No. 53 THE ABSOLUTE CALIBRATION OF THE ARIZONA PHOTOMETRY

by H. L. JOHNSON

May 15, 1965

ABSTRACT

The absolute calibration of the Arizona Photometry, which now consists of photometric data in 12 wavelength bands ranging from 0.36 μ in the ultraviolet to 13.1 μ in the infrared, has been derived. This calibration may be used to compute the absolute fluxes for objects that have been measured on the system.

1. *Introduction*

The absolute calibration of the multicolor photometric work that is now under way at the University of Arizona is needed for many uses of the data. This calibration, which we have already used in several investigations (Johnson 1964a, 1964b, Mitchell 1964), is given here along with a description of the procedures used for its derivation. We have not actually made any absolute measures in our work, but, instead, have relied upon published absolute measures of the Sun and other stars.

2. *Standards Used*

The absolute measures upon which our calibration is based are, for the Sun, from Saiedy (1960) and Allen (1963); for the stars, from Code (1960) and Stebbins and Kron (1964). The stellar data of Code and of Stebbins and Kron may be used directly since we have also measured most of their stars. In order to use the solar data, it is necessary to know the solar values on the Arizona Photometric System. We have not actually measured the Sun, so it is necessary to infer its colors from the work of Stebbins and Kron (1957) and Kron (1963). We have observed nine of the ten stars which Kron compared with the Sun; our data for these stars are listed in Table 1, along with data for six other G-dwarfs. For U−V, B−V, V−R, and V−I, the solar values were obtained by comparing Kron's (1963) data with those of the first part of Table 1, and then transforming Kron's solar data to the Arizona System. For V − J, V − K, and V−L, the solar values were interpolated for G2V from all of the data in Table 1, with special attention given to the data for λ Aur and λ Ser. Kron's data indicate that these two stars are more like the Sun in the infrared than are the others. The derived solar data are listed in Table 2. The values of V−M and V−N were obtained by interpolation among the available data, using the shorter-wavelength data of Table 2 as argument.

3. *Derivation of Effective Wavelengths of Filter Bands*

The next step in the calibration procedure was to derive the effective wavelengths of the several filter bands. We used as effective wavelength the quantity:

$$\lambda_0 = \frac{\int_0^\infty \lambda \phi(\lambda) d\lambda}{\int_0^\infty \phi(\lambda) d\lambda} \qquad (1)$$

where $\phi(\lambda)$ = the relative sensitivity of the measuring instrument, including the telescope.

TABLE 1
THE SOLAR COMPARISON STARS

STAR										
B.S.	NAME	V	U–V	B–V	V–R	V–I	V–J	V–K	V–L	SP
					Kron Stars					
458	50 And	4.10	+.60	+.54	+.46	+.75	+ .93	+1.25	+1.32	F8V
483	—	4.96	+.72	+.62	+.53	+.86	+1.09	+1.39	+1.54	G2V
1729	λ Aur	4.70	+.75	+.63	+.52	+.83	+1.07	+1.42	—	G0V
3881	—	5.10	+.70	+.62	+.53	+.86	+1.04	+1.38	—	G1V
4983	β Com	4.26	+.65	+.57	+.48	+.77	+1.03	+1.37	+1.50	G0V
5868	λ Ser	4.43	+.70	+.60	+.51	+.83	+1.05	+1.38	+1.42	G0V
7504	16 Cyg B	6.20	+.87	+.66	+.44	+.78	+1.14	+1.53	+1.61	G5V
8729	51 Peg	5.49	+.87	+.67	+.54	+.88	+1.12	+1.50	+1.71	G4V
—	HD 157089	7.00	+.56	+.57	+.58	+.87	+1.18	+1.46	+1.72	G0V
					Other G Stars					
219	η Cas	3.44	+.60	+.58	+.50	+.86	+1.08	+1.47	—	G0V
937	ι Per	4.05	+.73	+.60	+.54	+.83	+1.00	+1.34	—	G0V
4496	61 UMa	5.35	+.96	+.72	+.62	+.93	+1.31	+1.71	—	G8V
4785	β CVn	4.27	+.64	+.59	+.54	+.85	+1.04	+1.43	—	G0V
7503	16 Cyg A	5.95	+.84	+.64	+.45	+.78	+1.06	+1.44	+1.54	G2V

TABLE 2
THE MAGNITUDE AND COLORS OF THE SUN

STAR	V	U–V	B–V	V–R	V–I	V–J	V–K	V–L	V–M	V–N	SP
Sun	−26.74	+.70	+.64	+.52	+.78	+1.06	+1.41	+1.53	+1.40	+1.46	G2V

As King (1952), Strömgren (1937), and Wesselink (1950) have shown, instrumental magnitudes behave to a first-order approximation like monochromatic magnitudes at wavelength λ_0. This definition differs from that which we have used in earlier papers; the effective wavelengths given here should be substituted for the earlier ones.

The definition of λ_0 in Equation (1) implies that, at least to a first-order approximation, our broad-band filters should be directly comparable with Code's monochromatic magnitudes, for $\lambda = \lambda_0$. We have made comparisons for U, B, V, R, and I; as a result of these comparisons, slight empirical corrections to the values computed from Equation (1) were made, so that λ_0 is essentially independent of stellar temperature. These empirically determined values of λ_0 for U, B, V, R, and I are listed in Table 3, along with those computed from the photometer-response functions (Johnson 1965) and Equation (1), for the longer wavelengths. The effective wavelength of the I filter, judging from the comparison with Code's data, cannot be made entirely independent of stellar temperature; it shifts slightly to the red for cool stars and the calibration derived here yields absolute energies about 10 percent too great for such objects. We emphasize, however, that the effective wavelength, λ_0, is a first-order approximation to monochromatic magnitudes at this wavelength. The term "monochromatic" is not used here in the strictest sense but refers to an averaged or smoothed energy distribution over the region of the filter band-pass. Because of the absorption lines and other spectral features in stellar spectra, we do not expect the absolute calibration of the wide-band photometry to yield absolute energies that are identical to those obtained from narrow-band photometry or spectrophotometry; instead, the absolute fluxes obtained from the calibration derived here apply to rather thoroughly smoothed stellar spectral-energy distributions.

4. *Determination of Apparent Solar Magnitude*

Next was the determination of the apparent magnitude of the Sun. The modern photoelectric determinations are listed in Table 4. Those attributed to Willstrop and Code were computed from their measured fluxes for a star of V = 0.00 and Allen's (1963) solar flux. The probable errors are those given by the several authors. The weighted mean of −26.74 has been entered in Table 2.

5. *Calibration Procedure*

The absolute calibration of the Arizona Photometery was obtained by interpolating in Allen's (1963) solar-energy table, using the effective wavelengths listed in Table 3. For the N band, the work of Saiedy (1960) was also used. These values were then reduced by 26.74 mag, yielding the absolute-energy distribution of a solar-type star of V = 0.00. Correction according to the solar colors in Table 2 produced the absolute calibration for mag = 0.00 in each of the filter bands. The interpolation using the effective wavelengths λ_0 has been checked by computations using the measured photometer-response functions (Johnson 1965) and Allen's solar-energy distribution. The agreement is good.

6. *Calibration Checks*

Stebbins and Kron (1957) and Kron (1963) have pointed out that their I value for the Sun deviates systematically from those for some of the other stars they observed. In order to check the calibration, especially in the 1 μ region, we used the monochromatic magnitude data of Code (1960). The absolute filter photometry of Stebbins and Kron (1964) was compared with Code's data; the two agree almost perfectly at all six points of the Six-Color Photometry, including the I point. (This agreement of the two *measured* absolute calibrations implies that Oke's [1964] calibration, which depends upon a model-atmosphere computation for α Lyr, should be corrected to agree with Code's data.) The calibration of the Arizona Photometry from Code's data agrees with that from the solar-energy curve within a few percent for all five bands, U, B, V, R, and I. Thus, Stebbins and Kron's measured I for the Sun is confirmed. The resultant absolute calibration, which below 1 μ is the mean of the two calibrations, is given in Table 5.

TABLE 3
THE EFFECTIVE WAVELENGTHS

FILTER BAND	λ_0	FILTER BAND	λ_0
U	0.36 μ	K	2.2 μ
B	0.44	L	3.4
V	0.55	M	5.0
R	0.70	N	10.2
I	0.90	O	11.5
J	1.25	P	13.1

TABLE 4
THE APPARENT MAGNITUDE OF THE SUN

SOURCE	V	p.e.
Stebbins and Kron (1957)	−26.73	±0.03
Gallouët (1964)	−26.70	±0.01
Kariagina (1955)	−26.83	±0.06
Nikinov (1949)	−26.81	±0.07
Willstrop (1960)	−26.77	±0.08
Code (1960)	−26.74	±0.05
Weighted Mean	−26.74	±0.01

TABLE 5
THE ABSOLUTE CALIBRATION OF THE ARIZONA PHOTOMETRY
Absolute Flux Density (mag = 0.00)

FILTER BAND	λ_0	WATTS/CM^2/μ	WATTS/M^2/HZ
U	0.36 μ	4.35×10^{-12}	1.88×10^{-23}
B	0.44	7.20×10^{-12}	4.44×10^{-23}
V	0.55	3.92×10^{-12}	3.81×10^{-23}
R	0.70	1.76×10^{-12}	3.01×10^{-23}
I	0.90	8.3×10^{-13}	2.43×10^{-23}
J	1.25	3.4×10^{-13}	1.77×10^{-23}
K	2.2	3.9×10^{-14}	6.3×10^{-24}
L	3.4	8.1×10^{-15}	3.1×10^{-24}
M	5.0	2.2×10^{-15}	1.8×10^{-24}
N	10.2	1.23×10^{-16}	4.3×10^{-25}

For the wavelengths longer than 1 μ, the absolute calibration depends upon the derived colors of the Sun listed in Table 2. Since we have not actually observed the Sun, but only stars which were found by Stebbins and Kron (1957) and Kron (1963) to be like the Sun, it is essential to check to see whether our calibration for the longer wavelengths is reasonable. It should be mentioned again that we have used, in addition to the observations of Stebbins and Kron, the fact that the Sun's spectral type is G2V; it is, in fact, Morgan's (Morgan and Hiltner 1965) G2V standard. The spectral-energy distribution of the Sun is known, of course; its brightness temperature in the region of the V filter is about 5900°K, and drops to around 5000°K at 10 μ. Therefore, a 5800°K black body approximates the Sun, being a little brighter than the Sun at the longer wavelengths.

Oke (1964) used a model-atmosphere computation for α Lyr ($T_e = 9500$°K) with fair success; in fact, he bases his absolute calibration entirely on this computation. The zero points of our magnitude scales have been set so that, for an average A0V star, all magnitudes are the same (all color indices are zero). Therefore, let us assume that an A0V star behaves like the Sun — that its spectral-energy distribution approximates a black body of the star's effective temperature, but that the star is fainter at the longer wavelengths than the black body. Such behavior is expected on theoretical grounds (Underhill 1964; Gingerich *et al.* 1965).

We approximated the A0V star with a 10,000°K black body and normalized the black body to Code's data at 1.0 μ. We used a 10,000°K black body, instead of 9500°K, to compensate partially for the drop in brightness temperature at the long wavelengths. The resulting calibration is given in the second column of Table 6, and the solar calibration of Table 5, in the third column. The last column gives the ratio of the solar calibration of Table 5 to the 10,000°K black body calibration. These ratios are just about what we expected to find; the scatter may be due to errors in the calibration process or to unevenness in the solar spectral-energy distribution.

TABLE 6

Calibration Checks

Filter Band	10,000°K Black Body	Solar Calibration	Solar Black Body
J	3.70×10^{-10}	3.40×10^{-10}	0.92
K	4.96×10^{-11}	3.90×10^{-11}	0.79
L	9.74×10^{-12}	8.1×10^{-12}	0.83
M	2.22×10^{-12}	2.2×10^{-12}	0.99
N	1.39×10^{-13}	1.23×10^{-13}	0.88

Another check of the quality of our calibration was obtained by comparison with the stellar-model computations of Strom and Avrett (1964). They computed the emergent fluxes for 10,000°K stellar models; this temperature is almost exactly that which we believe to be the effective temperature of A0V stars. The comparison with our solar calibration is shown in Table 7, in which the second column gives a calibration derived from the computations of Strom and Avrett (their Model 3) on the assumption that V = 0.00. The solar calibration from Table 5 is given in the third column, and the ratios in the last column. The agreement is quite satisfactory out to the long-wavelength limit of the computations, thus confirming our calibration out to 3.4 μ (magnitude L). This confirmation could also be interpreted as indicating an effective temperature of 10,000°K for A0V stars.

TABLE 7

Calibration Checks

Filter Band	10,000°K Stellar Model	Solar Calibration	Solar Model
V	3.92×10^{-9}	3.92×10^{-9}	1.00
R	1.79×10^{-9}	1.84×10^{-9}	1.03
I	0.99×10^{-9}	0.90×10^{-9}	0.91
J	3.20×10^{-10}	3.40×10^{-10}	1.06
K	4.29×10^{-11}	3.90×10^{-11}	0.91
L	8.42×10^{-12}	8.1×10^{-12}	0.96

The indications are that our calibration procedure has led to results that are good to ±10 percent, or better, over the range of wavelength 0.36 μ to 3.4 μ. For the longer wavelengths, we depend upon the solar calibration (using derived solar colors) and the black-body check of Table 6. A further check on the long-wavelength calibration was made using the known fact (Low 1965) that the germanium bolometer we are using for these wavelengths has uniform response from 1.8 μ to more than 20 μ. Thus, the relative responses of the bolometer, used with the K, L, M, and N filters (taking into account the filter and atmospheric transmissions and the stellar-energy distributions), should be in accord with the solar calibration, if it is correct. We have performed this check, using the K, M, and N filters on several stars, with the result that the ratios of the K, M, and N calibrations (Table 5) are confirmed to a few percent. Since the calibration of the K magnitude seems to be good, this check has provided an effective confirmation of the M and N calibrations.

An independent procedure for calibration of the N band (10.2 μ) would be to use the flux value of 2.0×10^{-13} erg/s/cm^2/Å for an N = 0.00 star, derived from the measures of Wildey and Murray (1964). This flux is about 1.7 times that in Table 5. However, in a recent communication, Wildey (1965) stated that their absolute calibration has been revised and that it now agrees with our solar N-magnitude calibration "within a few percent."

7. *Conclusion*

It is emphasized that the derivation of this calibration of the Arizona Photometry has proceeded in three parts of differing precision. The first part consisted of the calibration of the UBVRI bands from comparisons with the absolute photometry of Code, and of Stebbins and Kron. This part seems quite solidly based and is unlikely to change much in the future. The second part consisted of the calibration of the JKL bands from observed absolute solar fluxes, and solar colors obtained from observations of nine stars compared directly with the Sun by Stebbins and Kron. This part of the calibration has lower weight than the first, but the checks indicate that it is unlikely to be in error by more than 10 percent. The last part, the calibration of the M and N bands, is similar in procedure to the second, but the results are less certain because the V−M and V − N colors for the Sun had to be inferred from stars which have not been compared directly with the Sun. In other words, we depended in this part upon the assumption that the solar spectral-energy distribution in the long wavelengths is essentially the same as those of other stars of similar temperature and spectral type. However, the check using the known uniform response of the germanium bolometer confirmed the solar-based calibration, as did the revised Mount Wilson–Palomar calibration reported by Wildey (1965).

Acknowledgments. The Arizona photometric work, of which this paper is a part, has received financial support from the Office of Naval Research under Grant Nonr(G)-00018-65 and from the National Science Foundation under Grant GP-3736. I am much indebted to Dr. F. J. Low for valuable discussions on these subjects.

REFERENCES

Allen, C. W. 1963, *Astrophysical Quantities* (London: Athlone Press).
Code, A. D. 1960, *Stellar Atmospheres* (Chicago: University of Chicago Press), chap. 2.
Gallouët, L. 1964, *Ann. d'Ap.*, *27*, 423.
Gingerich, O., Mihalas, D., Matsushima, S., and Strom, S. 1965, *Ap. J.*, *141*, 316.
Johnson, H. L. 1964*a*, *Ap. J.*, *139*, 1022.
———. 1964*b*, *Bol. Obs. Tonantzintla y Tacubaya*, *3*, 305.
———. 1965, *Ap. J.*, *141*, 923.
Kariagina, S. W. 1955, *Izvest. Astr. Inst. Alma-Ata*, *1*, 85.
King, I. 1952, *A. J.*, *57*, 253.
Kron, G. E. 1963, *Pub. A.S.P.*, *75*, 288.
Low, F. J. 1965, private communication.
Mitchell, R. I. 1964, *Ap. J.*, *140*, 1607.
Morgan, W. W. and Hiltner, W. A. 1965, *Ap. J.*, *141*, 177.
Nikinov, E. K. 1949, *Izvest. Crimean Astr. Obs.*, *4*, 114.
Oke, J. B. 1964, *Ap. J.*, *140*, 689.
Saiedy, F. 1960, *M. N.*, *121*, 483.
Stebbins, J. and Kron, G. E. 1957, *Ap. J.*, *126*, 266.
———. 1964, *ibid.*, *139*, 424.
Strom, S. E. and Avrett, E. H. 1964, *Ap. J.*, *140*, 1381.
Strömgren, B. 1937, *Handbuch der Experimentalphysik* (Leipzig: Akadamische Verlagsgesellshaft), *26*, 392.
Underhill, A. B. 1964, *Les Spectres Infrarouges des Astres* (Liège: Université de Liège), p. 469.
Wesselink, A. J. 1950, *Trans. I. A. U.*, *7*, 269.
Wildey, R. L. 1965, private communication.
Wildey, R. L. and Murray, B. C. 1964, *Ap. J.*, *139*, 435.
Willstrop, R. V. 1960, *M. N.*, *121*, 17.