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CALIBRATION OF A WEDGE PHOTOMETER

In the spring of 1900, the Lick Observatory agreed to take part in a determination of standards for faint stellar magnitudes, in accordance with a coöperative plan suggested by Professor Pickering, Director of Harvard College Observatory. Wedge photometers of a special type (see description by Mr. J. A. Parkhurst, *Ap. J.* 13, 249), devised by Professor Pickering and provided for from the Rumford Fund of the American Academy, were distributed from the Harvard College Observatory. Photometer No. 3, containing photographic wedge III, was received at the Lick Observatory in May, 1900.

The part assumed by the Lick Observatory involved the comparison of stars near the limit of the great refractor with stars of about the twelfth magnitude. With the apparatus as originally arranged, it was found that the artificial star could not be made bright enough for comparison with stars brighter than about the fourteenth magnitude in the great telescope. The small incandescent lamp originally inserted at *S* through the side of the tube (see Fig. 1) was therefore removed and a brighter lamp *A* was placed lengthwise at the end of the tube. At the same time, the piece of blue glass supplied, was replaced by a piece *B* of darker blue. The resulting artificial star is well defined and is perhaps a trifle more reddish than the average real star. In addition, the cell carrying the two shade glasses *L* was attached to the tube *T* so that either or both could be interposed in the rays of the real star. After the drawing of Fig. 1, a slight alteration was made by which the lamp *A* can be moved an inch closer to the diaphragm if desired. The brightness is thus increased by about a magnitude and a half. The image in any possible position of the lamp can be made nearly as small and sharp as the image of the real star under the best conditions.

Owing to pressure of work in other directions, the program was not entered upon here until June, 1902.

The observational part was then taken up by Dr. Aitken, assisted by several others, and completed in January, 1904. The photometer has been used to some extent, besides, in the observation of variable stars. The unsatisfactory condition of our knowledge of the constants of the instrument has delayed the final reduction of the measures.

Preliminary star measures of the "absorption" (strictly absorption and reflection) of the wedge, made by Dr. Aitken, early showed departures from the theoretical linear relation between scale reading and absorption in magnitudes. Rather smaller values of the relative absorption per division were found at large scale readings than at small scale readings. It became evident that for accurate determinations an "absorption" curve of the wedge would be required. Other observers found similar difficulties with their wedges. Mathematical and empirical absorption curves were derived. Two, as yet unpublished, have come to my notice. These were for wedges cut from the same plate as the Lick wedge; similar results might therefore be expected for the Lick wedge. In a preliminary investigation of the Virginia wedge, Professor Stone found the mathematical relation

$$\sigma = 0.132 - 0.00080(m - 31.8).$$

This was obtained by varying the aperture of the object-glass in known ratios. The integral curve, passed through the origin, is, using our own notation,

$$m = (0.1574 - 0.00040d) d.$$

The empirical curve "*A* 12," determined by Mr. J. A. Parkhurst for Wedge V at the Yerkes Observatory, is shown in Fig. 2 (*A*). I believe this was obtained by means of a wheel or polarizing photometer, point images being compared. A few preliminary measures of Pleiades stars by Dr. Aitken were used here in the attempt to derive a curve, assuming the values of the absorption per division to

be constant over stretches of five divisions. A curve following the general direction of Parkhurst's resulted. These preliminary measures showed that a very great number of star measures would be required to determine the curve with sufficient accuracy. On the other hand, it seemed that laboratory comparisons, made as nearly as possible under the

same conditions as those of practice, should yield the curve directly, and with greater facility. Accordingly, at the suggestion of Director Campbell, the photometer was taken to Berkeley in June, 1904, and adapted for comparison with the Lummer-Brodhun photometer, kindly placed at our disposal by Professor Slate.

FIG. 1. Wedge Photometer No. 3.—One-third size.

For convenience in making settings of the laboratory photometer, the tube X (see Fig. 1), carrying the wedge tube FF and terminating at X and X, was mounted in the optical axis on a carriage composed of the prism-box and one of the lamp-holders. This carriage was movable as a single rigid system; the lamp at the left end of the bench, together with its blue glass, diffusing surface, and diaphragm, being kept fixed. One of the moving pointers was read at a given setting, and the distance, d_2 , of the screen from the fixed source, s_2 , was obtained by subtracting a readily determined constant. Settings were made with the wedge at 0, 5, 10, ---, 65. The measures were then repeated in the reverse order, from 65 to 0. The following are illustrative settings, made 1904, June 13:

Wedge	0	5	10	15
	cm.	cm.	cm.	cm.
Settings	143.1	145.5	158.3	187.1
	142.4	144.3	160.9	186.9
	143.0	143.8	159.6	184.8
	142.2	144.9	159.3	186.2
		144.2		
	142.68	144.54	159.52	186.25

Diaph. I (2.92 cm.) over s_2 . Diaph. 0.29 cm. over wedge.
Reading of pointer, with meter-stick touching s_2 and screen....
163.66 cm.

A small correction, due to decreasing effective illuminating surface with increasing distance of the screen from the source, was taken into account by measuring distances, d_2 , from diaphragm to screen. The distance from s_2 to the diaphragm was 1.32 cm. d_2 was therefore 64.98 cm. less than the reading of the pointer. The reduction to magnitudes was carried on as follows ($\Delta m = \Delta \frac{\log (d_2^2)}{.4} = 5 \Delta \log d_2$):

Wedge	d_2	$\log d_2$	m
	cm.		
0	77.7	1.8904	0.000
5	79.6	1.9009	0.052
10	94.5	1.9754	0.425
15	121.3	2.0839	0.968

When the length of the bench forbade further settings with a given diaphragm over s_2 , a smaller diaphragm was used and settings were continued, a connected series being obtained by beginning at the last position of the wedge. The two following series resulted:

Wedge	I	II	Diff.	Mean
<i>d</i>	<i>m</i>	<i>m</i>	<i>m</i>	<i>m</i>
0	0.000	0.000	0.000	0.000
5	0.052	0.038	−0.014	0.045
10	0.425	0.402	−0.023	0.414
15	0.968	0.968	0.000	0.968
20	1.458	1.384	−0.074	1.421
25	1.809	1.736	−0.073	1.772
30	2.157	2.058	−0.099	2.108
35	2.601	2.512	−0.089	2.556
40	3.059	2.944	−0.115	3.002
45	3.397	3.342	−0.055	3.370
50	3.602	3.552	−0.050	3.577
55	3.655	3.566	−0.089	3.610
60	2.562	—	—	2.5
65	0.108	—	—	0.10

The difference at 15 is probably due to a particle of dust or an over-setting of the wedge in the second series. At this point, the mean curve is somewhat higher, relatively, than the other curves for this wedge or the other wedges. The differences could be smoothed and perhaps ought to be, as irregularities of the sort suspected at 15 might easily occur. It has not been done here, but can be done at any time if desirable. The mean curve is plotted in Fig. 2 (*D*), and designated as the Laboratory Curve.

The marked similarity of the laboratory curve to Parkhurst's Curve *A* 12 for Wedge V was noticed as soon as it was plotted. Their points of inflection

FIG. 2.

- A* — Curve *A* 12 — V (Yerkes)
- B* — Wedge Curve — III (Lick)
- C* — Laboratory Curve — III (Harvard)
- D* — Laboratory Curve — III (Lick)

occur at the same scale readings; they might be brought nearly into coincidence by a simple change of slope—except near the dense end, where the wedges are certainly different. The star observations by Dr. Aitken required an average slope ("wedge constant") about equal to that of Parkhurst's curve. It was fully expected that the laboratory investiga-

tion would yield such a slope, special care having been taken to place the light-diffusing surface at a distance from the wedge greater than five centimeters—in accordance with the conclusions reached by Mr. E. S. King on the effect of distance of the source of light from the photographic wedge (*Annals H. C. O.* 41, 244). It was necessary, however, be-

cause the Lummer-Brodhun photometer compares areas, and because the cone of rays forming the artificial star is less than a millimeter in diameter at the wedge, to place a diaphragm near the wedge. Lenses might have been used to render the divergent pencils nearly parallel at the wedge; but aside from the departure from the conditions of practice, loss of light would have resulted, and new internal reflections would have been introduced. Light conditions required the use of a diaphragm considerably larger than would otherwise have been employed. Its aperture was 0.29 cm. The construction of the wedge tube made it convenient to place the diaphragm 1.2 cm. from the wedge (film) and inconvenient to place it nearer. Just beyond the diaphragm, and separated from it by a cardboard washer, was the piece of blue glass ordinarily used with the artificial star. The distance from wedge to diffusing surface was 8 cm. The area of wedge uniformly illuminated (a_1 , Fig. 3) was 0.26 cm. in diameter, and the boundary of the area (a_2) surrounding, illuminated by smaller parts of the diffusing surface, was 0.94 cm. in diameter. a_1 and a_2 correspond somewhat to umbra and penumbra, with light substituted for shadow.

FIG. 3.

It has occurred to me that the following might be an explanation of the phenomena observed by King and myself. The diffusion of light by the silver grains is greater at the dense end of the wedge than at the thin end. Little of the light transmitted at a_2 without diffusion reaches the screen or field of the reference photometer, because of the greater angle of these rays with the optical axis. Much of this light is saved by diffusion at the dense end of the wedge. There will be some loss of the light of a_1 by diffusion at the same time, but this will probably be less than

the gain by a_2 , because of the smaller angle of the rays of a_1 with the optical axis. Thus arrangements in which a_2 bears a large ratio to a_1 will yield smaller values of the slope of the curve than arrangements in which the ratio is smaller. Larger and practically identical values result from star determinations or comparisons with photometers employing point images, a_2 being very small.

After the measures of the wedge, determinations of the absorption of the shade glasses were made with the Lummer-Brodhun photometer. The small shade (No. 2) next the projecting lens of the artificial star, was mounted (with the projecting lens) in the optical axis, 5 cm. from the blue glass that was placed against the rice paper diffusing surface. Twelve settings, in the order 3 shade out, 6 shade in, 3 shade out, gave 1.72 ± 0.001 magnitudes absorption. The shade glasses L were then adapted for determination. A diaphragm of aperture, 0.6 cm., approximately equal to the diameter at the shades of the cone of rays from the real star in the 36-inch or 12-inch refractors, was placed between the shades at the position of the cone in practice. Shade I was 8 cm., and Shade II 9 cm., from the source which was left as in the measures of the small shade No. 2. Twenty settings, in symmetrical order, gave 0.89, 0.86, and 1.75 magnitudes, respectively, for the absorption of Shade I, Shade II, and both shades together.

A second laboratory investigation of the wedge was made in January, 1905, with a view to determining the effect of position of diffusing surfaces, diaphragms, color, etc. Special attention was paid to securing greater intensity of illumination. The 32 candle-power incandescent lamps of June were replaced by 100 candle-power incandescent lamps, the lamps being connected always in parallel on the same circuit. A slit aperture, 0.165 cm. by 1.2 cm., placed close to the glass of the wedge, was turned at right angles to the direction of motion of the wedge. The area a_1 was about 0.06 by 1.2 cm., and the area a_2 about 0.3 by 1.3 cm. Thin rice-paper, 4 cm. from the lamp, and 8 cm. from the wedge, diffused the light transmitted. Ten determinations of the relative "absorption" between scale readings 10 and 50, with a piece of rice-paper touching the slit, gave 3.19 magnitudes, with a mean range of ± 0.03 . These observations were made with a variety of arrangements of diaphragms; with the candle-power reduced (by resistance in the circuit) to 70 and to 1; with blue glass; with red glass; etc. The sources were made similar in each comparison. No effect of color or candle-power was detected. The numerical result is practically that obtained in June (1904), 3.16 magnitudes, and seems to indicate that the blue glass

placed 1.4 cm. from the wedge in June behaved much as a diffusing surface. Eight determinations with rice-paper 3.0 cm. from the wedge gave 3.34 mag. Three, with rice-paper at both positions, gave 3.10 mag. With no diffusing surface between the wedge and the rice-paper 8 cm. away, three determinations gave 3.73 mag. No arrangement tried would yield a result nearer 4.0 mag., given by the star measures. In nineteen of the observations, settings were made at scale reading 30 as well as at 10 and 50. The mean of the nineteen ratios of the relative absorption between 10 and 30 to that between 10 and 50, was 0.548, mean residual ± 0.006 , probable error ± 0.0013 . The uniform value of this ratio shows that the different curves resulting from the various arrangements of the laboratory apparatus, could all be obtained by stretching one of them, say the laboratory curve of June, 1904. It therefore seemed reasonable that a curve accurate enough for all practical purposes would be obtained by stretching the laboratory curve in a ratio to be determined from star measures.

A series of measures of Pleiades stars, selected from the list determined by Müller and Kempf (A. N. 150, 203), was then made for this purpose by Dr. Aitken. Fifty-one pairs of stars were observed, the average range of a pair being 1.9 mag. The 12-inch refractor was employed, part of the time with full aperture and part of the time with 6-inch and 3-inch apertures. The shade glasses were used in some of the measures; the values of their absorp-

tion were taken from the laboratory determination. The stretching factor was derived from 51 equations of the form $f = \frac{\Delta M - \Delta m}{\Delta m}$, M being the magnitude from Müller and Kempf, and m the magnitude from the laboratory curve. The weight assigned to each determination was Δm . A fact already noted by Dr. Aitken, that the smaller apertures or use of shades give greater absorption per scale division, appears in the following tabulated results:

Aperture	Shades	Pairs	$[\Delta m]$	$[\Delta M - \Delta m]$	f	p.e.
12"	none	15	16.23	+3.99	+0.246	± 0.015
6"	none	16	24.18	+6.35	+0.263	± 0.020
6"	both	6	12.30	+3.58	+0.291	± 0.031
3"	none	14	22.45	+7.37	+0.328	± 0.049

It was thought best to combine these determinations in one result to be used for all apertures and conditions. In practice, a large range of wedge will rarely be used in comparisons, and single determinations will be liable to actual errors much larger than inaccuracies thus introduced. The tabulated determinations were therefore weighted in inverse ratio to the squares of their probable errors and combined, with the final result, $f = +0.261 \pm 0.011$. The ordinates of the laboratory curve were then increased by 0.261 of their own length. The resulting curve is plotted in Fig. 2 (B), and designated as the Wedge Curve. For practical use, the thousandths have been dropped, and the values tabulated as m with the argument scale division, d :

TABLE OF m WITH ARGUMENT d .

d	00	10	20	30	40	50		PP	11	12	13	14	15
0	0.00	0.52	1.79	2.66	3.79	4.51		1	1.1	1.2	1.3	1.4	1.5
1	0.00	0.67	1.89	2.76	3.90	4.54		2	2.2	2.4	2.6	2.8	3.0
2	0.00	0.82	1.98	2.87	4.00	4.56		3	3.3	3.6	3.9	4.2	4.5
3	0.01	0.96	2.07	2.99	4.09	4.57		4	4.4	4.8	5.2	5.6	6.0
4	0.02	1.10	2.15	3.10	4.17	4.57		5	5.5	6.0	6.5	7.0	7.5
5	0.05	1.22	2.23	3.22	4.25	4.56		6	6.6	7.2	7.8	8.4	9.0
6	0.10	1.34	2.31	3.33	4.32	*		7	7.7	8.4	9.1	9.8	10.5
7	0.17	1.46	2.39	3.45	4.38	*		8	8.8	9.6	10.4	11.2	12.0
8	0.26	1.57	2.47	3.57	4.43	*		9	9.9	10.8	11.7	12.6	13.5
9	0.38	1.68	2.56	3.68	4.47	*							
10	0.52	1.79	2.66	3.79	4.51	*							

The following will illustrate the method of reduction that I have been using. The stars here measured

are among the faintest on the Rumford program.

Field of R Draconis — Standards for Faint Stellar Magnitudes.

Wed., 1903, Aug. 19, 9:50-10:56, P.S.T.

*	d	m	Shades	Obs.	M	k	Obs. mag.	Obsr., R. G. Aitken.	
								Mean range	m
<i>a</i> I II	10.60	0.61	1.75	$k - 1.14 =$	11.12	12.26	11.51	± 1.2	± 0.18
<i>b</i> I II	12.78	0.93	1.75	$- 0.82$	11.82	12.64	11.83	0.9	.13
<i>c</i> I II	14.51	1.16	1.75	$- 0.59$	12.20	12.79	12.06	1.2	.14
<i>d</i> I II	18.66	1.64	1.75	$- 0.11$	12.38	12.49	12.54	0.7	.08
<i>e</i> I II	16.16	1.36	1.75	$- 0.39$	12.67	13.06	12.26	0.6	.07
									.12
<i>g</i> —	38.87	3.67	—	$+ 3.67$			16.32	1.6	.18
<i>r</i> —	40.37	3.83	—	$+ 3.83$			16.48	1.4	.15
<i>s</i> —	43.13	4.10	—	$+ 4.10$			16.75	1.7	.14
<i>t</i> —	44.14	4.18	—	$+ 4.18$			16.83	0.8	.06
<i>u</i> —	47.99	4.43	—	$+ 4.43$			17.08	2.2	.10
									.13
							Mean, 12.65		

The first three columns are taken from the record book and table. Column four gives the value of the shades employed (indicated in column one by Roman numerals). The measures being purely differential, a constant k is introduced in column five to express the absolute magnitude. The reference magnitudes M , in column six, are preliminary values supplied by the Harvard College Observatory. The individual determinations of k from the observation equations of columns five and six are entered in column seven. The mean value, at the foot of the column, is applied successively in column five, and the result of the observation is given in column eight. It will be noticed that the scheme at the same time conveniently exhibits data for an inter-adjustment of the reference magnitudes M . The corresponding data from all the observations can finally be combined and the best relative system of magnitudes M obtained. For example, observations of this field by the same observer on two other nights—a different combination of shades being employed each night—give:

*	II	III	Mean I, II, III
<i>a</i>	11.52	11.45	11.49
<i>b</i>	11.76	11.87	11.82
<i>c</i>	12.29	12.17	12.17
<i>d</i>	12.29	12.31	12.38
<i>e</i>	12.31	12.40	12.32
<i>q</i>	16.53	16.41	16.42
<i>r</i>	16.71	16.45	16.55
<i>s</i>	16.69	16.67	16.70
<i>t</i>	16.77	16.68	16.76
<i>u</i>	17.00	17.01	17.03

If the reference magnitudes given by the Harvard College Observatory were determined from three nights' work with a photographic wedge photometer, the magnitudes to be adopted finally should probably be the means of the values found at Harvard, Yerkes, and Lick Observatories. The individual and final results for q, r, s, t, u are unaffected by such adjustment made from any number of *complete* observations. Columns nine and ten may be added to give an idea of the accuracy of the results.

Since the determination of the curve adopted, I have plotted the curve of the wedge from the means of the measures of its absolute absorption (and reflection) made at Harvard by Messrs. King, Bard, and Cram (An. H. C. O. 41, 239, Wedge III). A plot of these measures shows that the maximum lies at about 3.2 of the scale there used. The maximum of the Harvard curve was then placed opposite the maximum of the Laboratory Curve in Fig. 2. If the ordinates of the Harvard curve be diminished by 0.39 mag. so that it will pass through the origin, the differences L. O.—H. C. O. become:

<i>d</i>	<i>m</i>	<i>d</i>	<i>m</i>	<i>d</i>	<i>m</i>
0	0.00	20	+0.03	45	+0.17
5	0.00	25	+0.03	50	+0.18
10	-0.04	30	+0.04	55	+0.14
15	+0.03	35	+0.09	59	+0.02
		40	+0.12		

These would be reduced materially by applying a stretching factor of about +0.05.

JAMES D. MADDRILL.

June, 1905.

ON THE LIGHT AND VELOCITY CURVES OF W SAGITTARII

After the completion of my paper on the radial velocity and orbit of W Sagittarii [L. O. Bulletin, No. 62], there came to hand the excellent set of photometric observations of this star appearing in The Annals of the Astronomical Observatory of

Harvard College, Vol. XLVI, Part II. The deductions from these observations possess certain points of interest that may well be pointed out in connection with my own radial velocity determinations of this variable.

VELOCITY AND LIGHT CURVES. W. SAGITTARII.

Forming the mean of ten determinations of light maxima of W Sagittarii from Table XVIII of the Harvard volume, and bringing this mean up to my epoch with Chandler's accurate period, I find for time of maximum, 1903, August 2.46 days. My value from Chandler's elements was, 1903, August, 2.86 days.

Adopting the new value, the only orbital element affected is T (Time of periastron passage after light maximum), which becomes 6.69 days. Thus the light maximum occurs 0.99 days instead of 1.39 days after periastron time, and almost exactly at velocity minimum instead of 0.4 days after it.

The greatest interest lies in the comparison of the light and velocity curves. In the accompanying diagram the Harvard light curve from Table XVII is drawn in parallel with the velocity curve to exhibit the correspondence of detail both in form and position referred to maximum. The striking concordance observed is certainly more than a coincidence. Indeed the strong general resemblance between the light and velocity curves of W Sagittarii is good evidence that the form of each is determined by the same underlying causes; but speculation on this point may properly wait until more data are available on similar stars.

The difference between the Harvard and Schmidt light curves seem hardly accountable on the ground

of observational errors. It is not impossible that the true explanation is to be found in actual changes in the system of this star in the interval of thirty years between Schmidt's observations and those of Harvard College Observatory. This variation in the form of the light curve, together with Schmidt's suspected perturbation in the light period, suggests that the light changes of W Sagittarii are complicated by factors whose forms and magnitudes cannot be determined until the spectrographic and photometric observations cover many years.

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May 20, 1905.