SIX-COLOR PHOTOMETRY OF STARS. X. THE STELLAR MAGNITUDE AND COLOR INDEX OF THE SUN*

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ABSTRACT

By means of a device originally designed and constructed by A. E. Whitford, the sun's light was reduced by reflections from a magnesium oxide disk and a small aluminized convex mirror to approximate equality with the light of a ribbon-filament tungsten lamp, operated at a color temperature near 2960° K and at a distance of 17.4 inches from the first reflector. After photoelectric comparison of the sun and lamp through this reducer, the photometer was transferred to the Crossley reflector, where the same lamp, at a distance of 1746 feet from the telescope and diaphragmed by a pinhole aperture, was readily compared with a number of stars of known magnitude, color, and spectral type. The results for the sun on the International scale are: photovisual magnitude, −26 73 ± 0.03; color index, +0 53 ± 0.01; color class, dg1 Mount Wilson or g2 V on the Yerkes system. All the photometric evidence shows that the sun is a normal dwarf star of spectral type G.

INTRODUCTION

To place the sun on the magnitude and color scales of the stars requires that its light, without change of quality, be reduced by a known amount to be approximately equal to that of one or more stars that can be measured through a telescope. This reduction has sometimes been made with an intermediate source like the moon or a standard lamp. For general usefulness the result should be convertible to the International system of magnitudes. The present report is on the application of a photoelectric cell to the measurement of the sun's light, with the same installation that had already furnished six-color results on some scores of stars with the 36-inch Crossley reflector of the Lick Observatory (Stebbins and Kron 1956).

CELL AND FILTERS

The photocell is a selected one made by the Continental Electric Company, their number CE-25 AB, our designation "g." The cylindrical cathode of cesium oxide on silver is 18 × 12 mm, and the U-shaped anode allows free space for an 8-mm extrafocal star image to be formed on the cathode by a quartz-fluorite Fabry lens at the focus of the main mirror. Because of the thermal emission of this type of cathode at room temperature, the cell in use is always refrigerated with dry ice. The cell box is designed to avoid frosting of the plane quartz window without electrical heating under all observing conditions. This cell was used in preference to a photomultiplier because of its greater range of spectral sensitivity, which, with the optics mentioned, extends from 3100 to 11500 A. Except for its lesser reach to the infrared, the cell is superior to the Western Electric cells used formerly by Stebbins and Whitford (1945) and by Stebbins and Kron (1956).

The combinations of the cell and filters of the new six-color system have been calibrated in the laboratory. The light from a small bright tungsten lamp, after passing through a quartz monochromator and a filter, was focused on the cathode of the cell at exactly the spot effective for the stars. By taking successive runs along the spectrum through each filter, exposing first the cell and then a thermopile to the same beam, we

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obtained the color curves of the cell and filters reduced to equal energy at all wave lengths. The results of this calibration, made on two days a month apart, are shown in Figure 1.

The new ultraviolet filter is composed of a 2-mm thickness of 80 per cent saturated copper sulphate solution between two 1-mm pieces of UG2 glass. With proper care the filter will last for months. So well does the copper sulphate cut out the infrared leak of the glass that with the present photocell the correction to the ultraviolet deflection is only about 1/7000 the deflection through the infrared filter. The new violet filter is composed of three glasses, 2 mm each of BG12, BG23, and GG13, which have reduced the leak of that filter from 1/200 to 1/800 the infrared response. The remainder of the six filters are not subject to leaks.

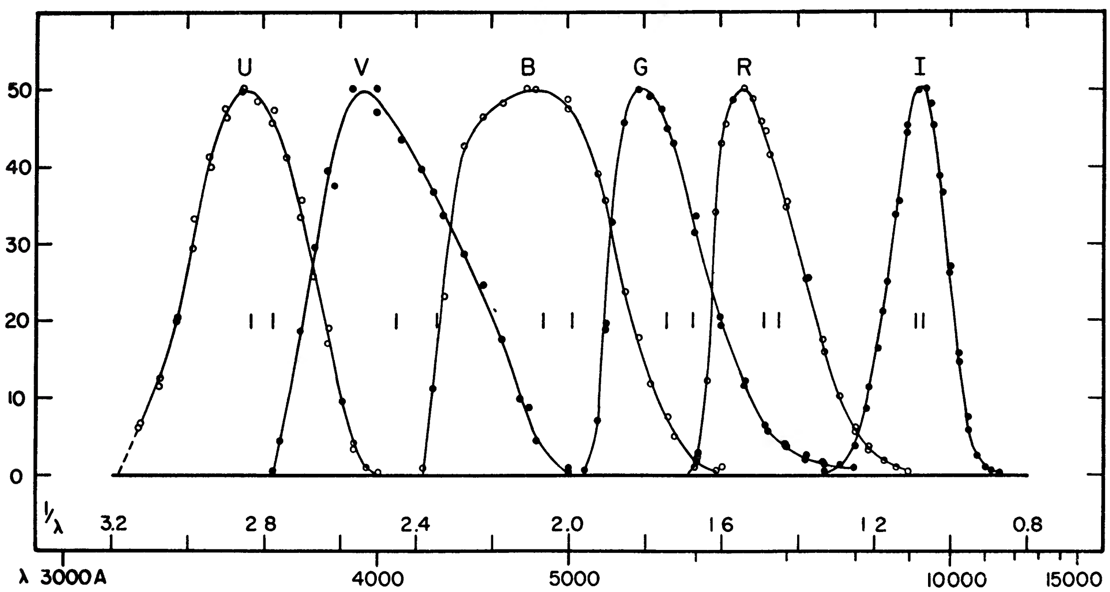

FIG. 1.—Sensitivity-curves of cell and filters

Since the effective wave length for each filter depends upon the temperature of the source measured, we proceed as follows. The energy from a black body in the interval $d\lambda$ is taken from the radiation tables as $J_\lambda d\lambda$. To express the energy on the $1/\lambda$ scale, putting $x = 1/\lambda$, we write, ignoring the negative sign,

$$J_\lambda d\lambda = J_\lambda \lambda^2 d\,\frac{1}{\lambda} = J_x dx\,.$$

Let $A(x)$ be the coefficient of reflection from two aluminum surfaces and $R(x)$ the relative response of the cell and a filter from one of the curves of Figure 1; then the effective inverse wave length for that filter and a source is given by

$$\frac{1}{\lambda_0} = x_0 = \frac{\int_0^\infty J_x A(x) R(x)\, x\, dx}{\int_0^\infty J_x A(x) R(x)\, dx}\,, \tag{1}$$

where in practice the integrals are taken over the interval in which $R(x)$ is significant. The integrations were done numerically with the convenient steps of $\Delta x = 0.04\ \mu^{-1}$, and the values from equation (1) are in Table 1. Those in the last line for constant energy without the mirrors are from the expression

$$\frac{1}{\lambda_0} \doteq x_0 = \frac{\int_0^\infty R(x)\, x\, dx}{\int_0^\infty R(x)\, dx}. \tag{2}$$

The values of $1/\lambda_0$ for 3000° and 25000° K under each color in the table are marked in Figure 1. As an example of the influence of a shift of effective inverse wave length with source temperature, it was found from the violet-filter curve that at 3000° K the energy of the source at the longest wave length in the pass band is fifteen times that at the shortest, while at 25000° K the ratio is 1.5 to 1 in the other direction. The table also shows that the effective inverse wave lengths for constant energy are about the same as those for 10000° K. On the $1/\lambda$ scale the maximum energy for 10000° K is near 2.0 μ^{-1}.

We note that, because of differential extinction, a star becomes redder with increasing zenith distance, but, when the corrections for extinction are determined empirically

TABLE 1

EFFECTIVE INVERSE WAVE LENGTHS

(Unit μ^{-1})

T (° K)	c_2/T	U	V	B	G	R	I
3000	4 78	2 78	2 36	2 00	1.68	1 45	1 08
6000.	2 39	2 82	2 42	2 06	1 72	1 47	1 08
10000	1 435	2 84	2 44	2 08	1 74	1 48	1 09
25000	0 574	2 85	2 46	2 09	1 74	1 49	1 09
Const. J		2 84	2 45	2 08	1 74	1 48	1 09

from measures at high and low altitudes, the relative intensities outside the atmosphere for the different filters are automatically freed from extinction. The stars are nearly enough like black bodies for the data of Table 1 to be sufficient for even approximate color temperatures.

THE SUN REDUCER

One of our first attempts to reduce the sun's light consisted simply of diaphragming the Crossley reflector down to several pinhole apertures of 0.9 mm, a reduction of 10^6 in area, and then of admitting to the cell the light from a circular hole 1/200 of the diameter of the focal image of the sun. This reduction of about 26 mag. gave manageable intensities for measures through the filters. However, we promptly found that variations in color sensitivity over the cathode would preclude the use of any such device. Each small spot of the main mirror was focused by the Fabry lens onto a different point of the cathode, and the records from different spots did not look as though they came from the same object or photocell. Two diametrically opposite spots on the main mirror gave a color difference of 0.6 mag. in V − I, or 0.2 mag. in International C. From our experience and from the literature we had reason to expect some such effect, but we were surprised to find it so large. As a result of this test we were forced to the conclusion that all measures of any kind would have to use the same photocell area, which in the sequel turned out to be a circle 8 mm in diameter.

The device finally used for reducing the sun's light to an intensity comparable with that of a terrestrial or other stellar source was originally designed and constructed by A. E. Whitford, who, with Stebbins, gave the instrument some preliminary trials at the

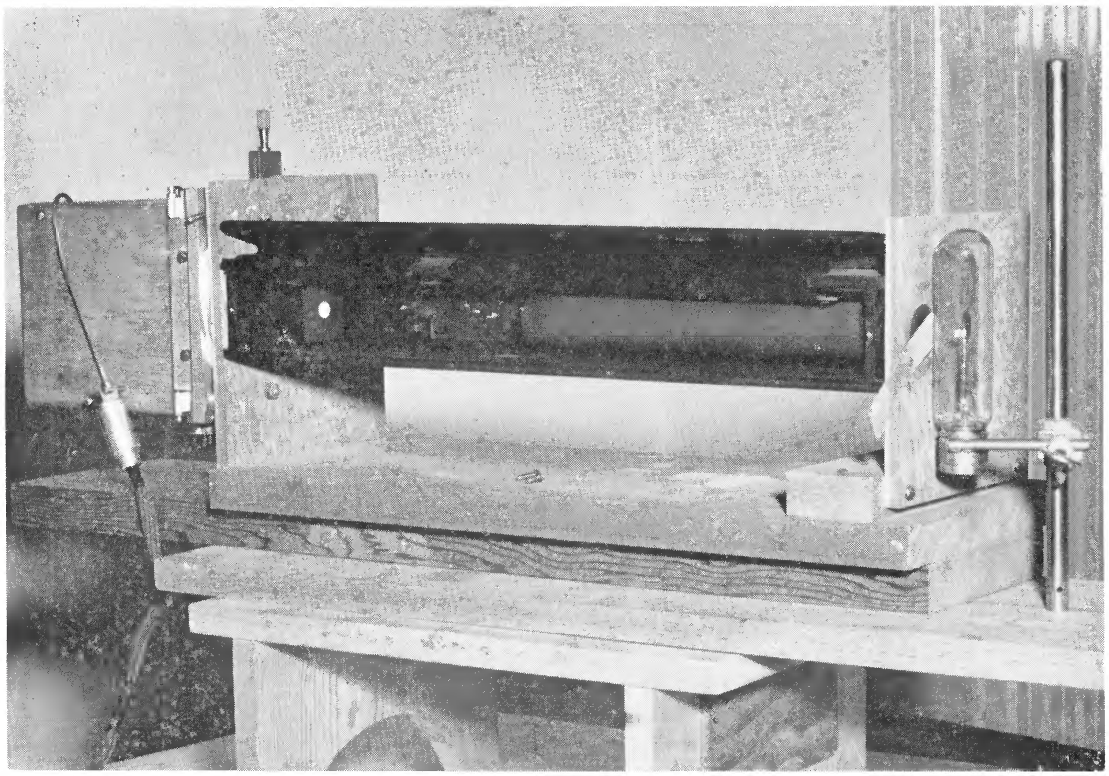

FIG. 2.—Photograph of sun reducer

Mount Wilson Observatory in 1946. Later, with several improvements, the reducer was kindly turned over to us by Whitford for measures of the sun at Lick. In the first form of the instrument the sun's image was made by successive reflections from two small aluminized convex spherical mirrors, each of about 1 inch in radius. We thought that the reflections from the aluminum mirrors would about equalize any color changes by the two aluminum mirrors of a reflecting telescope used at the Newtonian focus. With the optical system adopted for the reducer, the resulting intensity of the sun's light on the cathode of the photocell turned out to be about the same as that of a fourth- or fifth-magnitude star at the focus of a 60-inch or 36-inch telescope. However, although the intensity of the reduced sun was usable and its color was about right, we ran into unexpected discordances in repeated measurements. The trouble was finally ascribed to the fact that the virtual image in the second small mirror was so minute that when it happened to hit a hole or small defect in the aluminum film, diffraction effects would interfere with the simple geometric reflection. To overcome this difficulty, we substituted

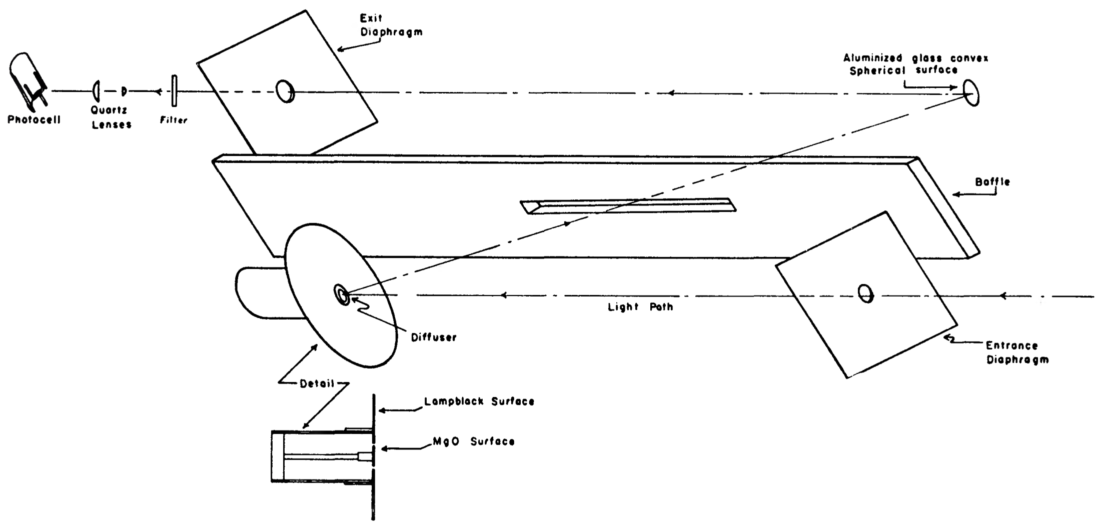

FIG. 3.—Schematic diagram of sun reducer

for the first mirror a small disk covered with magnesium oxide formed by exposing the disk to the smoke of burning magnesium.

A schematic diagram of the modified form of the reducer is shown in Figure 3, and a photograph of the same, with photometer and standard lamp in place, is in Figure 2. In Figure 3 light from the sun or the ribbon-filament lamp passes through the entrance diaphragm and falls on the diffuse reflecting MgO disk. Light from the direction of the virtual image of this disk formed by the small aluminized sphere, after passing through a filter, is focused by the quartz-lens system on the photocathode of the cell at the same spot as a star image at the focus of the Crossley reflector. Exact coincidence of sun and star images is perhaps not necessary, because the light from the sun and that from the intermediary lamp go through the same optical path. The only difference is that a 4-mm MgO disk was used for the sun and a 10-mm disk for the lamp. Figure 2 shows the reducer with the entrance side opened to disclose the 10-mm disk. The cell box of the photometer shows at the left, and the handle of the six-color filter slide projects up from the photometer. With the arrangement described, it turns out that the sun was observed with a 4-mm aperture and an optical system that reduced the light by 18.5 mag. Similarly, the lamp, which at 17.4 inches (442 mm) has a photovisual magnitude of -21, was measured with a 10-mm aperture and the same reduction of 18.5 mag. The difference of about 2 mag. between the two disks successively in place could be measured accurately with the photometer with the lamp as a source.

Several apparently minor details turned out to be important. The system of light-baffling at both entrance and exit of the real reducer is much more complicated than shown in the schematic diagram. Nevertheless, there remained a small area of illuminated lampblack background around each MgO disk as viewed from the small mirror. To equalize this background light, each disk in use was mounted on a pedestal in a blackened cavity, where the sides received no direct light from the source and the unwanted light was the same whether or not a disk was in place. For the sun, with the 4-mm disk, the light from the background was between 4 and 5 per cent of the total for all colors; for the lamp, with the larger disk, the extra light was proportionally much less. The reducer background was always measured in the same way as the sky background for a star. Incidentally, we found that dull black paper reflected too much to be useful and that the black velvet we tried was a strong reflector in the infrared.

When in use for the sun, the reducer with lamp and photometer was carried on the mounting of the 22-inch Tauchmann reflecting telescope in the dome on a small peak about 750 feet east of the main building. Guiding, which was not critical, was checked with a small auxiliary telescope serving as a finder. After a comparison of the sun and lamp, the lamp was left at the same station and diaphragmed with a pinhole, while the photometer was transferred to the Crossley reflector, where on the next available night this artificial star at the distance of 1746 feet was compared with real stars. Thus in both cases—sun and lamp and lamp and real star—the two sources were measured through the same optical systems.

ATMOSPHERIC EXTINCTION

Although, in ordinary stellar photometry, stars can be observed at nearly the same altitudes and thus the atmospheric extinction involves only differential corrections, in the present case, when referring the sun to the lamp and then stars to the lamp, the

TABLE 2

MEAN ATMOSPHERIC EXTINCTION COEFFICIENTS

	U	V	B	G	R	I
Day *a* .	$0^m.62$	$0^m.33$	$0^m.22$	$0^m.15$	$0^m.10$	$0^m.06$
Night *a* .	58	30	19	14	09	09
Horizontal, obs.	04	02	01	.01	01	03
Horizontal, comp.	0 04	0.02	0 01	0 01	0 01	0 01

extinction comes into its full extent by day and by night. Also the horizontal extinction in the air path of 1746 feet between the Crossley and the artificial star must at least be investigated. The final effects of extinction on the magnitude and color of the sun are then the differences between the errors of the adopted day and night extinctions, which may or may not partly cancel each other.

The adopted mean coefficients for extinction at the zenith are in Table 2. In several cases it was possible to determine the coefficients on the same day or night that observations for the program were undertaken; but for practical considerations it was not feasible to attempt solar observations in the morning and then to expect the same good conditions to hold through the following night, even if the Crossley were available when wanted. As is evident in the table, the day extinctions are somewhat larger than those at night, except for the infrared, where the effective wave length comes right in the midst of the ρ, σ, τ telluric band of water vapor. Each tabular value is the mean from three days or nights, and the probable error of a single determination of the coefficient comes out approximately ± 0.01 mag. for a day and ± 0.02 mag. for a night.

The horizontal extinction on Mount Hamilton was determined on five nights in two years by measuring a small lamp in six colors back and forth at distances differing by 2000 feet or more. Because of the slightly changing voltage of a small battery, we could not always apply the law of inverse squares, and the results were referred in color to the mean of blue, green, and red, which always agreed within less than 0.01 mag. with one another. Hence, by assigning 0.01 mag. to the average extinction for these three colors, we get the observed horizontal extinctions in Table 2. The computed values in the last line are derived from the consideration that a 1000-foot change in elevation at a mean altitude of 4000 feet corresponds to a 1-inch variation in a mean barometric pressure of 26 inches of mercury. Then 1746 feet of air would be $1746/1000 \times 26 = 1/15$ of the total air over the mountain, and the last line of Table 2 gives the night coefficients a each divided by 15. This assumption that an air mass at the local level is equivalent to that higher up is of doubtful validity, but to raise the horizontal extinction of blue, green, and red to 0.02 mag. would contradict the evidence on the nights when the checkback between stations was good enough to apply the law of inverse squares.

SUN AND LAMP

A sample comparison of the magnitudes of the sun and the standard lamp, as determined through the sun reducer, is contained in Table 3. Each source was allowed to

TABLE 3

SUN AND LAMP COMPARISON

Color	Blue	Green
Sun-lamp, obs.	$+0^{m}20$	$+1^{m}16$
Shunt. .	−4 50	−4 50
MgO disks	−1 95	−1 95
Sun-lamp, corr..	−6 25	−5 29
Reduction mean dist	−0 03	−0 03
Aug. 12, 1954	−6 28	−5 32
Aug. 5.	−6 21	−5 28
Aug. 19	−6 32	−5 38
Sept. 5	−6 33	−5 38
Mean	−6 28	−5 34
Prob. error	±0 02	±0 02

shine on its appropriate disk of MgO, the lamp with full filament at 17.4 inches. From the six colors used, the blue and green are selected here because they bracket the effective photovisual wave length in which the magnitude is to be expressed. Under each color the observed difference in magnitude in the first line has been corrected for extinction of the sun and for background light in the reducer for both sun and lamp. The shunt values were needed to equalize the two sources; the large and small magnesium disks differed photometrically by 1.95 mag. With all other corrections taken care of, we apply the reduction to the mean distance of the sun, which in August amounts to -0.03 mag. The results for August 12, for three other dates, and for the mean follow in order. The low values on August 5 look suspicious, but we have no reason for rejecting them. The probable errors of the means should give a fair measure of the accidental errors.

LAMP AND STAR

Table 4 gives a comparison of the lamp viewed through a pinhole and of a real star in the sky, both observed with the Crossley reflector. The artificial star is represented by the symbol (*), and the procedure is mostly self-evident. Under each color the sum of the first four quantities is the corrected magnitude difference between the artificial star at 1746 feet and the real star, NPS 1, both with no atmosphere. To these sums we add sun *minus* lamp from Table 3 and reduce to photovisual wave length at six-tenths the interval from blue to green. The difference of −7.21 mag. between lamp and artificial star follows from the ratio of areas of 16.38 mm^2 equivalent for the filament and 0.0219 mm^2 for the circular hole of diameter 0.167 mm. The ratio of inverse squares of the distances, R = 1746 feet and r = 16.95 inches, gives the difference of −15.46 mag.

TABLE 4

LAMP AND STAR COMPARISON

Date, 1954	Aug 10	
Star, spectrum	NPS 1, A2	
	Blue	Green
*−star, obs.	−0$^{\rm m}$10	−1$^{\rm m}$45
Horizontal extinction	−0 01	−0 01
Shunt	+3 00	+3 00
Screen over Crossley	−4 82	−4 82
*−star, corr.	−1 93	−3 28
Sun−lamp	−6 28	−5 34
Sun−lamp+*−star	−8 21	−8 62
Pv=B+0 6(G−B)	− 8 46	
Lamp−*.	− 7.21	
−5 log (R/r)	−15 46	
Sun−star	−31 13	
Star, Pv	+ 4 38	
Sun, Pv	−26 75	

Thus, in total, we have 31.13 mag. between the sun and real star, and hence Pv = −26.75 for the sun. The dimensions involved here and the possibilities of error along the way in this reduction will be discussed presently.

THE SUN'S MAGNITUDE

In Table 5 are the collected values of the sun's magnitude from comparisons with fourteen stars taken in groups on six nights. In the columns, following the HD number and the name of the star, the magnitude Pv is International photovisual, from Kron (unpublished) for the first four stars and from Johnson and Morgan (1953) for the remaining ten. The spectral types are from Mount Wilson and Yerkes. At the top of each column under the date are the dimensions in millimeters of the slit or the diameter of the small circular hole used on that night. Each magnitude in the body of the table is from a comparison involving the artificial star, as in Table 4. The stars chosen are polar standards and dwarf G stars in good positions, with Johnson-Morgan magnitudes and spectra available. We have various comparisons of these stars with one another and with other standards of the six-color photometry, but we have used here only the direct comparisons with the artificial star. Hence the system of magnitudes and colors of the present group is complete in itself. Although the means of the magnitudes of the sun in Table 5 were taken by rows and by columns to another decimal place, they are rounded off in the table.

A probable error of the final value, -26.73, may be derived in different ways. First, we note that the close agreement in the last column is illusory; it is only a confirmation of the Johnson-Morgan photometry of the last ten stars, with which the first four by Kron agree perfectly. Eggen's (1955) magnitude of $V = 5.46$ for 51 Pegasi would bring this discordant star up to agreement with the others, but he had not observed several of the list when our measures were taken. From the six means by nights at the bottom of the table, there follows p.e. $= \pm 0.013$ mag. for the mean of all; but these values all depend upon the same mean difference of sun *minus* lamp in the blue and green in Table 3, the individual values of which run high and low together and hence must contribute ± 0.020 mag. to the final probable error. Combining the two errors, we get

TABLE 5

SUN'S MAGNITUDE, 1954

HD	STAR	Pv	SPECTRUM		MAY 25 1 92× 0 135	MAY 26 0 358	AUG. 5 0 167	AUG 10 0 167	AUG 16 0 350	SEPT. 7 0 358	MEAN
			W	Y							
166205	NPS 1	4 38	A2		−26 70	−26 77		−26 75	−26 75		−26 74
166926	NPS 4	5 82	A3		−26 67	−26 78	.. ..	−26 72	−26 76		−26 73
107192	NPS 2S	6 28	dF2				−26 69	−26 77			−26 73
107113	NPS 3S	6 35	dF4	.. ...	.. ..	.. ..	−26 70	−26 76			−26 73
114710	β Com	4 28	dG0	G0 V	−26 69	−26 77	.. ..	−26 78			−26 75
141004	λ Ser	4 43	dG0	G0 5 V	−26 72	−26 78	−26 75	−26 76			−26 75
188512	β Aql	3 71	dG8	G8 V			−26 73	−26 80	.. ..	.. ..	−26 76
217014	51 Peg	5 53	dG0	G4 V			−26 61	−26 69	−26 71	−26 65	−26 67
150680	ζ Her	2 82	dG0	G0 IV				.	−26 76		−26 76
161797	μ Her, A	3 42	dG4	G0 IV					−26 73	.. ..	−26 73
9826	50 And	4 08	dF8	F8 V						−26 72	−26 72
10307	HR 483	4 94	dG0	G2 V						−26 73	−26 73
186408	16 Cyg, A	5 96	dG2 5	G2 5 V						−26 70	−26 70
186427	16 Cyg, B	6 20	dG2 5	G4 5 V						−26 72	−26 72
Mean.					−26 70	−26 77	−26 70	−26 75	−26 74	−26 70	−26 73

± 0.024 mag., but it seems best to allow for several possible contributions of ± 0.01 from other sources and to raise the figure to ± 0.03 mag. We then have at the bottom of Table 5 our definitive result for the sun:

$$\mathrm{IPv} = -26.73 \pm 0.03 \, .$$

SYSTEMATIC ERRORS

As far as accidental errors are concerned, we think there would be no advantage in taking more observations either by day or by night, and we now consider where systematic errors may have come in. To begin with, all measures of the sun and stars in Tables 3, 4, and 5 have been reduced to outside atmosphere. The over-all average extinction correction happens to have been 0.20 mag. in the photovisual for both the sun and the stars. We doubt whether this correction could have been off as much as 10 per cent on any single date, much less in the mean of all. Also we have a feeling that the errors in day and night extinction are more likely to have the same sign than the opposite. We therefore estimate that an accumulated uncertainty of, say, ± 0.02 mag. in the extinction could be the largest single systematic error. In Table 3 the allowances for the shunt and for the MgO disks should each be correct to less than 1 per cent; the same accuracy should hold in Table 4 for the shunt and screen ratios; that for the screen has been determined many times. The adoption of the photovisual wave length at six-tenths the distance between our blue and green, or about 5400 A, is checked in part by the agreement in Table 5 of the earlier-type polar stars with those like the sun and those of later type.

The quantities in Table 4 that depend upon linear dimensions are critical, and they were determined with care. The 6-volt tungsten lamp has a ribbon filament 1.92 × 8 mm without a notch in the middle, the longer dimension being horizontal in operation. The 1.92-mm section can be determined accurately with a measuring microscope, but the 8-mm is distorted at the ends by the cylindrical glass bulb. Moreover, as is natural, the filament is measurably hotter and brighter at the ends than in the middle. Table 6 gives the results of scanning the filament in two colors along its length with a small hole at intervals of 1 mm. The Δm's indicate the amount that each region is brighter than the central one at position 4, and they show that the ends of the filament were about 15° hotter than the middle, which was near 2960° K. At the bottom of the table the mean intensities in terms of the central spot as unity were determined by graphical integration.

To evaluate the equivalent area of the whole filament in terms of the central spot, a rectangular aperture 4.179 mm long was placed over the entrance opening of the sun

TABLE 6

RELATIVE INTENSITIES OF FILAMENT

Position	Δm		Position	Δm	
	Violet	Infrared		Violet	Infrared
0	0 075	0 032	6	0 065	0 030
1	0 070	0 037	7	0 070	0 045
2	0 050	0 028	8	0 070	0 040
3	0 032	0 015			
4	0 000	0 000	All	1 0459	1 0255
5	0 032	0 025	2–6	1 0264	1 0155

reducer, giving the equivalent of an undistorted filament 4.179 mm long and 1.92 × 16.95/17.4 = 1.870 mm wide at the distance of 16.95 inches from the MgO disk of the reducer. Photometric comparisons of the 4.179-mm section with the whole filament then gave for the whole filament area, in terms of the intensity of the central spot, 16.96 mm² in the violet and 16.63 mm² in the infrared. We interpolate for photovisual and obtain

$$Pv = \mathrm{V} + 0.41(\mathrm{I} - \mathrm{V}) = 16.83\ \mathrm{mm}^2 .$$

This is the equivalent area of the whole filament used for the sun, to be compared with the pinhole apertures used for the artificial star. In the example in Table 4, the pinhole was 0.167 mm in diameter, and we have

$$\Delta m = -2.5 \log \left(\frac{16.83}{\pi \times 0.0835^2} \right) = -7.21 ,$$

which was used. The three holes and the slit in Table 5 were intercompared and checked photometrically. Since a relatively large area of the filament was behind each hole when observed as a star, no effects of diffraction came in.

For the law of inverse squares, the effective distance from the filament to the MgO disk, r = 16.95 inches (430.5 mm), was easily measured to 0.01 inch. The distance from the Crossley mirror to the artificial star at the Tauchmann telescope dome was taken from an accurate map of the mountain and, with allowance of 109 feet (33.2 m) difference in the altitude of the stations, came out as $R = 1746$ feet (532.2 m). Since we did not have the original data for this map, we resurveyed the distance with an engineering transit from a not-too-favorable base line of 256 feet (78.0 m) on the level mountain top near the main building. The result, $R = 1755$ feet (534.9 m), differing by $\frac{1}{2}$ per cent from the map, would give a change of only 0.01 mag., so we assume that the map was good enough, and we derive -15.46 mag. in Table 4 from the law of inverse squares. The atmospheric extinction was allowed for in the brightnesses of both sun and star and in the distance R.

The 31.13-mag. difference between the sun and NPS 1 in Table 4 was made up in round numbers as follows:

Sun to lamp	$5^{m}7$
Lamp to *	7 2
* to star	2 7
Inverse squares	15 5
	31 1

None of these differences put any strain on the photometer. Other stars in Table 5 run from 1.5 mag. brighter to 2.0 mag. fainter than NPS 1, a range easily taken care of. For the brightest stars a 2.4-mag. screen was used on the Crossley.

In summary, except in the extinction, we do not see where unsuspected systematic errors larger than 0.01 mag. could creep into the final result. Thus the conservative probable error of ± 0.03 mag. assigned to the sun's magnitude appears large enough to include some systematic errors as well. These conclusions are based upon observations in two colors—blue and green. The color index of the sun on any system is best determined from all six colors, to which we now turn.

SIX COLORS OF THE SUN AND STARS

In extending the work from two colors to six, we are likely to run into complications. We begin with the standard lamp and mirror data in Table 7, all shown graphically in

TABLE 7

SIX COLORS OF LAMPS AND MIRRORS

Comparison	U	V	B	G	R	I
A 5 50 v$-B$ 5 10 v	$+0^{m}02$	$-0^{m}01$	$-0^{m}01$	$0^{m}00$	$+0^{m}01$	$0^{m}00$
A 5 50 v$-F$ 2960°	+ 08	− 01	− 02	+ 01	+ 02	+ 08
A reducer$-A$ direct	00	− 03	00	+ 01	− 01	− 03
A aluminum$-A$ direct	− 07	− 04	− 03	+ 01	+ 02	− 04
A Crossley$-A$ direct	+0 41	+0 11	+0 08	−0 04	−0 05	−0 18

Figure 4. Each line of magnitudes in the table gives the measured differences between two sources, reduced to the mean of blue, green, and red. As mentioned before, all measures were made with the light falling on the same spot of the photocell.

The first line gives the difference between the standard lamp A, run at controlled 5.50 ± 0.01 volts and a second lamp, B, of the same type, which at 5.10 ± 0.01 volts was practically a duplicate of lamp A. The lamps were operated below their rated 6 volts, to get a longer life, and both were aged for several hours before the comparison was made. We also had two more of the same lamps in reserve.

The second line gives the difference between lamp A and an electric furnace run at

2960° K in a physics department laboratory in Berkeley. This comparison and its application to the stellar temperature scale will be discussed in a later paper. Let it suffice to note here that the lamp, even with its glass envelope and the deviations of +0.08 mag. in the end colors, should serve very well for a black body in comparisons with the stars.

The third line of the table gives the differences of lamp A measured first through the sun reducer and then directly in the laboratory. The two differences of -0.03 mag.

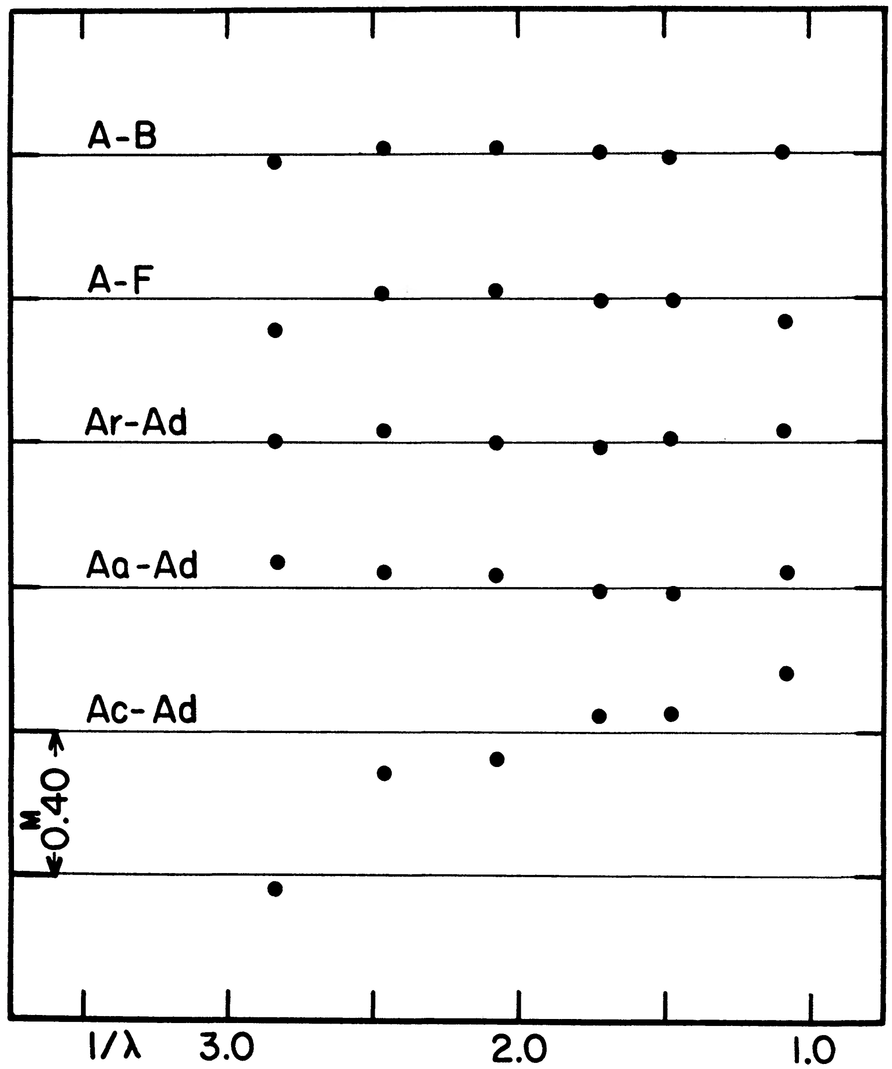

FIG. 4.—Comparison of lamps

represent practically the only effects on the quality of the light by the MgO disk, the small aluminized sphere, and the small quartz lens. These effects are surprisingly small, but that is the way they resulted. The home-made diffuse reflectors were evidently nearly enough white for our purpose. Owing to slight blemishes made in handling, both the large and the small disks were renewed in the course of the measures, with a redetermination of their brightness ratio when needed.

The fourth line gives the difference between the lamp measured first directly and then by reflection from a freshly aluminized plane mirror. The greater reflection in the short wave lengths than in the green and red is to be expected for aluminum (Strong 1943). The average reflectivity was about 89 per cent.

The last line in Table 7 gives the loss in magnitude for the Crossley combination of main mirror and Newtonian flat; these values have been corrected for horizontal extinction. The surfaces were three years old and did not seem to show excessive deterioration (Stebbins and Smith 1951). Nothing was done to the mirrors except to wash them occasionally during the present work. The effects of the Crossley mirrors on the effective wave lengths of the filters were negligible compared to the effects of different colors of the stars.

In Table 8 are the comparisons of the sun with the lamp A, also of a sample star, 51

TABLE 8

SIX COLORS OF SUN, LAMP, AND STAR

1954	Comparison	U	V	B	G	R	I
Aug. 5	Sun−lamp	$-2^{\mathrm{m}}59$	$-1^{\mathrm{m}}63$	$-0^{\mathrm{m}}81$	$+0^{\mathrm{m}}11$	$+0^{\mathrm{m}}69$	$+1^{\mathrm{m}}67$
12	Sun−lamp	−2 61	−1 64	− 84	+ 13	+ 71	+1 67
19	Sun−lamp	−2 64	−1 64	− 81	+ .11	+ 71	+1 76
Sept 5	Sun−lamp	−2 64	−1 62	− 84	+ 10	+ 74	+1 73
Mean	{Sun−lamp	−2 62	−1 63	− 82	+ 11	+ 71	+1 71
	Lamp−*	−0 03	−0 01	00	00	00	+0 01
	Sun−*	−2 65	−1 64	− 82	+ 11	+ 71	+1 72
Aug. 5	51 Peg−*	−2 53	−1 63	− 84	+ 12	+ 71	+1 57
10	51 Peg−*	−2 52	−1 58	− 82	+ 13	+ 70	+1 64
Sept. 7	51 Peg−*	−2 44	−1 57	− 80	+ 10	+ 70	+1 62
Mean	51 Peg−*	−2 50	−1 59	− 82	+ 12	+ 70	+1 61
	51 Peg−Sun	+0 15	+0 05	0 00	+0 01	−0 01	−0 11

TABLE 9

SIX COLORS OF SUN AND STARS

Star	*W*	*Y*	U	V	B	G	R	I	V−R	$(B-V)$
50 And	dF8	F8 V	−0 10	−0 13	−0 05	+0 01	+0 04	+0 01	−0 17	+0 54
β Com	dG0	G0 V	− 08	− 07	− 05	+ 03	+ 02	− 01	− 09	+ 56
λ Ser	dG0	G0 5 V	− 05	− 07	− 04	+ 02	+ 02	− 06	− 09	+ 60
HR 483	dG0	G2 V	+ 06	00	00	00	00	− 09	00	+ 63
Sun	dg1	g2 V	00	00	00	00	00	00	00	+ 63
16 Cyg, A	dG2 5	G2 5 V	+ 15	+ 04	+ 01	− 01	00	− 08	+ 04	+ 64
51 Peg	dG0	G4 V	+ 15	+ 05	00	+ 01	− 01	− 11	+ 06	+ 66
16 Cyg, B	dG2 5	G4 5 V	+0 18	+0 05	+0 01	0 00	−0 01	−0 12	+0 06	+0 68

Pegasi, with the artificial star, marked as (*). The differences "Lamp − *," or whole filament *minus* central spot, follow from the data of Table 6. We note that no artifice such as a blue glass was used to make the over-all color of the lamp more nearly equal to that of a solar-type star. The range of some 4 mag. between the ultraviolet and the infrared does not put much strain on the linear response of the photocell, and in any event the constants of such a glass would have to be determined.

In Table 9 are the results for seven stars, each treated like the sample of 51 Pegasi in Table 8. These stars were selected from those of Table 5 to form a satisfactory grouping about the spectrum and color of the sun. After the observations were completed, the list was submitted without prejudice of order to Messrs. Joy at Mount Wilson and Morgan at Yerkes, with the simple statement that the sun was bracketed somewhere in the group. Each of them kindly made an independent new spectral classification from plates on hand, with the results in Table 9 under *W* and *Y*, respectively.

The comparison of the sun with the seven stars is also shown in Figure 5. It is at once evident that the ultraviolet and infrared values run off systematically from the

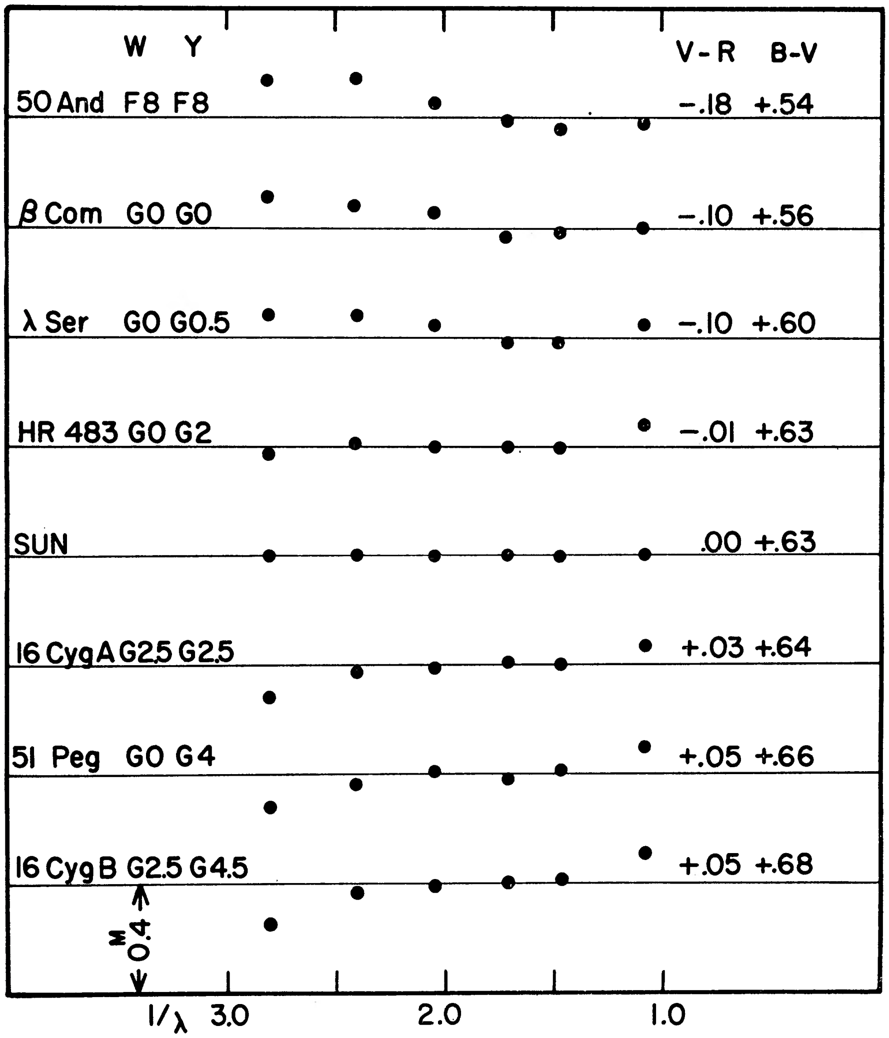

FIG 5 —Six colors of sun and stars

other colors. As it seems much more probable that these discordances are caused by instrumental effects or observational errors than by a deviation of the sun from other stars of its class, we are forced to the conclusion that, despite the care taken in the comparison, the two extreme colors of the six are not so reliable as the others. It was in these extremes that the corrections for atmospheric extinction were most uncertain, but we did not anticipate systematic errors of the size indicated. The agreement of the seven stars with one another is so good that we must attribute the discordance of the sun either to peculiarities of the sun reducer or to an undetected difference between the day and night extinctions. However, if we discard the ultraviolet and infrared, the range of the four colors from violet to red is still about double that of the International color system, and on this shortened base line the sun fits in well enough with stars of about the same spectral type.

In Table 9 the V − R is differential between each star and the sun, but the $(B - V)$ in the last column is the color index given by Johnson and Morgan (1953). We can probably do no better than to conclude by inspection of the table and of Figure 5 that the sun is of color class dg1 Mount Wilson, or g2 V Yerkes, with color index $(B - V) = +0.63$ on the Johnson-Morgan system. This last figure is the exact mean for stars of spectrum G2 V on that system (D. L. Harris, private communication). To reduce the $(B - V)$ to International color, we take the formula of Eggen (1955):

$$IC = (P - V)_E = 1.038(B - V) - 0.125\,,$$

and get $IC = +0.53$, with a probable error of scarcely more than ± 0.01 mag. This color index is exactly the one that Kuiper (1938*b*) adopted twenty years ago.

SUMMARY

We now bring together the results of the present paper on the magnitude, color index, and color class of the sun (Table 10).

TABLE 10

SUMMARY FOR THE SUN

Photovisual magnitude	IPv	−26 73±0 03
Color index	IC	+ 0 53±0 01
Photographic magnitude	IPg	−26 20
Absolute magnitude	M_{pv}	+ 4 84
Absolute magnitude	M_{pg}	+ 5 37
Color class, Mount Wilson		dg1
Color class, Yerkes		g2 V

DISCUSSION

With the innovation of the sun reducer and the photoelectric cell, we have ended not far from previous visual and photographic determinations. The magnitude −26.73 differs by only 0.01 mag. from −26.72, which Russell (1916) derived from the mean of determinations available to him. Russell's magnitude for the sun, however, was Harvard visual, and the close agreement with our figure is accidental. Likewise, his color index of +0.79 was on a different scale. After Russell, the next generally accepted magnitude of the sun has been that deduced by Kuiper (1938*a*), $IPv = -26.84$. The various results discussed by Kuiper ranged from −26.60 to −26.94, the latter from a radiometric determination by Pettit and Nicholson (1928) to which Kuiper gave a weight practically equal to all the others combined. If we omit the −26.94 as not being a particularly direct measurement and use Kuiper's weights for the others, we get −26.75. There is also a more recent value by Woolley and Gascoigne (1948), rediscussed by de Vaucouleurs (1949), $IPv = -26.91$, which was a photographic spectrophotometric measurement depending upon the single star Sirius. But it is not our purpose here to discuss the work of others; we think that the precision of our value of −26.73 is well represented by the assigned probable error of ± 0.03 mag.

While it is satisfying to have the sun's color index come out in agreement with its spectral class, we do not give too much significance to that fact because of the appreciable spread of color for stars of the same spectral type. In our independent six-color photometry (Stebbins and Kron 1956) the range of V–I for the five stars of type G0 V is from -0.22 to -0.31, and the two stars of G2 V have -0.25 and -0.27; the sun was pretty sure to fall somewhere in the range. In any event, the color and absolute magnitude of the sun places it as a normal, dwarf G-type star, which we already knew.

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REFERENCES

Eggen, O. J. 1955, *A.J.*, **60**, 65; *Lick Obs. Bull.*, No. 532.
Johnson, H. L., and Morgan, W. W. 1953, *Ap. J.*, **117**, 313.
Kuiper, G. P. 1938*a*, *Ap. J.*, **88**, 437.
———. 1938*b*, *ibid.*, p. 432.
Pettit, E., and Nicholson, S. B. 1928, *Ap. J.*, **68**, 307; *Mt. W. Contr.*, No. 369.
Stebbins, J., and Kron, G. E. 1956, *Ap. J.*, **123**, 440; *Lick Obs. Contr.*, Ser. II, No. 59.
Stebbins, J., and Smith, J. L. 1951, *Pub. A.S.P.*, **63**, 202.
Stebbins, J., and Whitford, A. E. 1945, *Ap. J.*, **102**, 318; *Mt. W. Contr.*, No. 712.
Strong, J. 1943, *Procedures in Experimental Physics* (New York: Prentice-Hall), p. 375.
Vaucouleurs, G. de. 1949, *Ann. d'ap.*, **12**, 287.
Woolley, R. v. d. R., and Gascoigne, S. C. B. 1948, *M.N.*, **108**, 491.