometimes by as much as 50 per cent. Gradually the rate increases until it reaches a steady value; then one can begin making measures.

Measures of Sensitivity and Zero-Shift. The observation of the sensitivity consists in bringing the electrometer thread to ground potential, then (by use of the sensitivity switch) charging it to +1.5 volts, and noting the change in its position on the scale. I generally worked with a potential difference of 100 to 130 volts between the knives, and adjusted the tightness of the thread so that the sensitivity was about 54 div./volt. But when there was wind sufficient to shake the telescope, it was necessary to tighten the thread to 30 div./volt or less.

The sensitivity is measured with greater or less frequency depending on how rapidly it is changing. As a rule the measure is made about every half hour. These sensitivity measures serve also to determine the zero-shift. (cf. p. 112.)

Measures of Dark-Current, Background, and Leakage. At intervals during the night's work measures are made of dark-current, background, and leakage.

Dark-current is so-called because it flows even when no light falls on the cell. This drift is superposed on every deflection measured and a correction must be applied for it. The measurement of dark-current consists in shutting all light away from the cell and then measuring the rate of drift.

Background is the deflection caused by skylight which is unavoidably measured with the star light. This current becomes largest on moonlit nights, particularly if there is much moisture in the atmosphere. The observation of background consists in putting the star image slightly off the diaphragm aperture and measuring the drift of the thread due to sky-light alone.

The measurement of leakage consists in shutting all light away from the cell, giving the thread a potential from the sensitivity cell and observing the rate at which it loses its charge. In dry weather the leakage is nearly always negligible.

Battery Tests. Sometimes the thread is seen to jump suddenly through two or three divisions. This means the presence of a bad cell in the battery supplying the knife potentials. Interruptions due to this cause are guarded against by testing the individual batteries each evening before beginning work. Naturally, a close watch is kept on the battery supplying the potential at the anode of the photo-electric cell; it is obvious (from Figs. 8 to 10) that serious errors are introduced if this potential fluctuates. Also, the voltage of the sensitivity cell is measured frequently; the slightest evidence of deterioration is a signal for replacing this cell.

METHOD OF REDUCING OBSERVATIONS

Conversion into Δ Magnitude. *Explanation of Table IV.* Conversion of the observational data is effected by use of the familiar formula

$$\Delta M = \frac{\log A - \log B}{0.4}$$

where A and B are the light intensities of the two stars, and ΔM is their difference of magnitude. The first step in the reduction is to change the observed rates,¹⁶ div./sec, into volts/sec, by multiplying by the values of the sensitivity, volts/div.

A sample block of the reductions is given in Table IV. The stars observed were α and β Cephei, on 1921,

¹⁶ Each "observed rate" is the mean of three or four settings; one setting consists in a measure of the rate of charging of the thread as indicated by the speed of the drift across the scale.

Fig. 1. The Photo-electric Photometer on the telescope ready for use.

Fig. 3. Disk, motor and diaphragm.

Fig. 2. Diagram of mechanism for rotation.

Fig. 4. Diagram of safety switch and catch for sectored disk.

Fig. 5. Mechanism which operates the grounding key.

Fig. 6. The Electrometer.

Fig. 7. Side view of electrometer, showing interior of microscope.

TABLE IV
SAMPLE BLOCK OF REDUCTIONS TO Δ MAGNITUDE

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Star	Rate Div. Sec.	Sens. volts div.	log. Sec.	log. Div. sec.	log Sens.	log Rate volts sec.	Nat. rate	Σ Corr.	Net rate	log R	Sub. 7.7	Δ M	θ	z	Ext.	Δ M +Ext.
α	5 17.4	[.0271]	1.2406	9.4584	8.4330	7.8914	.00779	+.00002	.00781	7.893	0.193	0.482	-1 ^h 53 ^m	30 ^s 2	mag. .048	mag. 0.530
β	17.2	.0271	.2355	.4634		.8964	788		790	.898	.198	.495	2 0	36.4	.081	.576
α	17.4	.0271	.2406	.4584		.8914	779		781	.893	.193	.482	1 43	29.4	.045	.527
β	17.4	.0271	.2406	.4584		.8914	779		781	.893	.193	.482	1 49	35.8	.078	.560
α	17.4	.0271	.2406	.4584		.8914	779		781	.893	.193	.482	1 33	28.6	.042	.524
β	17.1	.0271	.2330	.4660	.4330	.8989	792		794	.900	.200	.500	1 39	35.3	.076	.576
α	17.3	.0272	.2380	.4609	.4346	.8955	786		788	.896	.196	.490	1 24	28.0	.040	.530
β	16.7	.0272	.2227	.4762		.9108	814		816	.912	.212	.530	1 30	34.9	.074	.604
α	17.1	.0272	.2330	.4660		.9005	795		797	.901	.201	.502	1 13	27.3	.038	.540
β	16.9	.0272	.2279	.4711		.9056	805		807	.907	.207	.518	1 19	34.5	.072	.590
α	16.8	[.0272]	.2253	.4737		.9082	810		812	.910	.210	.525	1 03	26.7	.036	.561

August 17. The first column gives the star; the second column gives the number of scale divisions and the time in which this interval was traversed by the thread. Column 3 gives the sensitivity; the bracketed values are observed, the others are interpolated. Columns 4 to 8 contain the computations of the rates in volts per second. To these rates must be applied corrections for dark-current, background, leakage and zero-shift. The corrections are computed on a separate sheet (see Table V) and only their sum is given in the column " Σ Corr." Columns 8 and 9 are added to obtain 10. Frequently Σ Correction = zero, in which case columns 8 to 11 can be omitted. Column 11 gives the logarithm of the net rate; from each of these logarithms is subtracted an amount arbitrarily selected to reduce the size of the number. The amount subtracted is determined from a consideration of the particular computation at hand; a different constant may be used for another series of observations taken on the same night. Through the subtraction of the constant, we obtain the convenient numbers of column 12; multiplying these by 2.5 gives the Δ magnitudes in column 13. These Δ

magnitudes are the numerical differences between the stars observed and a fictitious star the logarithm of whose net rate (in the present case) is 7.7. Δ Magnitudes increase numerically with brightness, a convention which is convenient in many cases. The true difference in magnitude between two stars is the same as the numerical difference of their Δ magnitudes, with the sign changed. In column 14 appears the hour-angle. For each star there has previously been drawn a curve with hour angles as abscissae and zenith distances as ordinates. From this curve are read the quantities z in column 15; and from tables for atmospheric extinction (see p. 112) are read the quantities in the 16th column. The addition of columns 16 and 13 gives 17, the final Δ magnitudes.

Corrections for Dark-Current, Background, Zero-Shift, and Leakage. In previous sections explanation has been given of the corrections for dark-current, background, and zero-shift. The leakage correction remains to be discussed. On account of leakage, the measured star-drift is smaller than it would otherwise be; hence the leakage correction always has the + sign. The

TABLE V
SAMPLE TABLE OF Σ CORRECTIONS
Corrections

Star	Time	Dark current volts sec	Background volts sec	Leakage volts sec	Zero-shift volts sec	Σ Corr. volts sec
δ	8 ^h 00 ^m	-.00020	-.00008	+.00001	-.00001	-.00028
γ	05	20	3	1	1	23
δ	10	20	8	1	1	28
γ	15	20	3	1	1	23
δ	20	20	8	1	1	28
γ	25	20	3	1	1	23
δ	30	20	8	1	1	28
γ	40	20	3	1	0	22
δ	45	20	8	1	0	27
γ	50	20	3	1	0	22
δ	55	20	8	1	0	27
γ	9 ^h 00 ^m	20	3	1	0	22

amount of the correction depends upon the number of divisions over which the star-drift has been observed. The rule is to apply the observed leakage multiplied by one-half the proportional part of the scale over which the star-drift was watched. On the night of August 17, when the measures of Table IV were taken, the average leakage was .00055 volts/sec. The number of scale divisions over which the star-drift was measured was 5; the sensitivity was measured over 56 divisions, i.e. the leakage was measured from the 56th division beyond the zero-point. Therefore the leakage correction was

$$\frac{1}{2} \times \frac{5}{56} \times .00055 \frac{\text{volts}}{\text{sec}} = .00002 \frac{\text{volts}}{\text{sec}}$$

On the same night dark-current and background were zero, and zero-shift for these particular measures was negligible. Therefore all of Σ Corr. is due to leakage.

The above is a typical example of Σ Corr. There is no case in my observing sheets thus far where all four corrections must be applied. Therefore a hypothetical case is given below to illustrate all of them.

Suppose two stars, γ and δ , are observed in alternation from Pacific Standard Time 8^h00^m to 9^h00^m, at the rate of one star in five minutes. γ is about one magnitude brighter than δ , and is therefore reduced by a sector. The following measures were made for determining the corrections:

$$\begin{aligned} \text{At } 7^{\text{h}}55^{\text{m}}, \text{ Sens.} &= 10.0^{\text{div}} - 90.0^{\text{div}}, \text{ per } 1.5 \text{ volts} \\ d.c. &= +1^{\text{div}} \text{ in } 90^{\text{sec}} \\ b.g. \text{ (without sector)} &= +1^{\text{div}} \text{ in } 70^{\text{sec}} \\ \text{leakage} &= -1^{\text{div}} \text{ in } 50^{\text{sec}} \end{aligned}$$

$$\begin{aligned} \text{At } 8^{\text{h}}30^{\text{m}}, \text{ Sens.} &= 11.0^{\text{div}} - 90.5^{\text{div}} \\ d.c. &= +1^{\text{div}} \text{ in } 92^{\text{sec}} \\ b.g. &= +1^{\text{div}} \text{ in } 65^{\text{sec}} \\ \text{leakage} &= -2^{\text{div}} \text{ in } 102^{\text{sec}} \end{aligned}$$

$$\begin{aligned} \text{At } 9^{\text{h}}00^{\text{m}}, \text{ Sens.} &= 11.2^{\text{div}} - 89.7^{\text{div}} \\ d.c. &= +1^{\text{div}} \text{ in } 100^{\text{sec}} \\ b.g. &= +2^{\text{div}} \text{ in } 131^{\text{sec}} \\ \text{leakage} &= -2^{\text{div}} \text{ in } 120^{\text{sec}} \end{aligned}$$

These measures are combined and reduced as follows:

$$d.c. \left\{ \begin{array}{lll} .0111 \frac{\text{div}}{\text{sec}}, \text{ Sens. } .0188 \frac{\text{volts}}{\text{div}}; d.c. = .00021 \frac{\text{volts}}{\text{sec}} \\ .0109 & .0189 & .00021 \\ .0100 & .0191 & .00019 \\ \text{Mean, } .00020 \end{array} \right.$$

Background is about the same each time; therefore it is assumed to be constant.

$$b.g. \left\{ \begin{array}{lll} .0143 \frac{\text{div}}{\text{sec}}, \text{ Sens. } .0188 \frac{\text{volts}}{\text{div}}; b.g. = .00027 \frac{\text{volts}}{\text{sec}} \\ .0154 & .0189 & .00029 \\ .0153 & .0191 & .00029 \\ \text{Mean, } .00028 \end{array} \right.$$

The difference .00028 — .00020 gives the true value of the background, .00008 $\frac{\text{volts}}{\text{sec}}$. The full amount is applied to each of the measures of star δ ; 0.4 of the amount is applied to the measures of γ , because this star was diminished with a one-magnitude sector.

$$\text{leak-} \left\{ \begin{array}{lll} .0200 \frac{\text{div}}{\text{sec}}, \text{ Sens. } .0188 \frac{\text{volts}}{\text{div}}; \text{leakage} = .00038 \frac{\text{volts}}{\text{sec}} \\ .0178 & .0189 & .00033 \\ .0196 & .0191 & .00037 \\ \text{Mean, } .00036 \end{array} \right.$$

The sensitivity was measured over about 89 divisions, on the average; thus the leakage was measured from the 89th division beyond the zero-point. The star-drift was measured over 5 divisions; half the proportional part of the scale is

$$\frac{1}{2} \times \frac{5}{89} = \frac{1}{28}$$

The leakage correction is

$$\begin{aligned} \frac{1}{28} \times .00036 &= .00001 \frac{\text{volts}}{\text{sec}} \\ \text{zero-} \left\{ \begin{array}{l} \text{for measures } 8^{\text{h}}00^{\text{m}} \text{ to } 8^{\text{h}}30^{\text{m}}, \text{ shift} = +1^{\text{div}} \text{ in } 30^{\text{min}} = .00056 \frac{\text{div}}{\text{sec}} \\ \text{Mean. Sens.} = .0188 \frac{\text{volts}}{\text{div}}; \text{shift} = .00001 \frac{\text{volts}}{\text{sec}} \\ \text{for measures } 8^{\text{h}}30^{\text{m}} \text{ to } 9^{\text{h}}00^{\text{m}}, \text{ shift} = +0.2^{\text{div}} \text{ in } 30^{\text{min}} = .00011 \frac{\text{div}}{\text{sec}} \\ \text{Mean. Sens.} = .0190 \frac{\text{volts}}{\text{div}}; \text{shift} = .00000 \frac{\text{volts}}{\text{sec}} \end{array} \right. \end{aligned}$$

The remainder of the computation is given in Table V.

Atmospheric Extinction. No separate investigation of the atmospheric extinction has been made here, and all data on the subject derived to date have been obtained in the course of measures taken for other purposes.

In the reductions for the present paper extinction factors have been used which are based on the work of Guthnick and Prager. First the Mt. Hamilton visual extinction was derived by an interpolation between the Potsdam and Sntis tables.¹⁷ From the visual extinction table are made photo-electric extinction tables for stars of each spectral class, by multiplying by the following factors:

for Class B0	2.0
A0	1.80
F0	1.7
G0	1.54
K0	1.4
Ma	1.3

¹⁷ Mller, *Photometrie der Gestirne*, Anhang II a.

The above factors are obtained by interpolating in Guthnick and Prager's table,¹⁸ where factors are given for a sodium cell and for a rubidium cell; the values for our potassium cell are assumed to lie between the two. The interpolating factor 0.312 was derived from Shinomya's work.¹⁹ His curves show that, on the average, sodium cells made by Kunz have their maximum sensitiveness at λ 4350; rubidium, at λ 4750; potassium, at λ 4475.

In order to minimize errors introduced by the above process of deriving extinction tables, care was taken not to observe stars at large zenith distances. For β Cephei the largest zenith distance for any observation was 44 degrees. In most of the other work a limit of 30 degrees has been set.

It is obvious, from the foregoing discussion, that in selecting two stars to be compared, one should attempt to have them as nearly as possible at the same altitude and of the same spectral class. In practice it is seldom possible to satisfy both of these conditions, and one must make the best compromise possible.

According to Guthnick and Prager, the extinction factors vary with the transparency of the atmosphere. These observers find also that the transparency of the atmosphere for the violet end of the spectrum is least shortly after the end of twilight and increases during the night, but not regularly. Moreover, they find that the extinction varies according to the azimuth. The first of these considerations need give no concern in the case of β Cephei, because all the observations of this star were made during the dry season, when the transparency at Mt. Hamilton does not vary appreciably for weeks at a time. On a scale of 3, the transparency on the nights of observation was 2+ or 3 all of the time. As for a variation through the night: I have at times suspected that such a factor entered. But the evidence is not conclusive, and the variations observed here can probably be explained as due to an irregular increase in the sensitiveness of the cell during the course of a night's work. Therefore no attempt has been made to incorporate such a factor in the extinction corrections. Regarding a variation with azimuth, the measures to date give no clear evidence for the existence of such a factor at this observatory.

Method of Combining Measures. One complete observation, comparing two stars a and b is composed of 20 separate settings in the order $aaaa\ bbbb\ aaaa\ bbbb\ aaaa$, or 15 settings in the order $aaa\ bbb\ aaa\ bbb\ aaa$. In the reductions, as in Table IV, each of the rates in the second column of the table consists of the mean of four (or three) settings. If six successive values in the table are numbered $a_1\beta_1a_2\beta_2$ and so on, then the first whole observation consists of $a_1\beta_1a_2\beta_2a_3$ and the second

observation consists of $a_3\beta_3a_4\beta_4a_5$. The separate Δ magnitudes are combined thus:

Mean of $a_1a_2a_3$	= 0.527 mag.
Mean of $\beta_1\beta_2$	.568
Diff. in Δ mag.	.041
Sector	.443
True diff. ($\beta - a$)	.402

When the light fluctuations are very rapid, as is the case with β Cephei, it is desirable to have the separate points as close together as possible in order to show the true shape of the light-curve. For this reason I adopted the plan of employing intermediate points, which are obtained by combining the last measures in one observation with the first measures in the succeeding observation. Thus in the case cited above, the intermediate point is obtained by combining $a_2\beta_2a_3\beta_3a_4$. In Table VIII these intermediate points are given in the same way as the others. The result of the above process is to diminish the weights of all the points, because they are not strictly independent.

OBSERVATIONS OF THE PLEIADES

Observations have been made on the *Pleiades* for the double purpose of testing the accuracy and range of the photometer, and of checking the conclusion derived in the laboratory that the illumination-current relation for the photo-electric cell is linear proportionality for stellar intensities. The stars observed were those designated by Bessel as $\eta, b, c, d, e, f, g, h, l, 28, 32, 34$ and 38; they range in brightness from 2.87 mag. to 6.74 mag., and they belong to some one of the spectral classes B5, B8 or B9. These stars are thus so nearly of the same class that the color-indices can (for the present purpose) be assumed to be equal,²⁰ and it does not greatly matter whose magnitude determinations are employed for purposes of comparison with the photo-electric magnitudes. I used the photographic magnitudes as derived by Schwarzschild.²¹ If Schwarzschild's magnitudes and the photo-electric Δ magnitudes are both on a scale consistent with Pogson's rule, then when the former are plotted against the latter, the resulting curve should be a straight line with a slope of 45 degrees. The deviations from this line will furnish an indication of the accuracy of the observations and will serve to show for how great a range of magnitudes the cell exhibits illumination-current proportionality.

It was found that for each of the 13 series of observations made on 6 different nights a 45 degree line represents the points very well. This work is considered to be only preliminary and the data are too meager to

²⁰ In *Lick Obs. Bull.* 10, 111, 1921, are given Hertzsprung's values for the color-indices of the *Pleiades*. For the stars which I observed most frequently (η to h inclusive) the indices range from -0.18 to -0.22 mag. For the fainter stars the indices are smaller.

²¹ *Göttingen Aktinometrie*, B, p. 14.

¹⁸ *Veröffent. Berlin-Babelsberg*, 2, part 3, page 36.

¹⁹ *Ap. Jour.* 49, 303, 1919.

justify drawing positive conclusions regarding the accuracy of the measures; but it appears thus far that two stars as faint as 6.7 magnitude can be compared with accuracy only slightly less than that for the brighter stars, in spite of the fact that the rates for the faint stars are very slow and the various corrections (see p. 112) proportionately greater. It should be stated, however, that the fainter stars of the sequence were not measured at all on those nights when the dark-current, background or leakage were appreciable. For the present it is not considered feasible to attempt measures of stars fainter than those in this sequence. But subsequent work on the characteristic curves (cf. p. 106) may show that anode potentials greater than 310 volts can be safely employed for the fainter stars, in which case the range of the photometer may be considerably increased.

CALIBRATION OF THE SECTORED DISKS

To date seven sectorized disks have been made. They diminish the light by about $\frac{1}{4}$, $\frac{1}{2}$, 1, $1\frac{1}{2}$, 2, $2\frac{1}{2}$ and 3 magnitudes respectively. The calibrating of the sectors could be done in daytime with an artificial light source, but it was found convenient to do the work at night. Measures were made in the same way as when two stars are compared,—4 settings with the sectorized disk stopped, 4 with disk revolving, 4 with disk stopped, and so on. These measures are reduced in the same way as star measures. Each observation consisted of 15 or 20 separate settings. The Δ magnitude differences "sector minus clear aperture" give the value of the sector. The results of the calibration are given in Table VI. This

TABLE VI
VALUES OF THE SECTORED DISKS

Disk No.	Δ Mag.	Prob. error	Number of determinations
1	0.232	$\pm .002$	24
2	0.443	$\pm .004$	14
3	0.90	$\pm .01$	20
5	1.93	$\pm .02$	11
7	2.76		4

table gives accurate values for the first, second, third and fifth sector, and the approximate value for the seventh. The fourth and sixth sectors have not been calibrated as yet. The probable errors in the third column of the table illustrate the point that large differences of magnitude cannot be observed so accurately as small differences. In the case of the quarter-magnitude sector, the probable error of a single observation consisting of 20 settings was $\pm .008$ mag.

It is expected that in the course of the photometric work here special sectors will be made in every case where the observer wishes to attain high accuracy by bringing the stars under observation to very nearly the same brightness.

It might be of theoretical interest to measure accurately the apertures of the sectors and to see how close is the agreement between the percentages thus determined and the observed values. It is known that the transmission of sectors as measured photographically is not strictly proportional to the sector openings. Coblentz²² and Fowle²³ have found that when a sectorized disk is used with a thermopile, the energy transmitted is greater than the theoretical value. But in a letter Dr. Coblentz states that he observed this phenomenon only when using a radiometer and that no such effect was found by him in photo-electric photometry. Moreover, Kunz²⁴ and Ives²⁵ have found that Talbot's law holds very exactly for photo-electric cells.

COLOR-INDEX CURVE AND COLOR-EQUATION

In February and March, 1921, and again in September, observations were made for determining the color-index curve for the photometric system. For this purpose groups of stars were chosen so that the different members were at about the same altitude and of various spectral classes. Each group contained at least one star of class A0. For instance, one group consisted of δ , σ , η , ϵ , ρ and 16 *Hydrae*. Of these, two are of class A0, two of class K0, and one each of classes B3 and F8. The visual magnitudes range from 3.30 to 4.54. In choosing the groups an effort was made to have A0 stars with visual magnitudes as near as possible to those of the other stars. The best arrangement is to have the A0 stars at the ends of the series.

The observations were made in the usual manner, from 4 to 6 settings on each star. Sectors were used in a few cases, where certain stars were more than a magnitude brighter than the others in the group. But no attempt was made consistently to equalize the stars so as to conform with the half-magnitude rule. Thus the errors may be large, but on the average they will balance. Generally the range of brightness in a given group was less than two magnitudes, and in only one case was it as great as 3.1 mag.

The reductions to Δ magnitude are made in the usual way. Then for each group of stars the photo-electric Δ magnitudes are plotted against the Harvard visual magnitudes. If, now, one connects all the points for the stars of a certain spectral class, the curves should approximate straight lines with a slope of 45 degrees. It was found that in general this condition was fulfilled very well. The deviations from the 45 degree line will be due not only to errors in the observations but also to the inaccuracy of the assumption that all stars of one

²² *Bull. of Bur. of Stand.* 4, 455, 1907; also, No. 319, p. 535.

²³ *Smithsonian Miscell. Coll.* 68, No. 8, p. 14, 1917.

²⁴ *Ap. Jour.* 45, 69, 1917.

²⁵ *Ap. Jour.* 43, 24, 1916.

spectral class have the same color-index.²⁶ Added to these errors are those inherent in the Harvard magnitudes and spectral classifications. For about half of the stars observed, the Henry Draper classification was not available, and it was necessary to use the values given in the *Revised Harvard Photometry*. The abscissae of such points may in some cases be in error by several tenths of a spectral class.

Having drawn a 45-degree line to represent as nearly as possible the A0 stars in a group, I next measured the vertical distance from this line to each of the other stars, thus obtaining their color-indices. In all, 15 groups were observed, yielding the color-indices of 60 stars. In Figure 12 are shown the individual points.

Fig. 12. Color-index curve for the Photometric system.

It is not possible to draw a satisfactory curve through them, but the curved line in the figure is perhaps a fair compromise. Table VII is made by reading from the

TABLE VII
COLOR-INDICES (PROVISIONAL VALUES)

Spectral Class	Color Index mag.
B0	-0.14
B5	-0.08
A0	0.00
A5	+0.10
F0	+0.22
F5	+0.32
G0	+0.45
G5	+0.60
K0	+0.76
K5	+0.92
Ma	+1.10
Mb	+1.28

smooth curve the mean color-index for each spectral class. The provisional value for the color-equation²⁷ of

²⁶ This latter source of error is not so serious as might be supposed, because the late-type stars observed were all of visual magnitude 5.0 or brighter. I am told by specialists in the subject that all such stars are "giants;" thus the present problem is not complicated by the matter of the variation of the color-indices of the late-type stars as a function of their absolute magnitudes.

²⁷ That is, the difference in photo-electric magnitude between A0 and K0 stars of the same visual magnitude.

the photometer when used with the 12-inch refractor and with the cell Q, is +0.76 mag.

The color-index curve (Fig. 12) depends principally upon the color-sensitiveness curve of the cell; if there are changes in the cell which alter its color-sensitiveness curve we cannot legitimately combine color-index measures taken on widely separate dates; indeed the terms color-index and color-equations will be meaningless. Ives²⁸ has published an account of observing a progressive change in the λ -sensitiveness curve of a potassium-helium cell. But I have found no published account of similar behaviour in the case of argon-filled cells. Shinomya,²⁹ who studied intensively the λ -sensitiveness curves for the cells made by Professor Kunz, makes no mention of such a phenomenon. In Figure 12 the points were observed at two dates separated by about seven months; the points designated by circles are the early observations. There is no good evidence here of any marked change in the color-index curve between the two epochs.

A STUDY OF β Cephei

The study of a variable star was undertaken as a further test of the photometer. For this purpose β Cephei was chosen, primarily because it has been observed³⁰ with the photo-electric photometer at Berlin-Babelsberg. Thus the results obtained serve the purpose of comparing the performance of the present photometer with that of another instrument of the same class.

The Observations. The star was observed on 16 nights from 1921, June 30, to September 22, inclusive. α Cephei (visual magnitude 2.60, Class A5) was used as comparison star, its brightness reduced with the 0.443 magnitude sector. Guthnick and Prager employed this same comparison-star, and they have shown that its light is constant, at least for long intervals.

TABLE VIII
OBSERVATIONS OF β CEPHEI

G.M.T.	Helioc. phase	$\beta - \alpha$ (mag.)	O - C (mag.)
1921 June 30 ⁴ 803	0 ⁴ 116	0.373	- .006
.813	.126	.329	- .035
July 7.840	.106	.379	- .010
.849	.115	.374	- .006
.858	.124	.362	- .007
July 10.807	.025	.331	- .026
.816	.034	.311	- .050
.824	.041	.341	- .024
.832	.049	.348	- .022
.841	.059	.395	+ .017
.850	.068	.389	+ .005

²⁸ *Ap. Jour.* **46**, 241, 1917.

²⁹ *Ap. Jour.* **49**, 303, 1919.

³⁰ *Veröffent. Berlin-Babelsberg*, **1**, part 1, page 23, 1914.
Veröffent. Berlin-Babelsberg, **2**, part 3, page 78, 1918.

TABLE VIII—(Continued)

G.M.T	Helio. phase	$\beta - \alpha$ (mag.)	O - C (mag.)	G.M.T	Helio. phase	$\beta - \alpha$ (mag.)	O - C (mag.)
1921 July 11 .847	0.112	0.358	-.026	1921 Aug. 18 .721	0.082	0.373	-.018
.854	.120	.361	-.012	.728	.089	.368	-.024
.862	.128	.357	-.005	.733	.095	.367	-.025
.869	.135	.337	-.019	.742	.103	.372	-.019
.876	.142	.339	-.014	.750	.112	.384	-.001
.883	.149	.336	-.021	.757	.118	.377	+.001
				.764	.125	.368	+.004
July 13 .828	.188	.328	-.015	.772	.134	.360	+.003
.838	.008	.323	-.020	.779	.141	.352	-.001
.849	.019	.351	0	.786	.148	.371	+.014
.858	.028	.392	+.035				
.867	.037	.379	+.017	Aug. 29 .674	.178	.338	-.014
				.683	.188	.323	-.020
July 14 .796	.013	.365	+.019	.690	.004	.335	-.006
.803	.020	.323	-.028	.697	.011	.337	-.007
.810	.027	.326	-.031	.704	.018	.365	+.015
.817	.035	.362	+.001	.713	.027	.376	+.019
.824	.041	.387	+.022	.722	.036	.375	+.013
.831	.049	.387	+.018	.729	.043	.371	+.006
.840	.057	.374	-.002	.736	.050	.398	+.028
.847	.065	.387	+.006	.743	.057	.401	+.025
.854	.072	.391	+.005	.750	.064	.403	+.022
.862	.079	.378	-.011	.758	.072	.383	-.003
				.840	.154	.384	+.023
July 15 .837	.102	.397	+.006	.849	.163	.371	+.007
.844	.110	.394	+.008	.857	.171	.362	+.003
.853	.118	.369	-.007	.865	.178	.331	-.021
.861	.126	.357	-.007	.872	.185	.319	-.024
				.881	.005	.347	+.006
July 18 .779	.188	.346	+.003	.890	.014	.369	+.023
.788	.006	.328	-.013	.897	.021	.372	+.020
.825	.043	.325	-.041	.906	.030	.373	+.014
.833	.042	.348	-.023				
.840	.059	.345	-.033	Aug. 30 .664	.026	.350	-.007
.849	.067	.369	-.014	.674	.035	.355	-.006
				.682	.044	.366	.000
Aug. 15 .729	.138	.361	+.007	.687	.048	.379	+.010
.737	.146	.346	-.009	.693	.055	.355	-.018
.744	.154	.362	+.002	.699	.060	.354	-.025
.751	.160	.363	-.001	.706	.067	.358	-.025
.760	.168	.383	+.021	.711	.073	.370	+.025
.769	.177	.357	+.004	.717	.078	.382	-.007
.778	.187	.365	+.022	.721	.082	.382	+.009
.789	.008	.373	+.030	.728	.089	.365	-.027
.909	.128	.385	+.023	.735	.097	.363	-.019
.921	.139	.356	+.003	.742	.103	.379	-.012
.929	.148	.320	-.036	.749	.110	.363	-.023
.938	.156	.343	-.019	.756	.117	.354	-.022
.946	.164	.368	+.004	.857	.028	.360	+.003
.954	.172	.377	+.019	.865	.036	.350	-.012
.962	.180	.368	+.020	.874	.045	.374	+.008
.972	.190	.381	+.040	.881	.052	.384	+.012
				.888	.059	.351	-.027
Aug. 17 .706	.020	.358	+.007	.893	.064	.374	-.007
.712	.026	.354	-.003	.899	.070	.393	+.008
.721	.035	.351	-.010	.906	.077	.379	-.009
.728	.042	.332	-.033	.911	.082	.372	-.019
.735	.049	.359	-.010	.918	.089	.398	+.006
.742	.056	.383	+.008				
.749	.062	.402	+.021	Aug. 31 .678	.088	.390	-.002
.798	.070	.402	+.017	.685	.094	.385	-.007
.804	.076	.384	-.005	.691	.100	.410	+.018
.811	.083	.390	-.001	.697	.106	.408	+.019
.819	.091	.400	+.008	.704	.113	.407	+.024
.826	.099	.398	+.006	.710	.119	.393	+.018
.882	.005	.346	+.005	.717	.126	.378	+.014
.889	.012	.350	+.004				

TABLE VIII—(Continued)

G.M.T	Helioc. phase	$\beta - \alpha$ (mag.)	O - C (mag.)
1921 Aug. 31 ^d 724	0 ^d 133	0.342	-.015
.731	.140	.342	-.011
.738	.147	.333	-.022
.744	.154	.351	-.010
.751	.160	.355	-.008
.757	.166	.363	.000
.861	.080	.422	+.032
.868	.087	.407	+.015
.875	.094	.400	+.008
.881	.099	.391	-.001
.888	.107	.379	-.010
.896	.115	.390	+.010
.903	.122	.372	+.002
.910	.128	.368	+.006
.915	.134	.370	+.014
Sept. 21.658	.115	.413	+.033
.664	.121	.403	+.031
.671	.128	.380	+.018
.678	.135	.386	+.030
.683	.140	.371	+.018
.690	.147	.374	+.018
.696	.154	.374	+.013
.794	.060	.408	+.029
.804	.070	.394	+.008
.814	.080	.379	-.011
.822	.089	.392	.000
.831	.097	.407	+.015
.840	.106	.397	+.008
Sept. 22.635	.139	.366	+.013
.640	.145	.368	+.013
.648	.153	.382	+.022
.655	.160	.371	+.008
.661	.166	.359	-.004
.668	.173	.354	-.005
.676	.181	.340	-.009
.683	.188	.363	+.020
.689	.003	.336	-.005
.696	.010	.321	-.022

In Table VIII are given the individual observations. About half these points are based upon 20 settings each; the rest, upon 15 settings each. The phases were at first computed using the elements:³¹ Helioc. Max. = 1913, August 5.350 (J. D. 2419985.350) G.M.T.

$$+E \times 0^d 190479$$

The resulting mean curve showed the maximum at phase about +^d006 or +^d010. This was taken to be a confirmation of Crump's³² correction +^d0000005 to the period. Confirmation has been given also by Henroteau and Henderson.³³ Adopting the elements: Helioc. Max. = 1913 August 5.350 (J.D. 2419985.350) G.M.T.

$$+E \times 0^d 1904795$$

I recomputed the phases, thus shifting the curve to the left by 0^d008 and bringing the maximum to zero phase.

³¹ Veröffent. Berlin-Babelsberg, 1, part 1, page 34.

³² Publ. Detroit Obs. 2, 151, 1916.

³³ Pubs. Dominion Obs. 5, 83, 1921.

The phases in column 2 of Table VIII are those computed by the corrected elements. The 3rd column gives the magnitude difference, β minus α ; the 4th column, the residual of each point from the computed curve (Fig. 14). From these residuals it appears that the probable error of a single observation is $\pm .012$ mag.

An examination of the individual observations at separate dates inclines the writer to think that the behavior of this star is not consistent but varies from epoch to epoch, although on any two consecutive epochs the light curves are about the same. Support

Fig. 13. Individual observations of β Cephei at successive epochs.

for this view is given by an examination of the two sets of observations obtained on August 15 (epochs 15394, 15395, 15396), on August 29 (epochs 15467, 15498, 15468), on August 30 (epochs 15473 and 15474), and on August 31 (epochs 15478 and 15479). These observations are shown in Figure 13. Significant, in this connection, is the fact that Crump³⁴ and Henroteau³⁵ have reported that the *velocity* curve of this star is not constant. The photometric data are too few to justify drawing positive conclusions from them. The point should be tested by an extensive series of observations taken so as to include consecutive epochs on many different nights. It would be interesting to compare such light curves with velocity curves obtained simul-

³⁴ Publ. Detroit Obs. 2, 153-156, 1916.

³⁵ Publ. Dominion Obs. 5, 77, 1921.

taneously. Do such light-variations as those of August 15 (cf. following paragraph) occur synchronously with unusual velocity variations such as were observed by Crump on October 1, 1912?

Normal Places and Mean Curves. The individual points of Table VIII have been combined into 43 normal places whose coördinates are given in Table IX.

TABLE IX
OBSERVATIONS OF β CEPHEI, *Normal Places*
(including all observations)

Number of the normal place	Phase	$\beta - a$ (mag.)	O - C (mag.)
1	0.003	0.349	+ .008
2	.007	.343	+ .001
3	.012	.348	+ .003
4	.017	.361	+ .012
5	.023	.344	- .010
6	.028	.354	- .003
7	.032	.357	- .003
8	.036	.361	.000
9	.041	.360	- .004
10	.044	.359	- .007
11	.049	.368	- .001
12	.052	.371	.000
13	.057	.376	.000
14	.060	.377	- .002
15	.064	.391	+ .010
16	.068	.379	- .005
17	.071	.390	+ .004
18	.076	.389	+ .001
19	.080	.388	- .002
20	.084	.388	- .003
21	.089	.387	- .005
22	.092	.387	- .005
23	.097	.386	- .006
24	.101	.393	+ .002
25	.105	.391	+ .001
26	.110	.380	- .006
27	.114	.382	+ .001
28	.117	.377	.000
29	.120	.381	+ .008
30	.125	.366	.000
31	.128	.363	+ .002
32	.132	.360	+ .002
33	.136	.357	+ .002
34	.140	.353	.000
35	.145	.355	+ .001
36	.148	.350	- .006
37	.154	.367	+ .006
38	.158	.363	.000
39	.163	.366	+ .002
40	.169	.370	+ .010
41	.176	.345	- .009
42	.184	.347	+ .002
43	.188	.341	- .001

Each normal place includes 4 points, except the 29th, which contains 5 points. The normal places are shown in Figure 14; the smooth curve is a computed harmonic curve for which the equation is:

$$y = 0.3665^{\text{mag}} - 0.0202 \cos \theta + 0.0032 \cos 2\theta \\ - 0.0048 \cos 3\theta - 0.0031 \cos 4\theta \\ + 0.0034 \sin \theta - 0.0048 \sin 2\theta \\ - 0.0033 \sin 3\theta + 0.0011 \sin 4\theta$$

Column 4 of Table IX gives the residuals from the computed curve. From these residuals it is found that the probable error of a normal place is $\pm .004$ mag.

Fig. 14. β Cephei, normal places and computed light curve.

A conspicuous feature of the mean curve in Figure 14 is the secondary maximum on the ascending branch at about 0.14 phase. This secondary maximum is accentuated by the observations of August 15 which, though agreeing among themselves, differ markedly

TABLE X
OBSERVATIONS OF β CEPHEI, *Normal Places*
(excluding observations of 1921, August 15)

Number of the normal place	Phase	$\beta - a$ (mag.)	O - C (mag.)
1	0.003	0.341	+ .007
2	.007	.330	- .006
3	.012	.355	+ .013
4	.019	.348	- .002
5	.024	.352	- .001
6	.028	.363	+ .007
7	.034	.350	- .009
8	.036	.364	+ .004
9	.042	.358	- .006
10	.045	.361	- .005
11	.050	.373	+ .003
12	.053	.368	- .005
13	.058	.379	.000
14	.061	.379	- .003
15	.065	.383	- .001
16	.069	.385	- .001
17	.072	.395	+ .008
18	.078	.381	- .007
19	.082	.389	.000
20	.086	.390	+ .001
21	.090	.381	- .008
22	.093	.393	+ .004
23	.098	.392	+ .003
24	.102	.389	.000
25	.106	.391	+ .003
26	.111	.374	- .011
27	.114	.396	+ .014
28	.118	.368	- .008
29	.120	.382	+ .009
30	.125	.366	+ .001
31	.128	.359	- .001
32	.134	.352	- .004
33	.139	.358	+ .003
34	.144	.356	- .002
35	.148	.360	- .002
36	.154	.369	+ .003
37	.158	.370	+ .004
38	.164	.364	+ .002
39	.174	.350	.000
40	.181	.332	- .006
41	.187	.338	+ .005

from the other series of observations. I have recomputed the normal places, excluding the observations of August 15. These new normal places are given in Table X and Figure 15. Each normal place consists of 4 points, except numbers 35 to 41, inclusive, which contain 3 points each. For the harmonic curve in Figure 15 the equation is:

$$y = 0.3653^{\text{mag}} - 0.0225 \cos \theta + 0.0005 \cos 2\theta \\ - 0.0049 \cos 3\theta - 0.0048 \cos 4\theta \\ + 0.0013 \sin \theta - 0.0052 \sin 2\theta \\ - 0.0033 \sin 3\theta + 0.0017 \sin 4\theta$$

If this star really has an inconstant light curve, then probably Figure 15 represents the *average* course of the variation better than does Figure 14.

Fig. 15. β Cephei, normal places and computed light curve (excluding observations of Aug. 15, 1921).

Fig. 16. Mean light curve of β Cephei, by Guthnick and Prager, 1913-1914. Each normal place is the mean of from 5 to 13 observations.

Comparison with Berlin-Babelsberg Light Curves. It is of interest to note that in Guthnick and Prager's³⁶ mean curve for 1913-1914, which is shown in Figure 16, there is an indication of a secondary wave in the ascending branch. For purposes of further comparison with Guthnick and Prager, an examination was made of their observations³⁷ taken January 14 to February 4, 1917. There are a few measures with blue filter and some in which 11 Cephei was used as comparison star; but the number of these points is so small that they cannot be used for the present purpose. There are, however, 45 measures with yellow-filter where the comparison star was α Cephei. These have been combined by the writer into normal places containing 2 or 3 observations each (see Table XI). The points thus formed are plotted in Figure 17. There is plain indication here of a secondary maximum such as appears in the Lick Observatory curve. In Table XII is given a comparison of the light curves as observed here and at Berlin-Babelsberg.

³⁶ Veröffent. Berlin-Babelsberg, 1, part 1, page 34.

³⁷ Veröffent. Berlin-Babelsberg, 2, part 3, page 151, 1918.

TABLE XI
OBSERVATIONS OF β CEPHEI AT BERLIN-BABELSBERG
(JANUARY 14-FEBRUARY 4, 1917), COMBINED
INTO Normal Places

Number of the normal place	Phase	$\beta - \alpha$ (mag.)
1	0.001	0.472
2	.006	.491
2	.012	.479
4	.018	.492
5	.029	.496
6	.037	.500
7	.049	.502
8	.054	.496
9	.070	.520
10	.089	.531
11	.108	.515
12	.127	.493
13	.134	.486
14	.145	.473
15	.154	.474
16	.164	.480
17	.175	.473
18	.183	.457
19	.188	.462

Fig. 17. Guthnick and Prager's observations of β Cephei, Jan. 14-Feb. 4, 1917. Each normal place is the mean of 2 or 3 observations.

TABLE XII
COMPARISON OF MEAN LIGHT-CURVES OF β CEPHEI

Curve	Range mag.	Length of descending branch days	Length of ascending branch days
Lick, 1921 (curve including all points)	0.051	0.09	0.10
Lick, 1921 (curve excluding observations of August 15)	0.056	0.10	0.09
Berlin-Babelsberg, 1913-1914	0.053	0.11	0.08
Berlin-Babelsberg, January and February, 1917	0.074	0.09	0.10

Comparison with Spectroscopic Observations. The velocity variations of β Cephei have been studied by Frost,³⁸ Crump,³⁹ and Henroteau.⁴⁰ Guthnick and Prager compared⁴¹ their 1914 light curve with Frost's spectroscopic observations taken near the same time and concluded that the maximum light came 0.034 before the descending node. Crump gives a figure which compares his velocity curve of 1912 with Guthnick and Prager's 1914 light curve; this comparison shows the maximum velocity of approach as occurring about 0.027 after the light maximum, and the mini-

³⁸ Ap. Jour. 24, 259, 1906.

³⁹ Publ. Detroit Obs. 2, 144, 1916.

⁴⁰ Publ. Dominion Obs. 5, 77, 1921.

⁴¹ Veröffent. Berlin-Babelsberg, 1, part 1, page 37, 1914.

imum velocity of approach as occurring about 0^d031 after the light minimum.

For each of the 6 cycles which were observed in 1920 by Henroteau and Henderson I have computed the times of maximum light, and compared these with the observed times of maximum velocity of approach. Also, I computed the times of minimum light (by adding to the time of maximum the value 0^d092 for the value M—m) and compared these with the observed times of minimum velocity of approach. On the average the maximum velocity of approach occurred 0^d041 later than the computed times of maximum light; the minimum velocity of approach, 0^d042 later than the computed times of minimum light.

Recently a series of plates of β Cephei, completely covering one cycle, was taken here with the 3-prism Mills spectrograph. Since these plates were obtained only a month and a half after the last photometric observations, they ought to furnish a reliable comparison between the spectroscopic orbit and the light curve. The plates were kindly measured by Miss Hobe, Assistant in the Observatory, who found the velocities to be:

Date	Velocity
J.D. 2423000.573	+ 9.9 km.
.586	+12.2
.596	+10.8
.610	+ 3.6
.631	— 6.2
.648	—13.8
.666	—17.2
.684	—13.6
.702	—12.4
.720	— 4.9
.738	+ 3.2
.753	+10.6
.778	+13.0
.795	+ 9.8
.811	+ 1.8
.827	— 1.1

The maximum velocity of approach (as read from a smooth curve) occurred about 0^d030 after the computed time of light maximum; the minimum velocity of approach occurred about 0^d040 after the computed time of

TABLE XIII
COMPARISONS BETWEEN PHOTOMETRIC AND SPECTROSCOPIC DATA FOR β CEPHEI
(on the assumption of a circular orbit)

Berlin-Babelsberg Light-Curve (1914) and Yerkes Spectroscopic Observations (1914).	Berlin-Babelsberg Light-Curve (1914) and Detroit Spectroscopic Observations (1912).	Lick Light-Curve (1921) and Ottawa Spectroscopic Observations (1920)	Lick Light Curve (1921) and Lick Spectroscopic Observations (1921).
Maximum light 0 ^d 034 (65°) before descending node.	Maximum light 0 ^d 027 (51°) before descending node.	Maximum light 0 ^d 041 (78°) before descending node	Maximum light 0 ^d 030 (57°) before descending node.
Minimum light 0 ^d 025 (47°) before ascending node.	Minimum light 0 ^d 031 (59°) before ascending node.	Minimum light 0 ^d 042 (80°) before ascending node.	Minimum light 0 ^d 040 (76°) before ascending node.
		Secondary light maximum 0 ^d 005 (9°) after ascending node.	
		Secondary light minimum 0 ^d 027 (51°) after ascending node.

Fig. 18. Comparison of Photometric and Spectroscopic results, on the assumption of a circular orbit.

light minimum. The above observations serve also as a confirmation of the period, checking exactly the correction of +⁰0000005.

In Table XIII are gathered the four different comparisons between velocity curves and light curves; the data are represented graphically in Figure 18, under the assumption of a circular orbit.

Conclusions. It has been customary to class β Cephei as a variable of δ Cephei type, in spite of its early spectrum (B1), the small eccentricity of its orbit, and other characteristics which have been mentioned in the preceding discussion. To the writer it seems advisable to consider this star as in a class by itself, and to look hopefully among early type stars for other examples.

When the facts set forth in preceding paragraphs are reviewed a few features stand out prominently:

1st, the similarity in shape of light curves observed on successive epochs, the disparity between individual curves observed at separate epochs, and the agreement in shape of *mean* curves derived at intervals of several years;

2nd, the variation in velocity curves, reported by Crump and by Henroteau;

3rd, the four comparisons between light and velocity curves, showing that the light maximum occurs about one-fifth of the period earlier than the greatest velocity of approach.

These points are difficult to explain on the hypothesis of simple orbital motion, or on any other theory which has been proposed. To the writer it seems unlikely that the peculiar behavior of β Cephei can be explained without the introduction of factors as yet unconsidered in theories regarding fluctuations in the light and velocity of stars.

SUMMARY

The photo-electric photometer of the Lick Observatory differs from other photometers of the same class in numerous details, most conspicuous of which is the mechanism for reducing the incident light in a known ratio. Other workers in this field have used objective diaphragms or neutral-tinted shade glasses for that purpose; in the present instrument sectorized disks driven by a small motor intermittently occult the incident beam. Additional respects in which this photometer differs from others are the manner of rotating the instrument, the optical system of the electrometer and the mechanism for operating the grounding key.

Two potassium-argon photo-electric cells were studied to determine their fitness for use in the photometer. The characteristic curves showed that for a given voltage the quartz cell is about twice as sensitive as the glass cell, and the former has other qualities which make it preferable. A series of characteristic curves of the quartz cell, taken with different illumina-

tions, showed that for a 3rd magnitude star a potential of 310 volts can safely be used; for objects brighter than 1.0 magnitude 260 volts or less must be employed. Investigation of the illumination-current relation for the quartz cell proved that this relation is linear within the limits of illumination which are encountered in stellar photometry. For greater intensities there are deviations from a straight line.

In the autumn of 1920 the photometer was mounted on the 12-inch refractor, and since that time it has been employed in observations of stars. A sequence in the *Pleiades* was measured as a check on the laboratory calibration and found to verify the conclusion stated above. Series of stars of different spectral classes were observed in order to derive the color-equation and the color-index curve for this photometric system. The provisional value of the color-equation is +0.76 mag.

Seven sectorized disks have been made to date; they cut down the incident light by about $\frac{1}{4}$, $\frac{1}{2}$, 1, $1\frac{1}{2}$, 2, $2\frac{1}{2}$, and 3 magnitudes, respectively. The exact values for the ratios of the 1st, 2nd, 3rd and 5th were derived by observations on stars.

A mean light curve of the star β Cephei was derived in the summer of 1921. The separate series of observations indicate that the light curve is not constant, although it is apparently about the same for two consecutive epochs. The mean curve differs slightly in form from that of Guthnick and Prager and a small correction to the period is indicated. The corrected period is in agreement with the spectroscopic period derived by Crump, and it is checked by recent spectrographic observations made here. Four comparisons of photometric with spectrographic data show that the light maximum occurs (in the mean) about 0.033 days before the maximum velocity of approach. On the assumption of a circular orbit, the difference in the anomaly is 62 degrees, or 0.17 of the period of variation.

When two stars *a* and *b* are being compared a single observation consists generally of 20 settings in the order *aaaa bbbb aaaa bbbb aaaa*. In order to determine the probable error of such an observation, measures of one star were alternated with measures of the same object when diminished with the $\frac{1}{4}$ -magnitude sectorized disk. The probable error of an observation was found to be $\pm .008$ mag. In the case of β Cephei the individual observations were compared with a harmonic curve of 9 constants; the residuals thus formed give for the probable error $\pm .012$ mag. The accuracy of the photometer is greater than would be indicated by the above figure if, as seems likely, the curve of β Cephei is not really constant.

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