SIX-COLOR PHOTOMETRY OF STARS

I. THE LAW OF SPACE REDDENING FROM THE COLORS OF O AND B STARS*

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ABSTRACT

The new photoelectric photometer described makes possible measures of stars and nebulae in six spectral regions from λ 3530 to λ 10,300 A. With the 60-inch reflector useful results can be obtained for stars as faint as the ninth magnitude.

Measures (Table 3) have been obtained of the colors of 69 stars of spectrum O and B of various degrees of reddening. The scale for the difference, ultraviolet *minus* infrared, is about five times the international scale for color index.

The deviations from the 1/λ law of selective absorption (Table 6) are in the sense that the intermediate regions are fainter than they would be if the 1/λ law held from λ 3530 to λ 10,300 A. There is no reason to change the previous determination of a high ratio of total to selective absorption, $A_{pg}/E_{int} = 6$, but the numerical value of this ratio must remain uncertain in the absence of observations in the far infrared.

The law of selective absorption is found to be the same for all directions in the Galaxy, indicating that interstellar material is essentially uniform in quality everywhere.

The present series of papers is the result of an attempt to utilize the advantages of a photoelectric cell with a large range of spectral sensitivity for color measures of stars and nebulae. Much of our previous work was with a combination of a Kunz potassium-hydride cell and two filters which gave equivalent effective wave lengths at λ 4260 and λ 4770 A, a range of only 500 A; but a new cesium-oxide cell from the Western Electric Company has yielded usable data from λ 3300 to λ 12,500 A, more than eighteen times the previous range. These extreme measures were obtained with a focal-plane spectrophotometer in which the converging beam from the mirror of the 60-inch or 100-inch reflector is made parallel by a negative lens and then, after passing through a prism, is brought by another lens to a focus on the slit (of the photometer) which isolates the desired spectral region. Many measures with this instrument are on hand, but the final reductions will be delayed. In the meantime a combination of the same photocell with a series of filters has been developed which gives good measures in six spectral regions from λ 3530 to λ 10,300 A. The advantage of this arrangement is that it can be applied to extended surfaces like the nebulae, and the nebulae can be compared with stars of different types.

Plate V gives a general view of the instrument at the Newtonian focus of the 60-inch reflector. The photometer is attached by a square aluminum plate to the ring which fits to the double-slide base and is interchangeable with other attachments of the 60-inch or the 100-inch telescope. In the illustration the cell box and tank attached to a hinged plate have been swung back to the finding position. Four diaphragms, of which three are visible in the picture, are in a slide in the focal plane. Their diameters range from 1.5 mm to 19.0 mm, or from 0'.7 to 8'.6, on the 60-inch. The filter box is just inside the focal plane. A safety catch prevents opening the shutter to the cell unless the cell box is in the observing position. The window of the cell box is a positive lens, practically in

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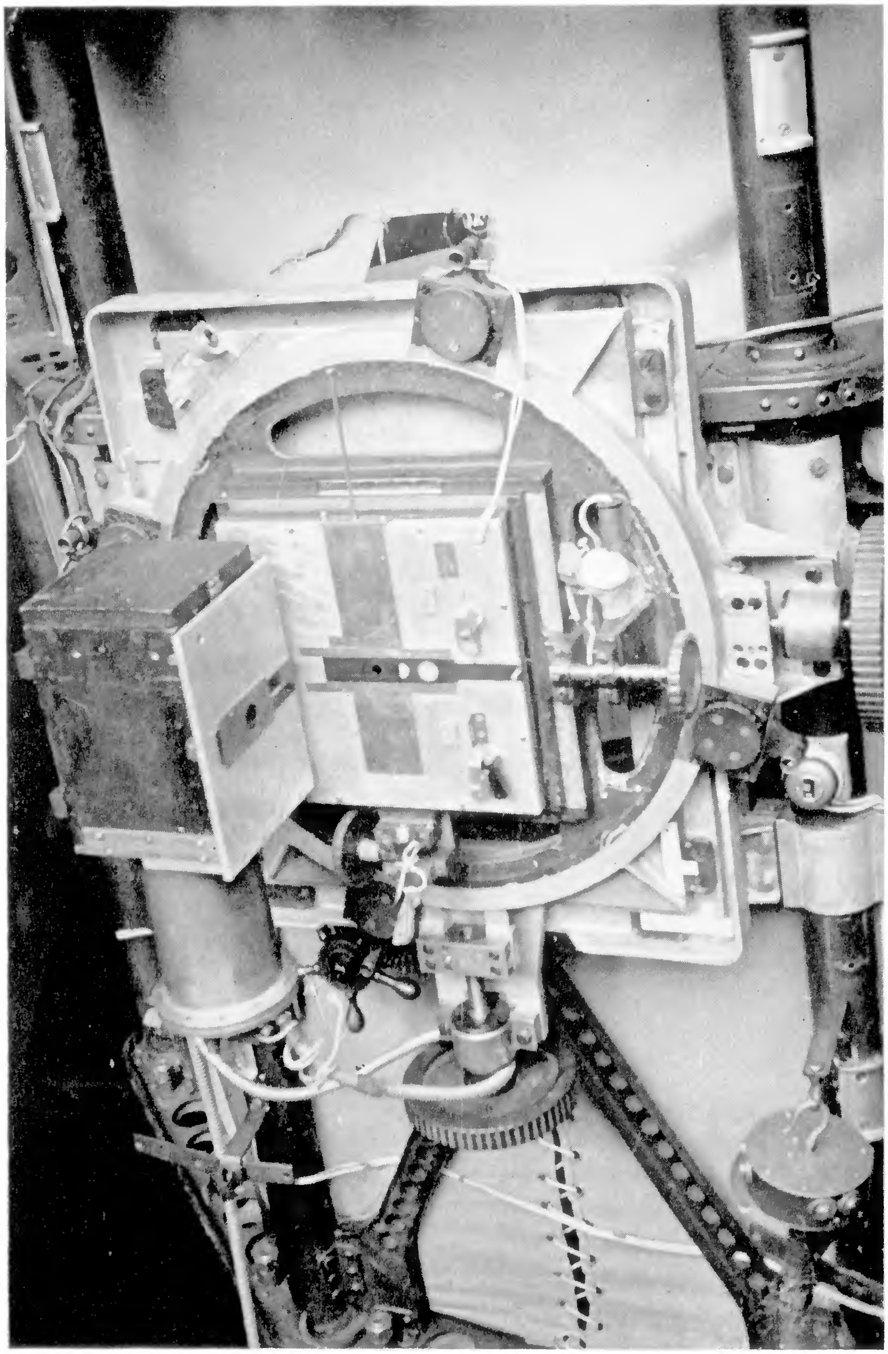
PLATE V



PHOTOMETER FOR STARS AND NEBULAE

the focal plane, which forms an image of the large mirror on the cell and hence gives the same uniform extrafocal image whether the source be a star, a nebula, or the sky background.

The arrangement of the photocell and amplifier is much like that described by Whitford.[3] The cesium-oxide cell is inclosed in a metal-covered glass tube which is sealed to a brass tank containing the amplifying tube. The combination permits the refrigeration of the cell and evacuation of the whole space containing the cell and amplifier. The refrigeration with dry ice reduces the dark current of the cell to less than 1/1000 its amount at room temperature. During an observing run the cell box is packed with dry ice about the middle of each afternoon, again half an hour before dark, and once more at midnight. A total of perhaps 2 or 3 pounds of dry ice are actually used, but during a run we aim to have available about 5–10 pounds per night. A metal-covered cable leads to the control box and galvanometer at the recorder's station in the clockroom of the 60-inch or at the foot of the north column of the 100-inch. When a large focal diaphragm is used, all the lights in the dome must be extinguished, especially red lights, to which the cell is very sensitive. We have not been troubled by diffuse sky radiation.

A summary of typical conditions of the circuit and installation on the 60-inch telescope follows:

August 13, 1942

Cell, Western Electric, Type D97087, No. X62042
Amplifying tube, Western Electric, Type 96475
Voltage on cell.................96 volts
Galvanometer sensitivity........4×10^{-10} amp/mm at 1.8 m
Resistance in circuit............3.06×10^{10} ohms
Voltage sensitivity..............63,000 mm/volt
Current sensitivity..............5.2×10^{-16} amp/mm
Current amplification...........1.3×10^{6}
Dark current....................4×10^{-15} amp.
Mean fluctuation in 5 seconds....±0.6 mm$=\pm10$ microvolts
Star, type cG0, 1 mm deflection...13.5 visual magnitude$=1.3\times10^{-11}$ lumen
Sensitivity of cell...............3.4×10^{-12} amp/mag 4.0$=$40 micro-amp/lumen

The sensitivity of the cell is referred to a cG0 star with a color temperature of about 5600° K, measured through the atmosphere. The intensity of the star at the focus of the 60-inch, in lumens of the same color, follows from the visual magnitude 0.8 for a standard candle at a distance of 1 km. We compare different cells by adopting as a standard the current from an A0 star of magnitude 1.0 with a 15-inch telescope, magnitude 4.0 with the 60-inch, or 5.0 with the 100-inch. With the present cell the over-all sensitivity is 0.3 mag. less for A0 than for cG0, and the sensitivity is considerably greater for K and M stars.

The over-all sensitivity of 3.4×10^{-12} amp/mag 4.0 for an A0 star and a dark current of 4×10^{-15} amp. are not particularly good for the photometry of faint stars, but the great range of spectral sensitivity makes this cell valuable. The Kunz potassium-hydride cell, described in the original paper by Whitford,[4] gave a response equivalent to 23×10^{-12} amp/mag 4.0 on the 60-inch, with a dark current of 10^{-16} amp. or less. We have yet to find anything superior to the Kunz cell for freedom from dark current and for great sensitivity to stars of color temperature of 10,000° K or higher. The Kunz cell has most of its sensitivity between λ 4000 and λ 5000 A, with a maximum near λ 4500 A.

The time for a full galvanometer deflection is 15 seconds. For faint stars a higher resistance of 15×10^{10} ohms increases the deflections fivefold, with times of 30 seconds. The range of intensity for linear response of the cell is something like 10 mag.; and, with

[3] John Strong and Others, *Procedures in Experimental Physics*, p. 424, New York, 1938.

[4] *Ap. J.*, **76**, 220, 1932.

TABLE 1

FILTERS

Color	Glass	mm	Glass	mm	Remarks
Ultra...........	UG1	2	....	....	
X..............	UG1	2	RG1	2	Cemented
Violet...........	BG12	3	GG13	2	
Blue............	C038	2	C430	5	
Green...........	C338	2	BG18	2	
Red............	RG1	2	C396	3	
Infra...........	C254	2	....	....	

TABLE 2

SENSITIVITY OF CELL AND FILTERS

λ	Cell	Ultra	Violet	Blue	λ	Cell	Green	Red	Infra
3200..........	....	8	....	....	5000........	64	18.6	....	....
3300..........	500	40	....	....	5200........	62	36.3	....	....
3400..........	450	50.4	....	....	5400........	63	39.1	....	....
3500..........	385	49.0	....	....	5600........	65	35.4	....	....
3600..........	280	35.2	....	....	5800........	70	29.6	....	....
3700..........	178	22.4	10.7	....	6000........	76	23.3	....	....
3800..........	150	18.0	26.4	....	6200........	84	17.1	26.9	....
3900..........	130	12.4	38.0	....	6400........	95	11.6	38.5	....
4000..........	112	4.4	44.8	....	6600........	102	7.4	40.5	....
4100..........	98	....	47.7	....	6800........	109	4.4	40.4	....
4200..........	90	....	45.0	16.2	7000........	116	2.7	38.1	....
4300..........	83	....	40.8	....	7200........	122	1.5	33.8	....
4400..........	77	....	35.1	30.5	7400........	129	0.4	29.2	....
4500..........	74	....	31.0	....	7600........	135	....	24.4	....
4600..........	72	....	25.2	37.2	7800........	139	....	20.3	....
4700..........	69	....	18.3	....	8000........	141	....	16.2	0.3
4800..........	67	....	10.4	36.7	8200........	141	....	12.8	....
4900..........	65	....	4.4	....	8400........	138	....	9.7	....
5000..........	64	....	1.0	34.0	8500........	137	....	....	3.0
5200..........	62	....	....	25.2	8600........	135	....	6.8	....
5400..........	63	....	....	17.9	8800........	130	....	4.9	....
5600..........	65	....	....	12.0	9000........	125	....	3.0	11.4
5800..........	70	....	....	7.8	9200........	118	....	1.9	....
6000..........	76	....	....	2.7	9400........	111	....	1.3	....
....	....	....	....	....	9500........	106	....	....	34.6
....	....	....	....	....	10,000........	80	....	....	41.2
....	....	....	....	....	10,500........	54	....	....	34.7
....	....	....	....	....	11,000........	32	....	....	22.1
....	....	....	....	....	11,500........	15	....	....	11.3
....	....	....	....	....	12,000........	7	....	....	5.6
....	....	....	....	....	12,500........	2.8	....	....	2.3
....	....	....	....	....	13,000........	1.9	....	....	1.6
....	....	....	....	....	13,500........	0.6	....	....	0.5
Mean λ....	....	3530	4220	4880	Mean λ...	....	5700	7190	10,300
$1/\lambda$.......	....	2.83	2.37	2.05	$1/\lambda$.......	....	1.75	1.39	0.97

the 60-inch, measures with filters can be made of stars of any type down to visual magnitude 9.0, though 7.5 is the ordinary convenient limit. For stars brighter than magnitude 4.0 a wire-gauze screen absorbing 3.0 mag., or even one absorbing 6.0 mag., is placed over the large mirror.

The filters for use with the present cell were selected, after repeated trials, to give nearly the same response in each of the six spectral regions for a solar-type star. They are Jena or Corning glasses in 1-inch squares, usually cut from 2-inch squares giving duplicate pieces of the same glass. The numbers and thicknesses are in Table 1. There are two glasses to each filter except the first and last. With so many recurring references to the individual filters we have shortened the names of these two to "Ultra" and "Infra."

Because of the strong infrared leak of ultraviolet glasses we used two filters, UG1 and the cemented combination, X = UG1 + RG1. Since the RG1 cuts out all the ultraviolet, the difference between Ultra and X is the net transmission of the ultraviolet, except for a small correction for the infrared absorption of the RG1 component of X. The transmissions of the filters at different wave lengths were determined with the cell and

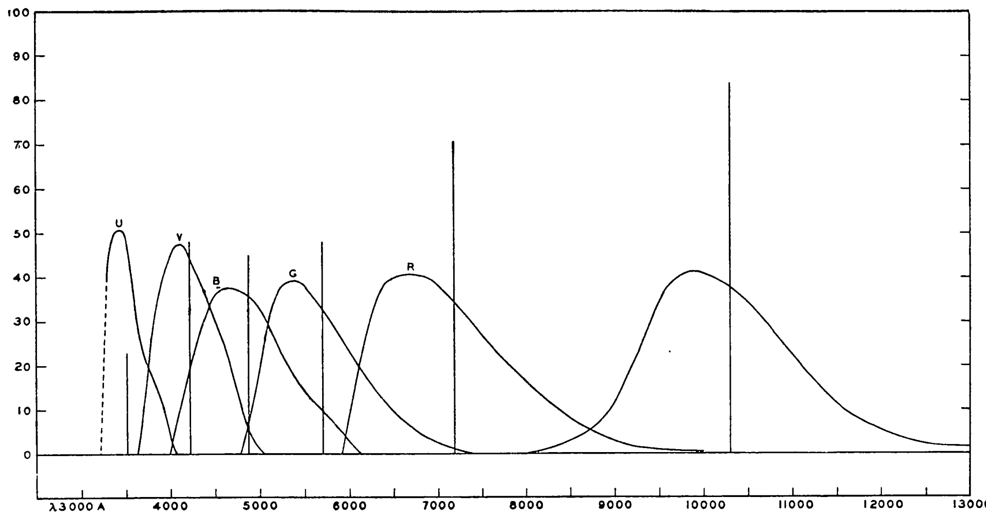


FIG. 1—Color-curves of filters

a monochromator. The color sensitivity of the cell itself was also determined in the laboratory with a monochromator, the results being reduced to constant energy for the source by simultaneous measures with a thermocouple. The values for the combination of the cell with each filter are in Table 2. Because of the high peak in the ultraviolet curve of the cell, the values for the Ultra filter have been divided by 5; otherwise the figures give the relative responses for a source of equal energy at all wave lengths.

At the bottom of Table 2 are the mean effective wave lengths for the combination of the cell with each filter. Then $1/\lambda$ is taken as the effective reciprocal wave length. The sensitivity-curves could have been plotted on a $1/\lambda$ basis and the means determined directly—there is little difference.

The data of Table 2 are shown in Figure 1. The curves overlap considerably, but that defect is inherent in the nature of filters which transmit a reasonable proportion of the original radiation. While it is true that the selected spectral regions are far from pure, the same criticism applies with even greater weight to photographic and visual receivers, on which most determinations of stellar colors have been based.

As mentioned previously, the primary object in the design of this photometer was the measurement of colors of extended faint surfaces like the nebulae. We already have satisfactory observations of about 10 extragalactic nebulae, together with a hundred or

TABLE 3

COLORS OF O AND B STARS

No.	HD	*m*	Spec.	C_1	U	V	B	G	R	I	U−I	Obs.
1.........	14633	7.3	O8	−0.30	−2.25	−1.15	−0.52	−0.03	+0.54	+1.45	−3.70	3
2.........	214680	4.91	O9s	− .23	−2.26	−1.16	− .53	− .05	+ .58	+1.33	−3.59	5
3.........	1337	6.12	O8n	− .20	−2.11	−1.07	− .46	− .05	+ .51	+1.14	−3.25	1
4.........	188209	5.51	O8s	− .17	−2.02	−0.99	− .44	− .05	+ .48	+1.09	−3.11	2
5.........	198846*	7.1	O9nn	− .13	−1.99	−0.97	− .43	− .14	......	+0.93	−2.92	1
6.........	203064	5.06	O8nn	− .16	−1.95	−0.94	− .39	− .02	+ .41	+0.92	−2.87	1
7.........	24912	4.05	O7n	− .14	−1.85	−0.89	− .36	− .03	+ .40	+0.91	−2.76	1
8.........	199579	6.01	O6	− .12	−1.77	−0.84	− .35	− .03	+ .38	+0.86	−2.63	1
9.........	209975	5.17	O9	− .12	−1.73	−0.81	− .34	− .04	+ .37	+0.81	−2.54	2
10.........	193322	5.82	O8	− .07	−1.64	−0.75	− .31	− .04	+ .35	+0.82	−2.46	1
11.........	210839	5.19	O6nf	− .04	−1.48	−0.61	− .23	− .01	+ .24	+0.56	−2.04	1
12.........	207198	5.97	O9s	+ .03	−1.31	−0.55	− .18	− .02	+ .20	+0.48	−1.79	1
13.........	207538	7.03	O9ss	+ .03	−1.22	−0.47	− .15	− .03	+ .18	+0.50	−1.72	2
14.........	192639	7.02	O7f	+ .02	−1.23	−0.49	− .16	− .02	+ .18	+0.38	−1.61	1
15.........	192281	7.47	O5	+ .07	−1.16	−0.43	− .10	− .01	+ .12	+0.37	−1.53	2
16.........	193514	7.29	O8	+ .10	−1.08	−0.35	− .07	+ .01	+ .05	+0.13	−1.21	2
1.........	5394*	2.25	B0ne	− .11	−2.21	−1.17	− .55	− .05	+ .61	+1.32	−3.53	2
2.........	204172	5.84	B0	− .19	−2.04	−1.02	− .45	− .05	+ .49	+1.16	−3.20	3
3.........	186994	7.32	*B0*	− .22	−1.99	−1.04	− .44	− .05	+ .48	+1.16	−3.15	3
4.........	10516	4.19	B0ne	− .14	−1.88	−0.91	− .36	.00	+ .36	+0.80	−2.68	2
5.........	209339	6.48	B0	− .12	−1.73	−0.85	− .35	− .03	+ .40	+0.87	−2.60	1
6.........	184915	5.04	B0n	− .14	−1.61	−0.83	− .33	− .05	+ .38	+0.92	−2.53	1
7.........	2905	4.24	cB0ea	− .09	−1.64	−0.77	− .30	− .04	+ .35	+0.73	−2.37	2
8.........	191201	7.12	B0	− .07	−1.53	−0.71	− .25	− .03	+ .28	+0.76	−2.29	1
9.........	206773	6.98	B0ne	− .05	−1.51	−0.61	− .18	− .03	+ .21	+0.48	−1.99	1
10.........	+35°3955	7.3	B0	− .04	−1.39	−0.63	− .23	− .07	+ .30	+0.55	−1.94	1
11.........	203374	6.64	B0ne	+ .01	−1.33	−0.53	− .17	− .01	+ .18	+0.43	−1.76	1
12.........	213087	5.66	cB0	+ .01	−1.19	−0.55	− .15	− .03	+ .18	+0.52	−1.71	1
13.........	192422	7.10	cB0	+ .05	−0.99	−0.37	− .06	− .01	+ .07	+0.10	−1.09	2
14.........	205196	7.36	cB0	+ .15	−0.77	−0.11	+ .02	+ .02	− .04	−0.10	−0.67	1
15.........	195592	7.15	cB0ea	+ .30	−0.14	+0.13	+ .18	+ .04	− .21	−0.62	+0.48	3
16.........	194839	7.45	cB0ea	+ .34	+0.09	+0.34	+ .30	+ .01	− .31	−0.80	+0.89	3
17.........	166734*	8.8	B0ea	+ .39	+0.09	+0.40	+ .38	+ .05	− .43	−1.06	+1.15	3
18.........	169034*	8.6	cB0	+ .45	+0.66	+0.63	+ .50	+ .05	− .55	−1.38	+2.04	2
1.........	205021	3.32	B1	− .25	−2.13	−1.17	− .54	− .07	+ .61	+1.36	−3.49	2
2.........	201819	6.40	B1n	− .18	−2.04	−1.07	− .47	− .05	+ .53	+1.24	−3.28	2
3.........	214993*	5.18	B1s	− .20	−1.97	−1.08	− .48	− .04	+ .52	+1.21	−3.18	4
4.........	218376	4.93	cB1	− .18	−1.88	−0.97	− .42	− .05	+ .47	+1.06	−2.94	2
5.........	198781	6.38	B1n	− .15	−1.67	−0.87	− .35	− .04	+ .38	+0.85	−2.52	1
6.........	24398	2.91	cB1	− .04	−1.59	−0.79	− .33	− .04	+ .37	+0.78	−2.37	1
7.........	205139	5.52	B1s	− .08	−1.57	−0.73	− .29	− .01	+ .31	+0.75	−2.32	1
7a........	173219*	7.9	B1e	− .07	−1.70	−0.76	− .26	.00	+ .27	+0.44	−2.14	1
8.........	190919	7.30	cB1	.00	−1.30	−0.61	− .17	− .02	+ .20	+0.60	−1.90	1
9.........	218342	7.46	cB1	+ .10	−1.11	−0.42	− .12	+ .03	+ .08	+0.22	−1.33	1
10.........	199216	7.13	cB1	+ .11	−0.87	−0.35	− .03	− .03	+ .06	+0.25	−1.12	1
11.........	203938	7.10	cB1	+ .13	−0.78	−0.33	− .07	− .01	+ .08	+0.15	−0.93	1
12.........	216411	7.16	cB1ea	+ .15	−0.71	−0.16	− .05	+ .05	− .01	−0.07	−0.64	2
13.........	169454	6.84	cB1e	+0.29	+0.03	+0.28	+0.30	+0.02	−0.31	−0.76	+0.79	2

TABLE 3—*Continued*

No.	HD	m	Spec.	C_1	U	V	B	G	R	I	U−I	Obs.
1.........	24760	2.96	B2	−0.20	−2.12	−1.14	−0.53	−0.07	+0.60	+1.33	−3.45	1
2.........	188252	5.70	B2s	− .18	−1.96	−1.08	− .49	− .05	+ .54	+1.24	−3.20	1
3.........	157056	3.37	B2	− .28	−1.92	−1.11	− .54	− .05	+ .60	+1.21	−3.13	1
4.........	217101	6.07	B2	− .17	−1.90	−1.05	− .50	− .05	+ .55	+1.21	−3.11	1
5.........	188439	6.15	B2nn	− .19	−1.92	−0.99	− .43	− .06	+ .49	+1.12	−3.04	1
6.........	166182	4.32	B2s	− .20	−1.77	−1.02	− .47	− .04	+ .51	+1.24	−3.01	2
7.........	224572	4.93	B2n	− .19	−1.87	−1.01	− .45	− .05	+ .50	+1.11	−2.98	1
8.........	193536	6.28	B2	− .17	−1.75	−1.03	− .49	− .06	+ .54	+1.17	−2.92	1
9.........	171871	7.39	B2s	− .14	−1.79	−1.07	− .44	− .02	+ .46	+1.08	−2.87	1
10.........	184279	6.78	B2se	− .19	−1.62	−0.85	− .37	− .05	+ .42	+0.84	−2.46	1
11.........	206165	4.87	cB2	+ .02	−1.19	−0.59	− .20	− .04	+ .25	+0.47	−1.66	1
12.........	197770	6.36	cB2	+ .03	−1.08	−0.53	− .18	− .03	+ .22	+0.44	−1.52	1
13.........	198478	4.89	cB2eα	+ .05	−0.98	−0.43	− .12	− .01	+ .12	+0.23	−1.21	2
14.........	193183	7.12	cB2	+ .08	−0.85	−0.35	− .07	− .02	+ .09	+0.25	−1.10	1
15.........	200857	7.16	cB2	+ .16	−0.52	−0.25	+ .01	− .03	+ .02	−0.02	−0.50	1
16.........	194279	7.05	cB2	+ .33	+0.20	+0.36	+ .34	+ .03	− .37	−0.92	+1.12	2
1.........	194335	5.68	B3ne	− .18	−2.30	−1.21	− .54	− .04	+ .58	+1.24	−3.54	1
2.........	214168	5.83	B3ne	− .14	−1.94	−1.06	− .45	− .04	+ .49	+1.16	−3.10	1
3.........	200120	4.86	B3ne	− .22	−2.00	−1.00	− .41	− .02	+ .43	+1.06	−3.06	2
4.........	199081	4.68	B3	− .16	−1.66	−1.06	− .50	− .03	+ .54	+1.21	−2.87	2
5.........	212455	8.0	cB3	+0.09	−0.87	−0.47	−0.11	−0.03	+0.14	+0.24	−1.11	1

NOTES TO TABLE 3

HD	
5394	γ Cassiopeiae. C_1 is discordant; color may be variable.
166734	From color presumably a c star.
169034	O'Keefe calls spectrum B2, $M = -5.2$. This is reddest of 1332 B stars.
173219	Spectrum peculiar; star omitted in Table 6.
198846	Red measure is obviously defective. Others retained, but all might be rejected.
214993	12 Lacertae, short-period variable. No change of color in three observations same night.

more stars of all spectral types for comparison. The present paper, however, deals with the colors of O and B stars which were observed more or less incidentally to the main program. It is now generally agreed that the reddened colors of early-type stars near the galactic plane are due to selective space absorption and that the interstellar material that produces this reddening is the same that produces the dark spots in the Milky Way and also obscures the extragalactic nebulae over the whole zone of low latitude. One of the current problems of astronomy is the determination of the nature of this absorbing cosmic dust. It is known that the absorption or scattering does not follow the Rayleigh law of variation, $1/\lambda^4$, but varies more nearly as $1/\lambda$. The colors of a number of O and B stars of different degrees of reddening in different parts of the sky should determine this law of space reddening and its uniformity in quality throughout the Galaxy.

In Table 3 are the colors of some 69 stars of spectrum O and B, selected from our previous list of 1332 stars.[5] The first column gives the running number for each spectral class. The second column gives the number in the *Henry Draper Catalogue;* an asterisk (*) refers to a note at the end of the table. The magnitude *m* in the third column is always visual. If given to two decimals, it is from the Harvard photometry; if to one decimal, it is a visual magnitude derived from photoelectric measures but still referred to the Harvard system.

[5] *Mt. W. Contr.*, No. 621; *Ap. J.*, **91**, 20, 1940.

The spectra in the fourth column are largely from Plaskett and Pearce,[6] but many of the cB stars and all the Be stars are from the classification of P. W. Merrill[7] and others at Mount Wilson. The spectra of many of these reddened B stars have been studied by J. A. O'Keefe;[8] where he gives an absolute magnitude of -4.0 or brighter, the star is noted as a c supergiant.

The fifth column contains the photoelectric color index C_1 taken from the list of 1332 B stars.

The sixth to eleventh columns contain the six colors of the present work, with the appropriate heading in each column. The corresponding wave lengths and reciprocal wave lengths are in Tables 2 and 4. The plus sign (+) stands for a lesser intensity. The colors of each star were reduced to outside the atmosphere and then referred on the magnitude scale to the mean of the blue, green, and red of that star. The tabular figure for each color is the difference in magnitude between that star and the mean of ten stars of the main sequence with an average spectrum of dG6. For instance, for the first star, HD 14633, the Ultra is 2.25 mag. brighter than standard, the violet is 1.15 mag. brighter, and so on. The three Δ mags. of blue, green, and red should add up to zero or to ± 0.01 mag.

TABLE 4

EXTINCTION AND PROBABLE ERRORS

Quantity	U	V	B	G	R	I	U−I
λ	3530	4220	4880	5700	7190	10,300	....
$1/\lambda$	2.83	2.37	2.05	1.75	1.39	0.97	....
a	$0^{M}530$	$0^{M}292$	$0^{M}180$	$0^{M}136$	$0^{M}058$	$0^{M}030$	....
P.E. 1 obs. $m<7.0$	± 0.016	± 0.008	± 0.009	± 0.008	± 0.008	± 0.017	± 0.027
P.E. 1 obs. $m>7.0$	± 0.053	± 0.025	± 0.020	± 0.015	± 0.018	± 0.039	± 0.073

The difference U − I in the next to last column is the color index with the extreme base line $\lambda\lambda$ 3530–10,300 A, the stars of each spectral class being arranged in the order of this difference.

The last column gives the number of observations, usually one observation per night. More than half the stars were measured on one night only, as it seemed better to increase the number of stars than to repeat all of them.

The usual approximate formula for the atmospheric extinction,

$$\text{Extinction} = a \sec z\,,$$

was considered to be sufficient. In Table 4 are the mean values of a for the different wave lengths, taken from C. G. Abbot's[9] determinations for Mount Wilson. The excellent agreement of the measures of the same stars on different nights justifies the use of a mean extinction.

In Table 4 are also the probable errors for each color for those stars in Table 3 with more than one observation each. The larger errors for the fainter stars are not due entirely to the smaller deflections; some of these stars had to be observed at larger zenith distances than average. From the way the Δ mags. are formed, the errors increase in both directions from the green; and any variation in the color gradient with the extinction will become most evident in the Ultra and Infra values. Even the maximum accidental error of $\pm$ 0.073 mag. in the difference U − I is practically negligible in comparison

[6] *Pub. Dom. Ap. Obs.*, **5**, No. 2, 1931; No. 3, 1933.

[7] *Mt. W. Contr.*, Nos. 471 and 576; *Ap. J.*, **78**, 87, 1933; **86**, 274, 1937.

[8] *Ap. J.*, **94**, 353, 1941.

[9] *The Sun*, p. 297, New York, 1929.

with the range of several magnitudes between normal and reddened B stars. We usually obtained two or more observations of the reddest stars.

Any pair of the colors gives a good color index of a star, but we have selected V−B and U − I for comparison with our previous C_1. The comparison is made graphically in Figure 2. Since there is naturally a close correlation between V − B and U − I, the graphs are a good check on C_1. Because of its discordance, one star, the variable γ Cassiopeiae, has been omitted from the diagram. There are four or five points which indicate errors up to 0.10 mag. in C_1; otherwise the agreements are satisfactory. There-

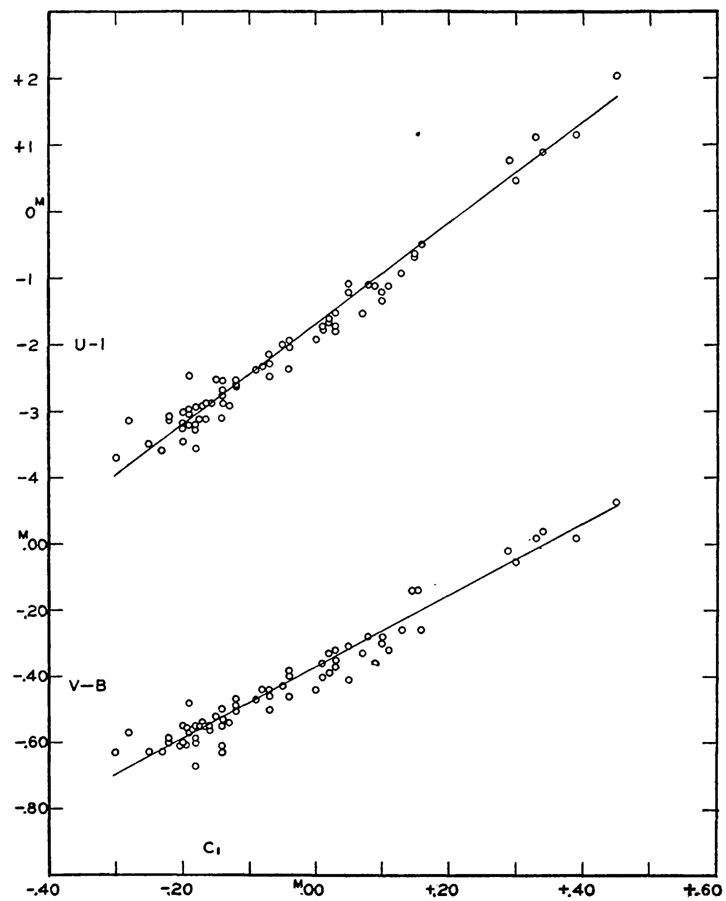


FIG. 2.—Comparison of scales

fore, assuming that there are probably no gross errors in the colors of Table 3, we proceed to derive the law of space reddening.

The method is shown in Table 5. The difference 9 − 1 is taken for each color of the first and ninth O stars of Table 3. This difference is divided by 1.16 to reduce to a standard value of 1.00 mag. for U − I. Then the computed values on the $1/\lambda$ law are interpolated linearly between $1/\lambda = 2.83$ and $1/\lambda = 0.97$, and the differences between the observed and the computed colors are in the last line of the table.

The same procedure was followed for 30 pairs of stars from Table 3; the results are in Table 6. Where there are several nearly normal stars, as in classes B2 and B3, a reddened star was compared with two or more whiter stars of about equal color. The mean deviations for each spectral class and the mean of all are at the end of Table 6. One difficulty in the use of filters is that, since the effective wave length transmitted depends upon the color of the source, a reddened star is measured effectively at a longer

TABLE 5

DIFFERENCE BETWEEN A REDDENED AND A NORMAL STAR

Quantity	U	V	B	G	R	I	U−I
1/λ	2.83	2.37	2.05	1.75	1.39	0.97	....
Difference, 9−1	+0.52	+0.34	+0.18	−0.01	−0.17	−0.64	+1.16
Difference/1.16	+0.45	+0.29	+0.16	−0.01	−0.15	−0.55	+1.00
Computed from 1/λ law	+0.45	+0.20	+0.03	−0.13	−0.32	−0.55	+1.00
Deviation from 1/λ law	0.00	+0.09	+0.13	+0.12	+0.17	0.00	....

TABLE 6

DEVIATION FROM THE 1/λ LAW

Spectrum	Difference	U	V	B	G	R	I	U−I
O	9− 1	0.00	+0.09	+0.13	+0.12	+0.17	0.00	1.16
	10− 2	.00	+ .06	+ .06	+ .04	+ .02	.00	1.13
	11− 3	.00	+ .11	+ .09	+ .09	+ .03	.00	1.21
	12− 4	.00	+ .04	+ .08	+ .06	+ .02	.00	1.32
	13− 5	.00	+ .03	+ .01	+ .03	....	.00	1.20
	14− 6	.00	+ .04	+ .03	+ .01	+ .02	.00	1.26
	15− 7	.00	+ .06	+ .07	+ .04	− .02	.00	1.23
	16− 8	.00	+ .10	+ .13	+ .12	+ .05	.00	1.42
B0	10− 1	.00	+ .07	+ .10	+ .05	+ .06	.00	1.59
	11− 2	.00	+ .10	+ .12	+ .12	+ .06	.00	1.44
	12− 3	.00	+ .03	+ .06	+ .03	+ .00	.00	1.44
	13− 4	.00	+ .03	+ .05	+ .01	+ .03	.00	1.59
	14− 5	.00	+ .13	+ .11	+ .11	+ .04	.00	1.93
	15− 6	.00	+ .08	+ .10	+ .12	+ .08	.00	3.01
	16− 7	.00	+ .06	+ .07	+ .07	+ .04	.00	3.26
	17− 8	.00	+ .10	+ .13	+ .13	+ .09	.00	3.44
	18− 9	.00	+ .02	+ .05	+ .06	+ .04	.00	4.03
B1	8− 1	.00	+ .08	+ .13	+ .09	− .01	.00	1.59
	9− 2, 3	.00	+ .12	+ .14	+ .13	+ .06	.00	1.90
	10− 4	.00	+ .04	+ .08	+ .04	− .01	.00	1.82
	11− 5	.00	+ .03	+ .04	+ .04	+ .02	.00	1.59
	12− 6	.00	+ .10	+ .07	+ .12	+ .04	.00	1.73
	13− 7	.00	+ .06	+ .10	+ .08	+ .06	.00	3.11
B2	11− 1	.00	+ .04	+ .08	+ .08	+ .05	.00	1.79
	12− 2, 3	.00	+ .07	+ .11	+ .07	+ .04	.00	1.64
	13− 4, 5	.00	+ .07	+ .10	+ .10	+ .06	.00	1.87
	14− 6, 7	.00	+ .09	+ .12	+ .09	+ .04	.00	1.90
	15− 8, 9	.00	+ .06	+ .10	+ .06	+ .05	.00	2.39
	16−10	.00	+ .08	+ .11	+ .09	+ .04	.00	3.58
B3	5− 1, 2, 3, 4	.00	+ .01	+ .06	+ .04	+ .05	.00	2.03
O	Mean	.000	+ .066	+ .075	+ .064	+ .041	.000	1.24
B0	Mean	.000	+ .076	+ .088	+ .077	+ .049	.000	2.41
B1	Mean	.000	+ .072	+ .093	+ .083	+ .027	.000	1.96
B2, B3	Mean	0.000	+0.060	+0.097	+0.076	+0.047	0.000	2.17
Mean of all		0.000	+0.067	+0.088	+0.075	+0.042	0.000	1.95
Correction for filters		.000	+ .004	+ .008	+ .003	+ .002	.000	....
Neglected decimals		0.000	−0.003	−0.001	+0.001	+0.004	0.000	....
Final deviations		0.000	+0.068	+0.095	+0.079	+0.048	0.000	....

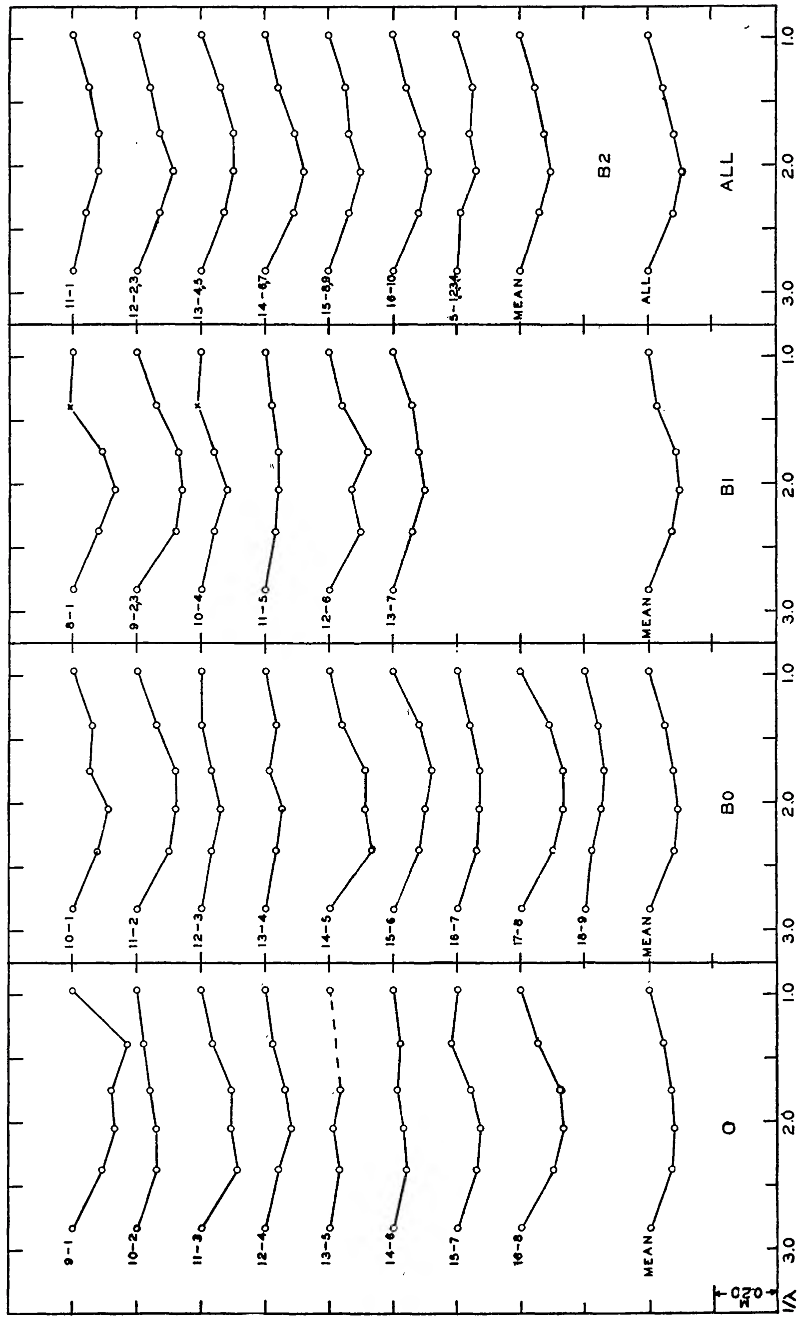


FIG. 3.—Deviations from 1/λ law of absorption

wave length than a normal star of the same type. The proper allowance for this effect is best made by a small correction to the magnitude, indicated as "Correction for filters" at the bottom of Table 6. There is also another small correction because the interpolated values on the $1/\lambda$ law were rounded off to 0.01 mag. When these two corrections are applied to the means, we have the final deviations from the $1/\lambda$ law over the range of wave length here studied.

The data of Table 6 are shown graphically in Figure 3, and a glance at the curves shows no outstanding discrepancy among these stars, which are well distributed over the sky. The procedure of basing the linear relation upon the Ultra and Infra values is purely arbitrary, but the mean results would come out about the same on any basis of linear variation with $1/\lambda$. For instance, the discordant point for the red in the first pair is due not to the red measure but to the Infra measure of the first star, HD 14633, the bluest star of all. If we had run the adopted straight lines through the red points, this Infra point would have been a high one, but it would have been counterbalanced in the mean by low Infra points in other stars. The Infra deflection for HD 14633 was only about 1 per cent of the clear deflection, the equivalent of the clear deflection from a twelfth-magnitude O star. It would be a simple matter to go back in cases like this and spend

TABLE 7

COMPARISON OF THREE STARS

HD	Spectrum	Quantity	U	V	B	G	R	I
194839	cB0	Deflection	13.1	11.8	18.5	21.7	26.9	47.5
166620	dK2	Deflection	10.2	15.2	25.4	24.8	27.0	32.6
16901	cG0	Deflection	13.9	24.7	41.7	43.2	45.7	56.1
....	cB0−dK2	Δ mag.	−0.44	+0.11	+0.18	−0.02	−0.16	−0.57
....	cB0−cG0	Δ mag.	−0.67	+0.07	+0.15	+0.01	−0.16	−0.55
....	cG0−dK2	Δ mag.	+0.23	+0.04	+0.03	−0.03	0.00	−0.02

half an hour or more in measuring the discordant color of a star, using a higher resistance which requires longer times for deflections; but we have let the results stand, assuming that most errors will be averaged out in the mean.

The deviation of the selective absorption from the $1/\lambda$ law is not a subtle phenomenon —it is conspicuous in the original galvanometer readings of every strongly reddened B star. As an illustration we give in Table 7 the deflections of three stars of about the same general color but with different spectra, a reddened B, a dwarf K, and a supergiant G star. The deflections are the original figures corrected slightly for sky background. The Δ mags. were formed from the log deflections, referred to the mean of blue, green, and red, and then differenced between the stars. The atmospheric extinction has been ignored.

The high intensities of the Ultra and Infra of the B star are conspicuous in both the deflections and the Δ mags. Also, the relative faintness of the Ultra in the cG0 star is a common effect where the other colors of a giant star almost match those of a dwarf. In the routine of observing, when a reddened B star comes along, the recorder at the galvanometer often thinks he has made a mistake of 5 or 10 whole divisions in a reading on the Ultra or Infra, but the regular check back on the deflections reassures him that it is only the effect of space reddening that he is seeing.

With the possibility of instrumental errors disposed of, the question remains whether there is a systematic selection of the so-called "reddened" B stars which makes them different from the normal or less reddened ones. The stars of all types from B to M are surprisingly like black bodies, giving nearly linear color-curves when log intensity or Δ mag. is plotted against $1/\lambda$, despite the absorbing effects of spectral lines and bands.

The exception is the lowered intensity in the Ultra caused by strong hydrogen absorption in the A stars. This effect extends to the F stars but is not noticeable in stars earlier than B5. In Table 3 it will be noticed that nearly all the B stars in the last half of each class are marked as c stars. In other words, a star must be of high luminosity to be seen at a sufficient distance through the absorbing cloud to be strongly reddened. Nevertheless, there is the same kind of absorption all the way down the list no matter how the stars are compared. We have not been able to find any systematic difference between the color-curves of stars with sharp and nebulous lines. When two early B stars are of the same general color, they yield the same intensity over the whole spectrum. This fact may be checked anywhere in the list. Moreover, the "c" designation was added to the spectra of a number of stars after they were known to be reddened.

The great sensitivity of the index U − I to a small effect of space reddening makes it difficult to find a normal O or early B star in the summer sky. On the basis of our previous color index, C_1, more than 20 of the 69 stars, or nearly one-third, have a color excess of +0.05 mag. or less; but there are only half a dozen stars with U − I within 0.20 mag. of the bluest star in each class, or fewer than 10 per cent. In fact, the only B0 star which looks normal is HD 5394, γ Cassiopeiae, a star one would scarcely choose for a standard of color. The bright Milky Way from Perseus through Cygnus down to the star clouds of Sagittarius is simply a region of general absorption when tested by the colors of distant early B stars. It is probable, however, that a number of normal B stars for standards can be found in the Orion region. We leave to further investigation whether the stars at the top of each class in our list are of extra high temperature or simply have less absorption than any others accessible to measurement.

TABLE 8

RATIOS OF SCALES

Quantity	Observed	Computed
$\frac{V-B}{C_1}$	1.09	1.13
$\frac{U-I}{C_1}$	7.59	7.52
$\frac{U-I}{V-B}$	7.05	6.67

In the course of the work on later-type stars, from A to M, a dozen cases of obvious space reddening among supergiants in low latitudes were found. The standards of comparison are more difficult to select for these stars than for the B stars. Nevertheless, it is obvious that the same law of reddening holds. There is the same excess of intensity in the Ultra and Infra for all reddened stars. In fact, all the evidence we have supports the conclusion that the selective absorption in space has the same quality everywhere.

The deviations from the $1/\lambda$ law of absorption would raise, rather than lower, the ratio of total to selective absorption which we derived in previous work on colors.[9] But before discussing that point we can take up again the relation between the previous color index C_1 and the new V − B and U − I shown in Figure 3. It is too much to expect that there will be a simple linear relation between any two pairs of colors selected for color indices, but for stars of simple spectra like the B stars, which approximate black bodies in their radiation, the different combinations of filters give results that are readily compared. If we take the slopes of the straight lines in Figure 3, neglecting the zero points, we have the ratios of scales as in Table 8. The ratio between U − I and V − B was determined independently in the same manner as the other two.

The effective wave lengths in the system C_1 are λ = 4190 and 4760, or $1/\lambda$ = 2.39 and 2.10, respectively, for a source of equal energy along the spectrum. The relative amounts of space absorption for the values of $1/\lambda$ were computed from the data at the end of Table 6. The agreement between the observed and computed ratios of the new scales to that of C_1 is in part accidental; and, since we are dealing with differences in $1/\lambda$, only about two figures are significant in the ratios. In all strictness the absorption of the optical systems of the telescopes and the energy-curves of the stars involved should be taken into account in comparing one color index with another. The colors here considered have all been reduced to outside the atmosphere.

The international scale of color index C_{int} is about 1.5 times the scale of C_1 for stars in the North Polar Sequence. Hence,

$$\frac{U-I}{C_{int}}=\frac{7.5}{1.5}=5.0\,.$$

This figure of five times the international scale is not necessarily applicable to all classes of stars, because the strong hydrogen absorption in the ultraviolet region of the A stars and the bands in the red region of the M stars introduce complications. Nevertheless, the increased leverage for color is ample to take care of many new problems for some time to come.

The final values of the observed absorption at different wave lengths and the extension to the infrared are in Table 9. The values of the absorption for U and I are taken as 1.00 mag. and 0.00 mag., respectively, and the intermediate values for the other colors are from Table 6. The absorption for I_1, $1/\lambda = 0.80$, is extrapolated from B and I, since measures with a slit spectrophotometer show that the $1/\lambda$ law holds very closely in this region out to I_1. The extrapolation on the same basis out to I_2, $1/\lambda = 0.00$, gives a reasonable upper limit for the zero point of the absorption.

Interpolations in the table for the blue and yellow of C_1, $1/\lambda = 2.39$ and 2.10, give $A_b - A_y = E_1 = 0.130$. Taking the photographic wave length as $\lambda = 4250$, $1/\lambda =$ 2.35, we have $A_{pg} - A_I = 0.813$. If the absorption in the infrared falls off between I_1 and I_2, the value of A_{pg} would lie between $0.813 + 0.106 = 0.919$ and $0.813 + 0.607 = 1.420$. Hence A_{pg}/E_1 would be between 7.1 and 10.9—say between 7 and 11.

TABLE 9

ABSORPTION AT DIFFERENT WAVE LENGTHS

Quantity	U	V	B	G	R	I	I_1	I_2
λ	3530	4220	4880	5700	7190	10,300	12,500	∞
$1/\lambda$	2.83	2.37	2.05	1.75	1.39	0.97	0.80	0.00
$A-A_I$	+1.000	+0.821	+0.676	+0.498	+0.274	0.000	−0.106	−0.607

In our previous discussion of absorption[10] from photoelectric colors we used $A_{pg}/E_1 = 9$, or, on the international scale, $A_{pg}/E_{int} = 6$; and, until the law of selective absorption is extended farther to the infrared, there seems to be no good reason to change these figures. The present work confirms the high ratio of total to selective absorption even if there is no nonselective absorption. We may note that Greenstein and Henyey[11] have concluded that the nonselective absorption is practically zero, and from other considerations they derive $A_{pg}/E_1 = 8.1 \pm 0.4$.

We are aware of no theory of the composition of the interstellar material which will help to extrapolate the value of the absorption for longer wave lengths. Even the simple $1/\lambda$ law requires *ad hoc* assumptions about the proportions of differently sized particles. The deviations from that law now give the theorist further material for study. One thing seems certain, since the law of space reddening is everywhere the same: some sort of equilibrium must have been reached, and the interstellar dust cloud is at least a semipermanent part of the Galaxy.

We are indebted to Messrs. G. M. Barthold Bouricius and Willard G. Bouricius for assistance in the observations and computations for this paper. The investigation has been supported in part by grants from the Alumni Research Fund of the University of Wisconsin and from the California Institute of Technology in connection with plans for the 200-inch reflector.

[10] *Mt. W. Contr.*, No. 617; *Ap. J.*, **90**, 213, 1939.

[11] *Ap. J.*, **93**, 327, 1941.