No. 54 INTERSTELLAR EXTINCTION IN THE GALAXY*

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ABSTRACT

Multicolor photometry, over the range of wavelength from 0.35 μ in the ultraviolet to nearly 10 μ in the infrared, has been interpreted in terms of interstellar extinction. The value of $R = A_V/E_{B-V}$ has been found to vary from 3.0 to more than 6. In addition to the high value that had previously been found for the Orion Nebula region, values of R in the neighborhood of 6 have been found for regions in Cepheus and Ara, and for the cluster NGC 2244. These variations in R plainly have serious implications regarding the distance scale and the structure of the Galaxy.

1. Introduction

One of the products of the multicolor photometric programs (Johnson and Mitchell 1962; Low and Johnson 1964; Johnson 1964) now under way at the University of Arizona has been additional and more accurate data concerning the law of interstellar extinction, especially for the infrared region of the spectrum. Earlier work by Stebbins and Whitford (1943, 1945) and Whitford (1948, 1958) has outlined the procedure for using multicolor photometry in the investigation of interstellar extinction, and has provided preliminary determinations of the law of extinction in certain regions of the sky. More recent investigations by Hallam (1959) and by Johnson and Borgman (1963) have indicated that the law of interstellar extinction is not everywhere the same; most recently (Johnson 1965), I have reported upon a very large deviation from the "normal" law in the direction of Cepheus. It is, however, evident that some investigators (Divan 1954; Rozis-Saulgeot 1956) are not in complete agreement regarding the existence of these local variations. In this publication I report the results of a more thorough investigation of this matter.

Most work on interstellar extinction has used multicolor photometry or spectrophotometry of unreddened and reddened stars as the basic observational material. Interpretations have been made by comparing the colors of unreddened and reddened stars of essentially the same spectral types, assuming that the differences in color are due to interstellar extinction. This procedure requires extrapolation to infinite wavelength (cf. Whitford 1948, 1958) for the determination of the absolute extinction. It is possible, however, to make a direct determination of the value of $R = A_v/E_{B-V}$ for distant clusters across which the reddening and extinction are variable. Two-color photometry on the *BV* system is required. This procedure has been applied by Johnson and Hiltner (1956*b*), Whitford (1958), Houck (1956), and others. Application of the data available at that time yielded a value of $R \simeq 3$ for a few regions of the sky.

2. Application of the Variable-Extinction Method

Since Whitford's (1958) paper, additional data usable for analysis by the variable-extinction method have become available. A more accurate determination of the absolute magnitudes corresponding to the spectral classifications on the MK system has been

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made by Blaauw (1963). The combination of photometric and spectroscopic data for several regions of the sky leads to interesting new results.

Our first application of the variable-extinction method is made for the region of the Double Cluster, h and χ Persei. The photometric and spectroscopic data have been published by Johnson and Morgan (1955) and Johnson and Hiltner (1956*a*). For this analysis, we compute the apparent distance moduli, $V - M_v$, from the observed V-magnitudes and the spectroscopic absolute visual magnitudes of Blaauw (1963). We also compute the color excesses, E_{B-V}, from the observed values of $B - V$ and the intrinsic colors tabulated by Johnson (1963). From these data Figure 1 is constructed. A distinct correlation between apparent distance modulus and color excess

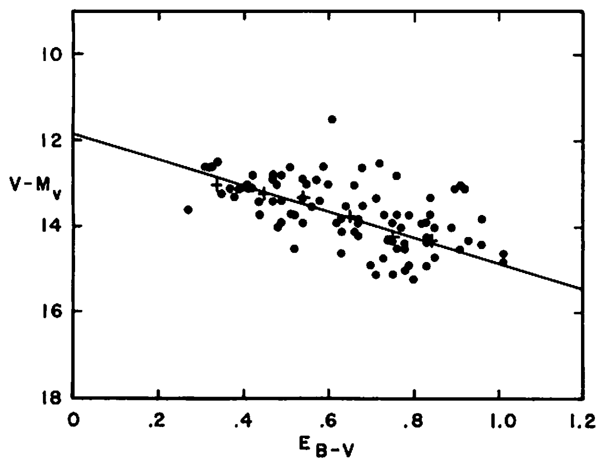

Fig. 1 $V - M_v$ versus E_{B-V} for the Double Cluster, h and χ Persei. The crosses designate mean values of $V - M_v$ for equal intervals of E_{B-V}.

is evident in this figure and the line represents $R = 3.0$, in agreement with earlier determinations (Johnson and Hiltner 1956*b*; Whitford 1958) from the same observational material.

Other regions where application of the variable-extinction method can be made are III Cep (Blaauw, Hiltner, and Johnson 1959) and I Ara (Whiteoak 1963). The diagrams for these two regions, constructed in exactly the same manner as Figure 1, are shown in Figures 2 and 3.

In some cases, for which MK spectral types are not available but where identification of an "unevolved" cluster main sequence is possible, we can use three-color *UBV* photometry for the derivation of intrinsic colors and (assuming all stars to lie on the zero-age main sequence) absolute visual magnitudes. Figures 4, 5, and 6 show diagrams constructed from such data for the Belt and Sword regions of Orion (Sharpless 1952, 1954, 1962) and the cluster NGC 2244 (Johnson 1962*c*). The intrinsic-color determinations follow Johnson (1958, 1963) and the zero-age main sequence is that of Johnson (1963). Construction of Figures 1–6 is dependent upon the assumption that the stars in the cluster or association are all at the same distance from the Earth.

From the diagrams of Figures 1–6, we derive the values of $R = A_v/E_{B-V}$ that are listed in Table 1. The value for the Double Cluster is the "normal"

TABLE 1

R FROM THE VARIABLE-EXTINCTION METHOD

REGION	$R = A_v/E_{B-V}$
Double Cluster	3.0
III Cep	5.4
I Ara	6.6
Orion (Belt region)	4.8
Orion (Sword region)	5.7
NGC 2244	6.0

value of 3. The value of R (5.7) for the Orion Sword region is in excellent agreement with that (6) found earlier by Sharpless (1952), who used MK spectral types and *BV* photometry. These redeterminations have not modified earlier results for these regions. The determinations for the other four regions are new, and all yield values of R greater than 3. In this connection, we note that Borgman and Blaauw (1964) have remarked that their analysis of Borgman's seven-color photometry indicates a value of

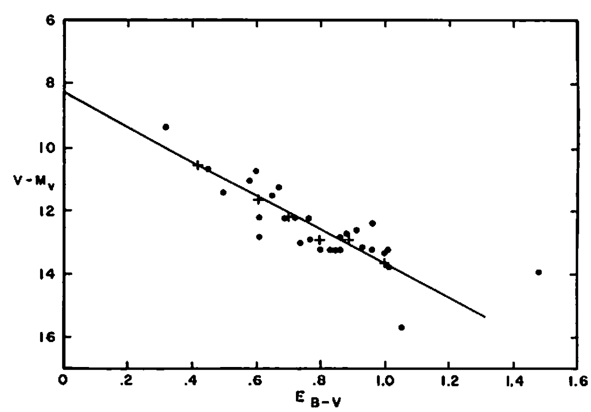

Fig. 2 $V - M_v$ versus E_{B-V} for the association, III Cep. The crosses designate mean values of $V - M_v$ for equal intervals of E_{B-V}.

R for III Cep much greater than the "normal" one. Houck (1956) obtained $R = 3.0$ for the I Cru association.

The interpretation of the I Ara association that is made here differs from that of Whiteoak (1963), who assumed $R = 3.0$ and found that the stars of the association are spread out over several thousand parsecs in the line of sight. Thus, the assumption that $R = 3.0$ for the Ara region resulted in the interpretation that the stars are distributed in a long, thin "cigar" pointed at the Earth; it seems to me that the interpretation of Figure 3, which assumes that the stars are all at essentially the same distance from the Earth, is preferable.

There is evidence (Hallam 1959; Sharpless 1962, 1963; Johnson and Borgman 1963) that R varies with distance from, and is largest in the immediate vicinity of, the Orion Trapesium. The stars plotted in Figure 5 lie at various distances from the Trapesium and none is a member of the Trapesium or is in its immediate vicinity; thus, we expect that the value of R for the Trapesium and its immediate vicinity is greater than that from Figure 5. A similar argument can probably be made for the Orion Belt region, Figure 4.

3. *Application of the Color-Difference Method*

Most of the values of R listed in Table 1 are larger than 3.0, the number which has usually been

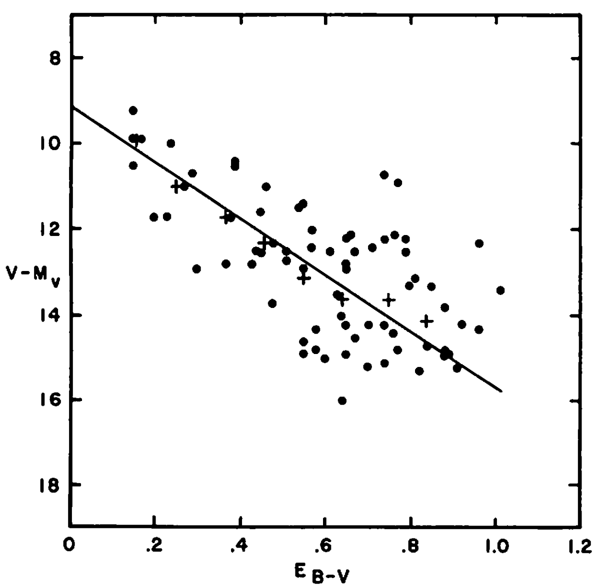

Fig. 3 $V - M_v$ versus E_{B-V} for the association, I Ara. The crosses designate mean values of $V - M_v$ for equal intervals of E_{B-V}.

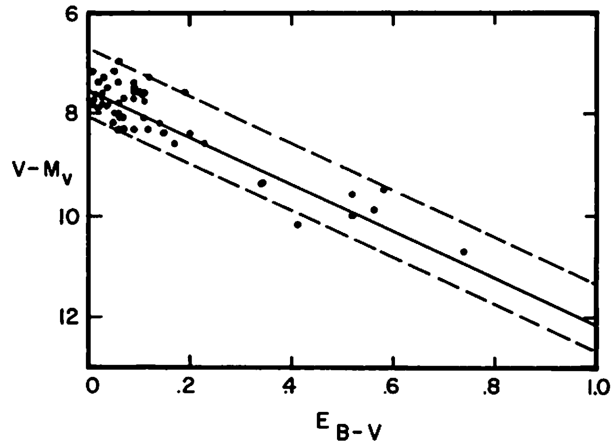

Fig. 4 $V - M_v$ versus E_{B-V} for the Orion Belt region.

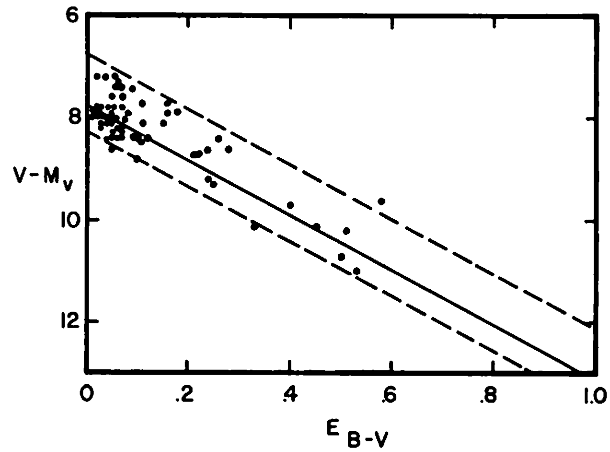

Fig. 5 $V - M_v$ versus E_{B-V} for the Orion Sword region.

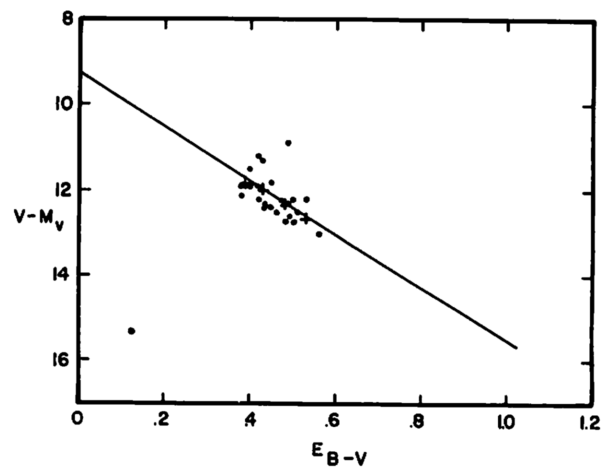

Fig. 6 $V - M_v$ versus E_{B-V} for the cluster, NGC 2244. The crosses designate mean values of $V - M_v$ for equal intervals of E_{B-V}.

accepted as "normal." For all of these regions, except I Ara, we now have multicolor data which can be used to investigate the interstellar extinction by the color-difference method. The relevant data that have so far been collected in our photometric programs are listed in Table 2, the columns of which contain (1) the number of the star in the table; (2) the *Henry Draper Catalogue* number; (3) the constellation name, if any; if none, the number in the *Bright Star Catalogue;* (4) the MK spectral type; the remaining columns give the photometric data on the system defined by Johnson (1964).

The data in Table 2, plus data published by Johnson (1964) and other data now being prepared for publication, have been used to derive the intrinsic colors listed in Table 3. The procedures used in this derivation are essentially similar to those of Johnson and Borgman (1963) and Johnson (1964); where the new results differ from the earlier ones, the data of Table 3 are preferable.

We now select stars from Table 2 and compute the color excesses, using the intrinsic colors from Table 3. The results of these computations for thirty-eight stars are given in Table 4; the stars are grouped to provide "Regional Means." The columns of Table 4 contain (1) the region of the sky; (2) the approximate mean galactic longitude of the region (new system; Blaauw, Gum, Pawsey, and Westerhout 1960); (3) the number of stars in the mean; the remaining columns give the color-excess ratios (the color excess normalized to $E_{B-V} = 1.00$). The intrinsic colors of Table 3 are sufficient for these computations, except for two stars, Nos. 89 (μ Cep) and 96 (BS 8752). They are the only stars used whose spectral types are later than A2. For No. 89, the comparison star is the mean of Nos. 49 (α Ori), 68 (α Sco, excluding $U-V$), and 75 (δ^2 Lyr); for No. 96, the intrinsic colors from Johnson (1964, Table 4). No. 96 = BS 8752 is fainter and redder than it was in 1951 (Johnson and Morgan 1953), suggesting that its spectral type may now be later than G0 Ib; accordingly, we use G2 I as the comparison type. Other intrinsic-color data could perhaps be used legitimately for these two stars, but the *shapes* of the derived extinction curves are essentially independent of such choices, over a rather wide range.

Data are included in Table 4 for three regions, Sco-Oph, Vulpecula, and Cygnus, for which variable-extinction determinations are not listed in Table 1. Johnson and Hiltner (1956*b*) found, however, that the value of R in Cygnus cannot be large compared to 3, by an approximate application of the variable-extinction method to the region of Cygnus.

Examination of the data in Table 4 shows that the extinction in the two Perseus regions is essentially the same. In the Sco-Oph, Vulpecula, and Cygnus regions the extinction is, likewise, essentially the same, although different from that in Perseus. Accordingly, we combine these data into two regions, called "Perseus" and "Cygnus."

Combinations of the data of Tables 1 and 4, plotted in the Whitford manner, are shown in Figures 7–11. It is plain from these diagrams that the values of $R = A_v/E_{B-V}$ obtained from extrapolation of the color-difference data to $1/\lambda = 0$ are in excellent agreement with the values of R obtained for the same regions by the variable-extinction method. The only significant exception is for the Orion Sword region (Fig. 10), where the value of R obtained from the extrapolation of the photometric data is about 8, compared with 6 obtained from the variable-extinction method. However, both determinations are relatively weak and, furthermore, as discussed above, there is reason to suppose that the true value of R for the Trapesium region (to which the photometric data apply) is greater than 6. We conclude that, within the accuracy of the data, the two methods of determining R are in agreement for all cases where the comparison has been made.

Many of the diagrams shown in Figures 7–11 indicate interstellar-extinction curves that differ greatly from that which has often been considered to be "normal," i.e., like the curve of Figure 7. The abnormal character of the curve for the Orion Nebula region was found earlier by Baade and Minkowski (1937), Stebbins and Whitford (1945), Stebbins and Kron (1956), and Hallam (1959). Hallam also noticed a deviation for NGC 2244.

4. The Regional Extinction Curves

Since the curves of Figures 7–11 have been drawn to $1/\lambda = 0$ (except for the Orion Sword region, Fig. 10), we invert them and compute the actual interstellar-extinction curves for the several regions. These data, normalized to $A_v = 1.00$ mag, are tabulated in Table 5 and plotted in Figure 12. In order to provide such data for the interesting Cygnus region, for which many photometric data are available, we extrapolate the color-difference curve to $1/\lambda = 0$, as indicated in Figure 13. This extrapolation accords with the tentative indication of R by Johnson and Hiltner (1956*b*).

The large variations in the law of interstellar extinction among the several celestial regions are

TABLE 2

The Observational Data

	HD	Name	Sp	V	U-V	B-V	V-R	V-I	V-J	V-K	V-L	V-M	V-N
1	886	γ Peg	B2 IV	2.84	-1.10	- .23	- .07	- .25	- .49	- .60	----	----	----
2	2905	κ Cas	B1 Ia	4.16	- .67	+ .13	+ .14	+ .20	+ .16	+ .24	+ .23	----	----
3	10516	φ Per	B2pe	4.06	- .97	- .04	+ .17	+ .19	+ .22	+ .70	+1.20	+2.41	----
4	12533	γ And	K3 II	2.10	+2.13	+1.21	+ .94	+1.63	+2.06	+2.89	+2.95	+2.70	----
5	12953	BS 618	A1 Ia	5.70	+ .60	+ .60	+ .61	+1.11	+1.42	+1.80	----	----	----
6	14134		B3 Ia	6.55	+ .08	+ .45	+ .52	+ .87	+ .94	+1.09	----	----	----
7	14142		M2 Iab	8.45	+4.95	+2.33	+1.87	+3.51	+4.54	+5.79	----	----	----
8	14143		B2 Ia	6.66	+ .05	+ .50	+ .55	+ .92	+1.08	+1.32	----	----	----
9	14270		M3 Iab	7.84	+4.88	+2.28	+1.90	+3.55	+4.56	+5.85	+6.19	----	----
10	14322		B8 Ib	6.86	- .03	+ .31	+ .41	+ .65	+ .76	+ .97	+ .97:	----	----
11	14330		M1 Iab	7.96	+4.80	+2.25	+1.75	+3.24	+4.21	+5.41	+5.78	----	----
12	14404		M2 Ib	8.12	+4.90	+2.30	+1.88	+3.46	+4.49	+5.76	----	----	----
13	14433		A1 Ia	6.40	+ .59	+ .56	+ .60	+1.06	+1.24	+1.51	+1.63	----	----
14	14535		A2 Iap?	7.47	+ .83	+ .70	+ .73	+1.31	+1.58	+2.01	+2.10	----	----
15	----	BD+56°595	M0 Iab	8.13	+4.70	+2.25	+1.68	+3.14	+4.16	+5.37	+5.78	----	----
16	14580		M0 Iab	8.42	+4.92	+2.30	+1.76	+3.23	+4.17	+5.40	+5.73	----	----
17	14818	BS 696	B2 Ia	6.30	- .32	+ .30	+ .39	+ .57	+ .62	+ .78	+ .90	----	----
18	14826		M2 Iab	8.24	+4.76	+2.32	+2.16	+3.92	+4.93	+6.28	----	----	----
19	15570		O5f	8.11	+ .29	+ .69	+ .68	+1.24	+1.55	+1.66	----	----	----
20	17506	η Per	K3 Ib	3.79	+3.60	+1.70	+1.23	+2.12	+2.70	+3.64	----	----	----
21	17520		O8 V	8.26	- .36	+ .32	+ .30	+ .53	+ .61:	+ .75	----	----	----
22	20902	α Per	F5 Ib	1.80	+ .88	+ .48	+ .45	+ .78	+ .92	+1.24	+1.26	+1.30:	+1.30:
23	21291	BS 1035	B9 Ia	4.21	+ .17	+ .41	+ .37	+ .75	+1.01	+1.25	----	----	----
24	21389	BS 1040	A0 Ia	4.55	+ .46	+ .56	+ .51	+1.01	+1.30	+1.65	+1.75	----	----
25	22928	δ Per	B5 III	3.03	- .62	- .12	+ .04	- .07	- .22	- .33	----	----	----
26	23260	η Tau	B7 III	2.86	- .44	- .10	+ .02	- .01	- .07	- .10	----	----	----
27	24398	ζ Per	B1 Ib	2.85	- .67	+ .11	+ .15	+ .24	+ .21	+ .20	+ .20	----	----
28	24760	ε Per	B0.5 V	2.89	-1.18	- .18	- .04	- .20	- .48	- .61	----	----	----
29	24912	ξ Per	O7	4.05	- .91	+ .01	+ .14	+ .14	+ .11	+ .09	+ .09	----	----
30	26630	μ Per	G0 Ib	4.14	+1.59	+ .95	+ .78	+1.34	+1.64	+2.19	----	----	----

Table 2 continued

	HD	Name	Sp	V	U-V	B-V	V-R	V-I	V-J	V-K	V-L	V-M	V-N
31	31398	ι Aur	K3 II	2.68	+3.31	+1.53	+1.07	+1.89	+2.38	+3.29	+3.47	+3.14	+3.88
32	32630	η Aur	B3 V	3.17	- .83	- .17	- .04	- .22	- .41	- .56	----	----	----
33	34085	β Ori	B8 Ia	.15	- .69	- .03	+ .03	.00	- .07	- .05	- .09	----	+ .01
34	35411	η Ori	B0.5 V	3.32	-1.09	- .17	- .08	- .29	- .43	- .58	----	----	----
35	35468	γ Ori	B2 III	1.64	-1.10	- .23	- .10	- .32	- .54	- .70	- .70	----	----
36	35497	β Tau	B7 III	1.66	- .62	- .13	.00	- .10	- .29	- .38	----	----	----
37	36389	119 Tau	M2 Ib	4.35	+4.27	+2.06	+1.75	+3.20	+4.04	+5.21	+5.59	----	----
38	36486	δ Ori	O9.5 II	2.20	-1.27	- .21	- .08	- .30	- .53	- .67	- .54	----	----
39	36512	υ Ori	B0 V	4.63	-1.33	- .26	- .08	- .33	- .65	- .83	----	----	----
40	36673	α Lep	F0 Ib	2.58	+ .47	+ .19	+ .22	+ .43	+ .54	+ .70	----	----	----
41	36861	λ Ori	O8	3.39	-1.18	- .18	- .03	- .19	- .38	- .53	----	----	----
42	37020-3	Trapesium	----	4.58	- .81	+ .05	+ .22	+ .43	+ .47	+ .86	+1.28	----	----
43	37041	θ^2 Ori	O9.5 Vp	5.06	-1.02	- .08	+ .15	+ .16	+ .04	+ .12	+ .79	----	----
44	37042		B1 V	6.38	-1.01	- .09	+ .16	+ .12	- .06	- .05	----	----	----
45	37043	ι Ori	O9 III	2.77	-1.29	- .23	- .07	- .25	- .51	- .71	- .66	----	----
46	37128	ε Ori	B0 Ia	1.70	-1.23	- .19	- .08	- .26	- .38	- .49	- .43	----	----
47	37742	ζ Ori	O9.5 Ia	1.74	-1.26	- .21	- .04	- .25	- .45	- .58	- .56	----	----
48	38771	κ Ori	B0.5 Ia	2.06	-1.20	- .18	- .01	- .18	- .41	- .53	- .57	----	----
49*	39801	α Ori	M2 Iab	.42	+3.96	+1.85	+1.64	+2.92	+3.42	+4.42	+4.72	+4.44	+5.09
50	41117	χ^2 Ori	B2 Ia	4.63	- .39	+ .29	+ .32	+ .54	+ .60	+ .77	----	----	----
51	46106		B0.5 V	7.91	- .60	+ .14	+ .17	+ .27	+ .46	+ .51	+ .83	----	----
52	46150		O6	6.80	- .70	+ .12	+ .24	+ .34	+ .30	+ .39	+ .77:	----	----
53	46223		O5	7.31	- .55	+ .22	+ .33	+ .49	+ .46	+ .70	+1.18	----	----
54	47839	15 Mon	O7	4.66	-1.31	- .24	- .08	- .30	- .64:	- .68:	----	----	----
55	53138	o^2 CMa	B3 Ia	3.01	- .95	- .11	+ .01	- .08	- .20	- .24	----	----	----
56	66811	ζ Pup	O5f	2.26	-1.39	- .28	- .10	- .32	- .50	- .67	----	----	----
57	87901	α Leo	B7 V	1.35	- .47	- .12	- .01	- .11	- .21	- .29	- .24	+ .23	+1.39
58	91316	ρ Leo	B1 Ib	3.85	-1.09	- .13	- .04	- .21	- .34	- .49	- .36:	----	----
59	106625	γ Crv	B8 III	2.59	- .45	- .10	- .02	- .12	- .16	- .23	----	----	----
60	108767	δ Crv	B9.5 Vn	2.94	- .14	- .05	- .05	- .09	- .06	- .13	----	----	----

Table 2 continued

	HD	Name	Sp	V	U-V	B-V	V-R	V-I	V-J	V-K	V-L	V-M	V-N
61	116658	α Vir	B1 V	.96	-1.17	- .23	- .08	- .31	- .55	- .73	- .69	----	----
62	120315	η UMa	B3 V	1.86	- .86	- .19	- .09	- .28	- .36	- .49	- .44	----	----
63	135742	β Lib	B8 V	2.61	- .48	- .11	- .04	- .13	- .23	- .30	----	----	----
64	143275	δ Sco	B0 V	2.33	-1.01	- .11	- .01	- .15	- .22	- .49	----	----	----
65	144217-8	β Sco AB	B0.5V+B2 V	2.55	- .90	- .08	- .03	- .10	- .14	- .23	- .01:	----	----
66	147165	σ Sco	B1 III	2.88	- .56	+ .14	+ .19	+ .31	+ .36	+ .44	----	----	----
67	147394	τ Her	B5 IV	3.89	- .71	- .15	- .10	- .27	- .33	- .49	- .43	----	----
68	148478-9	α Sco	M1 Iab+B	.97	+3.10	+1.80	+1.59	+2.80	+3.37	+4.50	+4.81	----	+5.03
69	149757	ζ Oph	O9.5 V	2.56	- .84	+ .02	+ .10	+ .07	- .03	- .08	- .06	----	----
70	155763	ζ Dra	B6 III	3.17	- .53	- .11	- .06	- .18	- .23	- .31	----	----	----
71	163800		O8	7.02	- .39	+ .30	+ .44	+ .61	+ .64	+ .60	----	----	----
72	166734		O8f	8.42	+ .94	+1.07	+1.09	+1.95	+2.43	+3.01	+3.42:	----	----
73	167971		O8f	7.54	+ .44	+ .76	+ .86	+1.47	+1.83	+2.28	+2.59:	----	----
74	172167	α Lyr	A0 V	.03	.00	.00	- .04	- .06	.00	+ .01	+ .07	+ .07	+ .04
75	175588	δ² Lyr	M4 II	4.30	+3.32	+1.67	+1.78	+3.41	+4.33	+5.47	+5.70	----	+5.45
76	180809	θ Lyr	K0 II	4.37	+1.45	+1.25	+ .87	+1.46	+2.00	+2.68	+2.82	----	----
77	183143		B7 Ia	6.86	+1.39	+1.22	+1.12	+2.07	+2.73	+3.38	+3.97	----	----
78	186791	γ Aql	K3 II	2.73	+3.21	+1.53	+1.08	+1.83	+2.41	+3.29	+3.49	----	----
79	190603	BS 7678	B1.5 Ia	5.65	+ .07	+ .53	+ .53	+ .93	+1.15	+1.54	----	----	----
80	192876	α¹ Cap	G3 Ib	4.26	+1.88	+1.08	+ .78	+1.30	+1.71	+2.32	+2.47	----	----
81	193237	P Cyg	P Cyg	4.81	- .16	+ .41	+ .54	+ .80	+1.01	+1.49	+1.92	----	----
82	194093	γ Cyg	F8 Ib	2.23	+1.21	+ .67	+ .49	+ .83	+1.07	+1.49	+1.53	----	----
83	195592		O9.5 Ia	7.08	+ .67	+ .87	+ .79	+1.48	+1.98	+2.44	----	----	----
84	195593	44 Cyg	F5 Iab	6.19	+1.74	+1.00	+ .86	+1.55	+2.07	+2.69	+2.94	----	----
85	197345	α Cyg	A2 Ia	1.26	- .14	+ .09	+ .11	+ .21	+ .24	+ .36	+ .50	----	----
86	200905	ξ Cyg	K5 Ib	3.70	+3.45	+1.65	+1.20	+2.10	+2.79	+3.79	+4.01	----	----
87	202109	ζ Cyg	G8 II	3.20	+1.75	+ .99	+ .69	+1.18	+1.54	+2.10	+2.21	----	----
88	202850	σ Cyg	B9 Iab	4.23	- .27	+ .12	+ .15	+ .29	+ .28	+ .45	----	----	----
89	206165	9 Cep	B2 Ib	4.74	- .23	+ .30	+ .31	+ .49	+ .37	+ .59	+ .77	----	----
90*	206936	μ Cep	M2 Ia	4.17	+4.71	+2.26	+2.10	+3.86	+4.69	+5.82	+6.22	+6.20	+7.45

Table 2 continued

	HD	Name	Sp	V	U-V	B-V	V-R	V-I	V-J	V-K	V-L	V-M	V-N
91	207198	BS 8327	09 II	5.94	- .33	+ .31	+ .28	+ .45	+ .55	+ .60	----	----	----
92	207260	ν Cep	A2 Ia	4.29	+ .63	+ .51	+ .50	+ .94	+1.14	+1.43	+1.59	----	----
93	209750	α Aqr	G2 Ib	2.92	+1.77	+ .98	+ .66	+1.13	+1.43	+1.96	----	----	----
94	210839	λ Cep	06f	5.04	- .49	+ .24	+ .28	+ .43	+ .41	+ .46	+ .69.	----	----
95	214680	10 Lac	09 V	4.88	-1.24	- .20	- .08	- .29	- .53	- .67	- .62	----	----
96*	217476	BS 8752	G0 Ia	5.13	+2.88	+1.55	+1.17	+2.02	+2.61	+3.33	+3.59	----	+4.18
						Clusters							
97*	NGC 2024	No. 1	0	12.17	+1.70	+1.41	+1.80	+3.46	+4.79	+6.24	+7.09	----	----
98*	NGC 6530	No. 7	05	5.97	- .90	.00	+ .25	+ .27	+ .18	+ .11	----	----	----
99*	NGC "	No. 65	BOnne	7.46	- .69	+ .21	----	----	+ .71	+ .85	----	----	----
100*	NGC 6611	No. 1	0	8.25	- .13	+ .47	+ .63	+1.04	+1.27	+1.62	----	----	----
101*	NGC 6910	No. 3	05	8.50	+ .71	+ .90	+ .87	+1.59	+2.07	+2.45	----	----	----
102*	VI Cyg	No. 9	05f	10.77	+2.64	+1.90	+1.82	+3.08	+4.25	+5.33	+6.29	----	----
103*	" "	No. 10	09 Ia	9.86	+1.89	+1.50	+1.44	+2.60	+3.38	+4.19	----	----	----
104*	" "	No. 12	B8 Ia	11.48	+5.72	+3.22	+3.22	+5.54	+7.16	+8.82	+9.54	----	----

*Notes:

No. 49, α Ori. Variable star; data for J. D. 24238400.0

No. 90, μ Cep. Variable star; data for J. D. 24238300.0

No. 96, BS 8752. Variable star; data for J. D. 24238300.0

No. 97. Identification chart by Johnson and Mendoza (1963).

Nos. 98-99. Identification chart by Walker (1957). UBV data for No. 99 from Walker.

Nos. 100-101. Identification charts by Hoag, et al (1961).

Nos. 102-103. Identification chart by Johnson and Morgan (1954).

No. 104. Identification chart by Morgan, Johnson, and Roman (1954).

TABLE 3

The Intrinsic Colors of Early-Type Stars

Luminosity Classes III, IV and V

Sp	U-V	B-V	V-R	V-I	V-J	V-K	V-L
05-7	-1.46	- .32	- .15	- .43	- .73	- .94	- .92
08-9	-1.44	- .31	- .15	- .43	- .73	- .94	- .92
09.5	-1.40	- .30	- .14	- .42	- .73	- .94	- .92
B0	-1.38	- .30	- .13	- .41	- .70	- .93	- .91
B0.5	-1.29	- .28	- .12	- .39	- .66	- .90	- .88
B1	-1.19	- .26	- .11	- .36	- .62	- .83	- .81
B2	-1.10	- .24	- .10	- .32	- .53	- .71	- .69
B3	- .91	- .20	- .08	- .27	- .44	- .59	- .57
B5	- .72	- .16	- .06	- .22	- .36	- .47	- .45
B6	- .63	- .14	- .06	- .19	- .31	- .41	- .39
B7	- .54	- .12	- .05	- .17	- .27	- .35	- .33
B8	- .39	- .09	- .03	- .12	- .18	- .24	- .22
B9	- .25	- .06	- .02	- .07	- .09	- .12	- .10
A0	.00	.00	.00	- .02	- .02	.00	+ .02

Luminosity Classes Ia and Ib

	Ia	Ib						
08-9	-1.41	-1.41	- .29	- .15	- .43	- .73	- .94	- .92
09.5	-1.37	-1.36	- .27	- .13	- .42	- .68	- .86	- .84
B0	-1.31	-1.29	- .24	- .11	- .36	- .59	- .77	- .75
B0.5	-1.26	-1.23	- .22	- .09	- .30	- .50	- .66	- .64
B1	-1.19	-1.15	- .19	- .07	- .25	- .45	- .58	- .56
B2	-1.13	-1.08	- .17	- .04	- .18	- .34	- .42	- .40
B3	-1.00	- .95	- .13	- .01	- .12	- .25	- .31	- .29
B5	- .87	- .81	- .09	+ .01	- .06	- .18	- .20	- .18
B6	- .80	- .74	- .07	+ .01	- .03	- .14	- .16	- .14
B7	- .73	- .67	- .05	+ .02	- .01	- .11	- .10	- .08
B8	- .62	- .55	- .02	+ .03	+ .02	- .06	- .03	- .01
B9	- .56	- .48	.00	+ .04	+ .05	- .01	+ .04	+ .06
A0	- .47	- .41	+ .01	+ .05	+ .08	+ .04	+ .11	+ .13
A1	- .35	-----	+ .03	+ .06	+ .11	+ .07	+ .17	+ .19
A2	- .23	-----	+ .05	+ .07	+ .14	+ .12	+ .22	+ .24

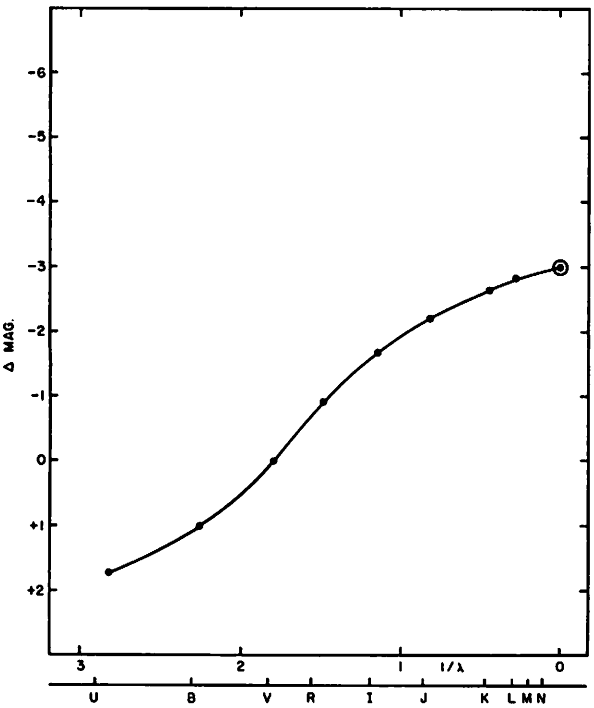

Fig. 7 The interstellar-extinction curve for the Perseus region. The spots designate data from the color-difference method; the spot within a circle, the value of R from the variable-extinction method.

again evident. The curve for Perseus (No. 1) appears to be quite similar to those computed by van de Hulst (1949), but those for NGC 2244 (No. 3) and Cepheus (No. 5) obviously are quite different from the theoretical curves. A cursory inspection of curves Nos. 3 and 5 (Fig. 12) suggests, however, that they might be caused by interstellar particles having a bimodal size distribution, with peaks near 0.3 and 3 μ.

5. *Special Objects*

Our discussion so far has been concerned with the mean characteristics of the interstellar extinction in several regions of the sky. There are stars listed in Table 2, however, whose observed colors are such as to merit individual comment. The following stars have been selected from Table 2.

No. 3, φ Per. Sp. B2pe. — If we assume that the observed colors of this star differ from a normal B2 V star because of interstellar reddening, the color-excess ratios in Table 6 are found. On this assumption, the extrapolated value of R for this star is greater than 16. The peculiar extinction curve for φ Per was also noticed by Stebbins and Kron (1956).

No. 31, ι Aur. Sp. K3 II. — This star exhibits an excess in magnitude N, much like that which we

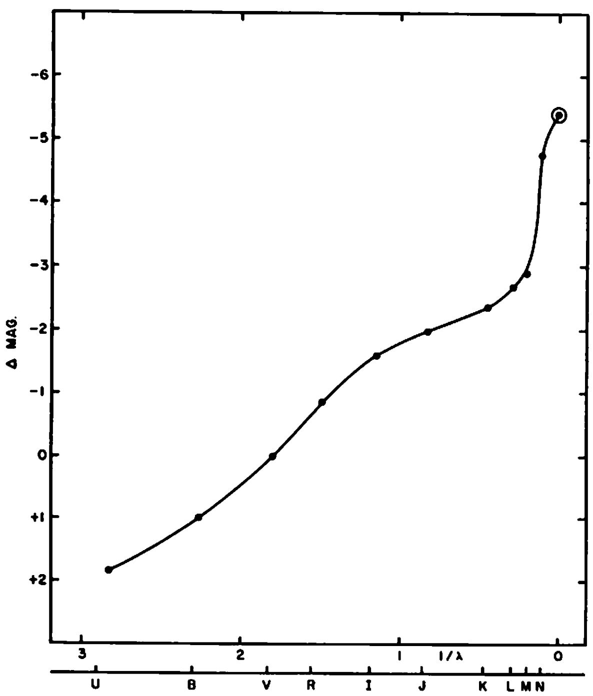

Fig. 8 The interstellar-extinction curve for the Cepheus region. The spots designate data from the color-difference method; the spot within a circle, the value of R from the variable-extinction method.

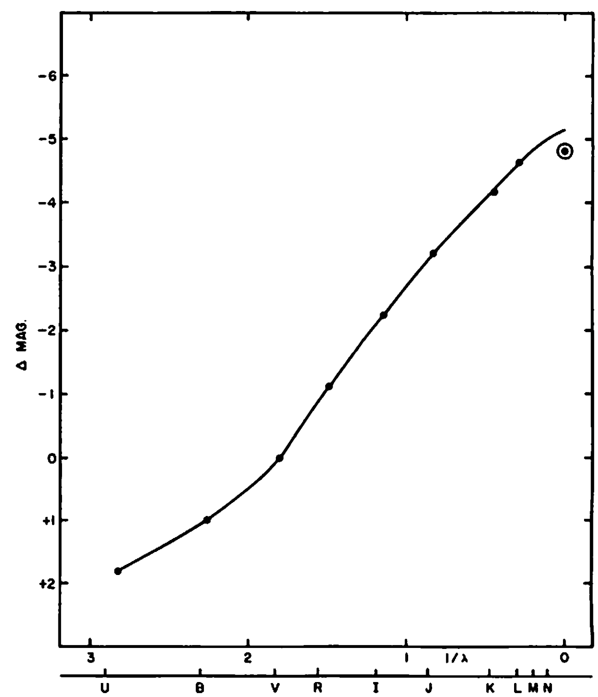

Fig. 9 The interstellar-extinction curve for the Orion Belt region. The spots designate data from the color-difference method; the spot within a circle, the value of R from the variable-extinction method.

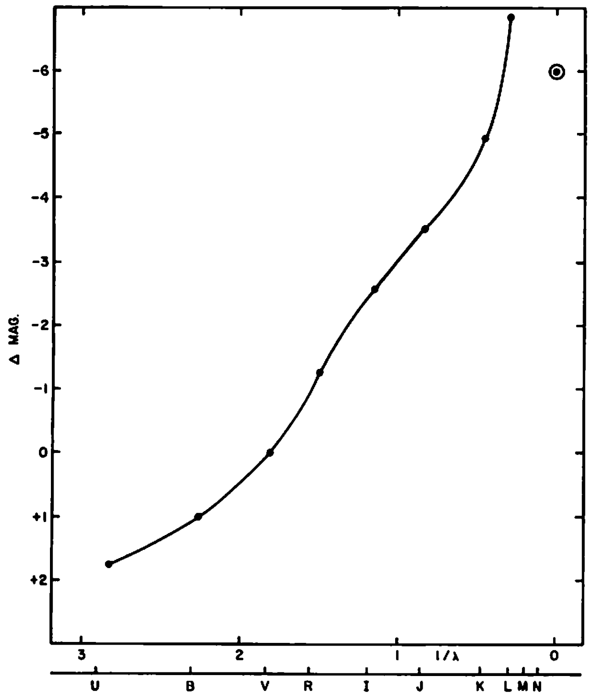

Fig. 10 The interstellar-extinction curve for the Orion Sword region. The spots designate data from the color-difference method; the spot within a circle, the value of R from the variable-extinction method.

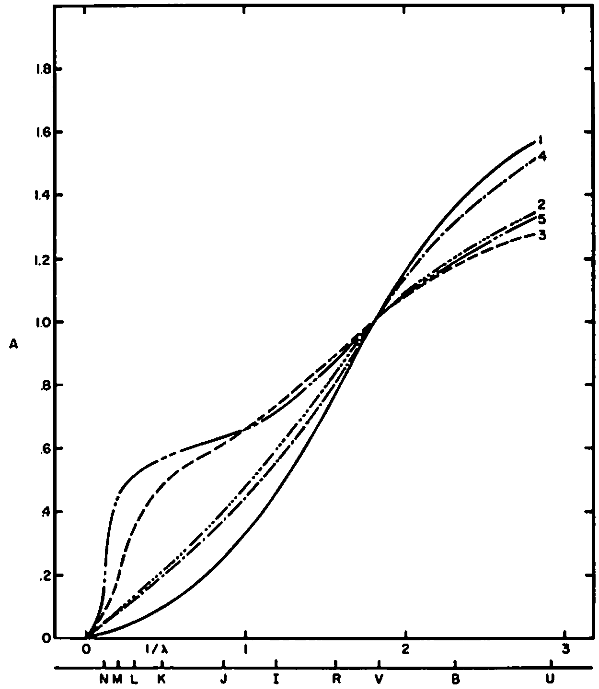

Fig. 12 The regional extinction curves. The data have been normalized to $A_v = 1.00$ mag. The regions are identified as follows: (1) Perseus, (2) Orion Belt, (3) NGC 2244, (4) Cygnus, (5) Cepheus.

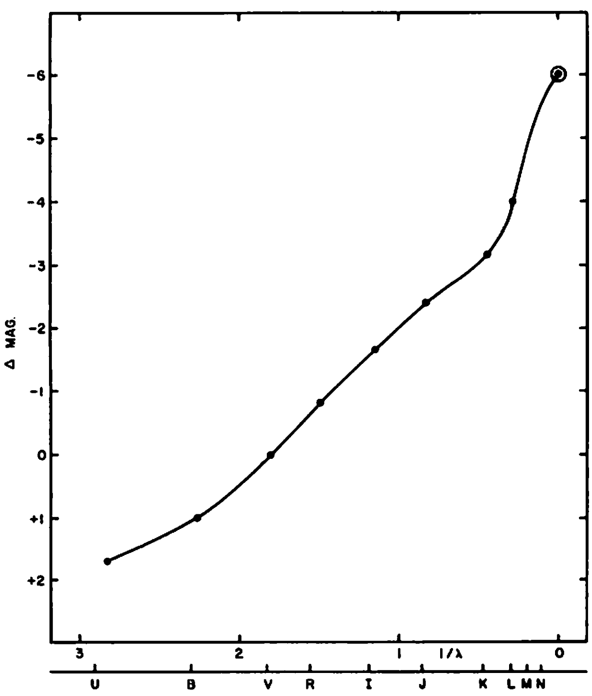

Fig. 11 The interstellar-extinction curve for the cluster, NGC 2244. The spots designate data from the color-difference method; the spot within a circle, the value of R from the variable-extinction method.

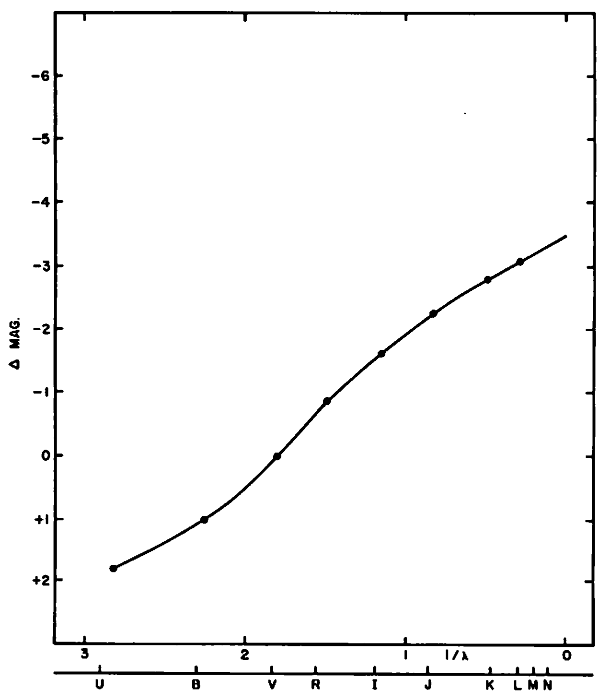

Fig. 13 The interstellar-extinction curve for the Cygnus region. The color-difference curve, extrapolated to $1/\lambda = 0$, indicates a value of $R \simeq 3.5$.

TABLE 4

REGIONAL MEAN EXTINCTION DATA

(Normalized to $E_{B-V} = 1.00$)

REGION	l^{II}	No. OF STARS	$\frac{E_{U-V}}{E_{B-V}}$	$\frac{E_{B-V}}{E_{B-V}}$	$\frac{E_{V-R}}{E_{B-V}}$	$\frac{E_{V-I}}{E_{B-V}}$	$\frac{E_{V-J}}{E_{B-V}}$	$\frac{E_{V-K}}{E_{B-V}}$	$\frac{E_{V-L}}{E_{B-V}}$	$\frac{E_{V-M}}{E_{B-V}}$	$\frac{E_{V-N}}{E_{B-V}}$
Double Cluster	134°	9	1.72	1.00	0.93	1.71	2.21	2.66	2.84		
II Persei	160°	4	1.68	1.00	0.81	1.69	2.38	2.86	2.88		
Orion Belt	207°	1	1.82	1.00	1.13	2.26	3.23	4.19	4.66		
Orion Sword	209°	3	1.74	1.00	1.26	2.58	3.53	4.96	6.87		
NGC 2244	206°	3	1.69	1.00	0.82	1.67	2.42	3.21	4.03		
Sco-Oph	10°	5	1.71	1.00	0.86	1.68	2.39	2.99	3.13		
Vulpecula	55°	2	1.71	1.00	0.84	1.63	2.20	2.80	3.21		
Cygnus	80°	6	1.81	1.00	0.87	1.63	2.27	2.81	3.10		
Cepheus	104°	5	1.84	1.00	0.85	1.60	1.98	2.37	2.69	2.89	4.75

TABLE 5

REGIONAL MEAN EXTINCTION DATA

(Normalized to $A_v = 1.00$ mag)

REGION	No. OF STARS	U	B	V	R	I	J	K	L	M	N
Perseus	13	1.57	1.33	1.00	0.70	0.43	0.24	0.09	0.05		
Orion Belt	1	1.35	1.19	1.00	0.78	0.57	0.38	0.20	0.11		
NGC 2244	3	1.28	1.17	1.00	0.86	0.72	0.60	0.47	0.33		
Cygnus	6	1.52	1.29	1.00	0.75	0.53	0.35	0.20	0.11		
Cepheus	5	1.34	1.18	1.00	0.84	0.70	0.63	0.56	0.50	0.46	0.12

found for μ Cep. If we assume that the color excesses of ι Aur are due entirely to interstellar reddening, we obtain the color-excess ratios in Table 6. The star is little reddened ($E_{B-V} = 0.21$ mag) and the ratios are, therefore, not very precise; nevertheless, they differ relatively little from the Perseus data of Table 4. Out to magnitude L, the reddening is essentially the same as for other stars nearby in the sky. The apparent existence of sinuous extinction curves (Figs. 8 and 11) does embolden us to suggest that ι Aur may be another such case. But, we hasten to point out that such interpretations imply the existence of a significant amount of *neutral extinction,* caused perhaps by particles 3–5 μ in diameter.

No. 57, α Leo. Sp. B7 V. — According to the published data of Wildey and Murray (1964), this star is much too bright at N to be compatible with the shorter-wavelength data. Our re-observation of α Leo, the results of which are listed in Table 2, confirms the existence of the excess N radiation, and we found also a smaller excess at M. The excess N radiation has been interpreted by Ney and Gould (1964) as Ne^{+} radiation at 12.8 μ, emitted by a circumstellar envelope. However, recent observations by Low (1964), using a narrow-band filter centered at 12.8 μ, show that the excess radiation is not present in the 12.8-μ region, but that it appears in the shorter-wavelength part of the N band.

It presumably is possible to interpret the excess radiation at M and N in terms of a very cool companion to α Leo; however, the fact that there is no excess observed at L and little at M implies that this companion must have a black-body temperature of only 300° K or so. Another possible interpretation is in terms of interstellar extinction. Since α Leo is not significantly reddened in visible wavelengths, this interpretation requires the existence of visually neutral extinction in this region of high galactic latitude. It is by no means certain that we should interpret the data for ι Aur and α Leo in terms of neutral

TABLE 6

SPECIAL OBJECTS

No.	NAME	$\frac{E_{U-V}}{E_{B-V}}$	$\frac{E_{B-V}}{E_{B-V}}$	$\frac{E_{V-R}}{E_{B-V}}$	$\frac{E_{V-I}}{E_{B-V}}$	$\frac{E_{V-J}}{E_{B-V}}$	$\frac{E_{V-K}}{E_{B-V}}$	$\frac{E_{V-L}}{E_{B-V}}$	$\frac{E_{V-M}}{E_{B-V}}$	$\frac{E_{V-N}}{E_{B-V}}$
3	φ Per		1.00	1.35	2.55	3.75	7.05	9.40	15.6	
31	ι Aur	2.10	1.00	0.57	1.57	1.81	2.52	2.76	2.86	5.6

extinction, but such interpretation is consistent with our earlier findings for Cepheus and NGC 2244. It also accords with Arp's (1962) showing that the *extinction* according to the cosecant law, determined from counts of galaxies, is too great to be compatible with the very small *reddening* that has been found for high galactic-latitude *stars*.

6. Summary

The combination of interstellar-extinction determinations from two independent methods — the variable-extinction method and the color-difference method — has resulted in dramatic confirmation of the non-"normal" extinction curves that had earlier been found for Cepheus and the Orion Nebula (Sword) region. It has also confirmed the reasonable supposition that extrapolation of the color-difference data to infinite wavelength ($1/\lambda = 0$) provides correct values of R. On the other hand, the curves for Cepheus and NGC 2244 show plainly that it is not possible to determine by the color-difference method the amount of extinction, from observations extending into the infrared only to 2.2 μ (magnitude K). Observations at considerably longer wavelengths are necessary for meaningful extrapolations. The *existence* of sinuous extinction curves such as those of Figures 8 and 11 may be inferred from observations out to 3.5 μ (magnitude L), but the exact extrapolation to $1/\lambda = 0$ from such observations remains quite uncertain.

If the interpretations presented in this paper are valid, it is plain that general application of the "normal" value of $R = 3.0$ can no longer be justified. From the evidence so far available, it appears that $R = 3.0$ may be the *minimum* value; if so, blanket application of this value results in a serious systematic error in the scale of our Galaxy. It also, because of the variation of R around the galactic plane, distorts the true galactic spiral structure. Much further work will be necessary before we will be able to resolve these questions.

Acknowledgments. Observers on this program have been K. Underwood, D. Steinmetz, M. Wirick, W. Wisniewski, as well as myself. All of the data reductions were performed on electronic computers, under the direction of R. I. Mitchell. Financial support of the observational program was provided by the Office of Naval Research. Construction of the photometric apparatus and the 28-inch telescope, with which most of the observations were made, was financed by the National Science Foundation.

APPENDIX

The Photometer Response Functions

The photometer response functions for the ten filter bands are given here in Tables A1, A2, and A3. The approximate effective wavelengths, for equal energy per unit wavelength, are given in Table A4.

Except for the U filter, these response functions include no corrections for atmospheric extinction, although such corrections are necessary for some of the bands. The R and I response functions include the reflectivity of two aluminized mirrors; no other response functions contain this correction, because the reflectivity of aluminum is essentially constant over the spectral regions of all filters except R and I. All response functions have been normalized to a peak response of unity and they should be used only for the computation of effective wavelengths, etc. Direct absolute comparison of one filter with another is not possible with these data.

Observations have been made with two L response functions, L^{I} and L^{II}. L^{I} applies only to the first L measures, using an InSb detector (Johnson 1962*a*, 1964); L^{II} applies to all current work, for which the detector is a PbS cell. The difference between the two bands is insignificant for stellar photometry. Unfortunately, the situation with regard to the UBV filters is somewhat ambiguous (Johnson 1962*b*), and caution in using the data for the U filter, especially, is advisable.

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Table A-1

The U, B, V, R, I Response Functions

λ, μ	U	B	V	R	I
0.30	0.00	----	----	----	----
0.31	0.10	----	----	----	----
0.32	0.61	----	----	----	----
0.33	0.84	----	----	----	----
0.34	0.93	----	----	----	----
0.35	0.97	----	----	----	----
0.36	1.00	0.00	----	----	----
0.37	0.97	----	----	----	----
0.38	0.73	0.11	----	----	----
0.39	0.36	----	----	----	----
0.40	0.05	0.92	----	----	----
0.41	0.01	----	----	----	----
0.42	0.00	1.00	----	----	----
0.44	----	0.94	----	----	----
0.46	----	0.79	0.00	----	----
0.48	----	0.58	0.02	----	----
0.50	----	0.36	0.38	----	----
0.52	----	0.15	0.91	0.00	----
0.54	----	0.04	0.98	0.06	----
0.56	----	0.00	0.72	0.28	----
0.58	----	----	0.62	0.50	----
0.60	----	----	0.40	0.69	----
0.62	----	----	0.20	0.79	----
0.64	----	----	0.08	0.88	----
0.66	----	----	0.02	0.94	----
0.68	----	----	0.01	0.98	0.00
0.70	----	----	0.01	1.00	0.01
0.72	----	----	0.01	0.94	0.17
0.74	----	----	0.00	0.85	0.36
0.76	----	----	----	0.73	0.56
0.78	----	----	----	0.57	0.76
0.80	----	----	----	0.42	0.96
0.82	----	----	----	0.31	0.98
0.84	----	----	----	0.17	0.99
0.86	----	----	----	0.11	1.00
0.88	----	----	----	0.06	0.98
0.90	----	----	----	0.04	0.93
0.92	----	----	----	0.02	0.84
0.94	----	----	----	0.01	0.71
0.96	----	----	----	0.00	0.58
0.98	----	----	----	----	0.47
1.00	----	----	----	----	0.36
1.02	----	----	----	----	0.28
1.04	----	----	----	----	0.20
1.06	----	----	----	----	0.15
1.08	----	----	----	----	0.10
1.10	----	----	----	----	0.08
1.12	----	----	----	----	0.05
1.14	----	----	----	----	0.03
1.16	----	----	----	----	0.02
1.20	----	----	----	----	0.00

Table A-2

The J, K, L Response Functions

λ, μ	J	λ, μ	J	λ, μ	K	λ, μ	L^I	L^{II}
0.96	0.00	1.30	0.63	1.80	0.00	2.9	0.00	0.00
0.98	0.02	1.32	0.66	1.85	0.10	3.0	0.14	0.14
1.00	0.03	1.34	0.68	1.90	0.48	3.1	0.68	0.68
1.02	0.06	1.36	0.70	1.95	0.95	3.2	0.95	0.95
1.04	0.16	1.38	0.70	2.00	1.00	3.3	1.00	1.00
1.06	0.35	1.40	0.66	2.05	0.98	3.4	1.00	1.00
1.08	0.62	1.42	0.60	2.10	0.96	3.5	1.00	0.98
1.10	0.93	1.44	0.46	2.15	0.95	3.6	0.89	0.85
1.12	0.85	1.46	0.27	2.20	0.97	3.7	0.81	0.69
1.14	0.78	1.48	0.14	2.25	0.96	3.8	0.65	0.39
1.16	0.78	1.50	0.09	2.30	0.94	3.9	0.59	0.21
1.18	0.80	1.52	0.06	2.35	0.95	4.0	0.65	0.10
1.20	0.85	1.54	0.02	2.40	0.95	4.1	0.40	0.02
1.22	0.93	1.56	0.00	2.45	0.84	4.2	0.04	0.00
1.24	0.75			2.50	0.46	4.3	0.00	----
1.26	0.64			2.55	0.08			
1.28	0.63			2.60	0.00			

Table A-3

The M and N Response Functions

λ, μ	M	λ, μ	N	λ, μ	N
4.1	0.00	7.0	0.00	11.6	0.68
4.2	0.04	7.2	0.10	11.8	0.71
4.3	0.25	7.4	0.34	12.0	0.76
4.4	0.48	7.6	0.59	12.2	0.76
4.5	1.00	7.8	0.70	12.4	0.76
4.6	0.93	8.0	0.76	12.6	0.71
4.7	0.92	8.2	0.84	12.8	0.63
4.8	0.89	8.4	0.89	13.0	0.54
4.9	0.84	8.6	0.98	13.2	0.50
5.0	0.78	8.8	0.92	13.4	0.46
5.1	0.76	9.0	0.79	13.6	0.43
5.2	0.79	9.2	0.68		
5.3	0.74	9.4	0.60		
5.4	0.68	9.6	0.63		
5.5	0.60	9.8	0.69		
5.6	0.49	10.0	0.73		
5.7	0.32	10.2	0.72		
5.8	0.26	10.4	0.65		
5.9	0.21	10.6	0.60		
6.0	0.19	10.8	0.60		
6.1	0.09	11.0	0.61		
6.2	0.02	11.2	0.64		
6.3	0.00	11.4	0.65		

Table A-4

The Effective Wavelengths of the Filter Bands (for Equal Energy at All Wavelengths)

Filter Band	λ_{eff}, μ	Filter Band	λ_{eff}, μ	Filter Band	λ_{eff}, μ	Filter Band	λ_{eff}, μ	Filter Band	λ_{eff}, μ
U	0.36	R	0.70	J	1.25	L^I	3.5	M	5.0
B	0.44	I	0.88	K	2.2	L^{II}	3.4	N	10.4
V	0.55								

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