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ABSTRACT

Filter photometry has been obtained of 16 BO stars at ten effective wavelengths in the range $\lambda\lambda$4250-1430Å. The wavelength dependence of the interstellar reddening law, deduced from a least-squares fit of the observed values to the reddening line at each band, is found in satisfactory agreement with that derived by Bless and Savage (1972). Towards the shorter wavelengths the increase of the computed probable error of the slope of the mean reddening line suggests that large fluctuations in the law may occur from star to star. Similar computations, separating main-sequence stars and supergiants, indicate that the large fluctuations of the law appear to be well related to the luminosity of the stars; the supergiants show systematically less extinction, this deficiency becoming large towards the far UV. The small number in the sample however, does not allow a general conclusion to be drawn. At 1550Å supergiants are found to be $0\overset{m}{.}9$ fainter than main-sequence stars relative to their V magnitude and giants about $0\overset{m}{.}3$ fainter.

Subject Headings: Early-Type Stars - Interstellar Reddening - Spectrophotometry

I. INTRODUCTION

Theoretical calculations following Van de Hulst (1949) indicate that a size distribution of coated or non-coated grains is a possible way to explain the wavelength dependence of the interstellar reddening law. The nature of the grains has been related to the formation of molecules in the upper atmosphere of oxygen-rich and carbon-rich stars (Gilman, 1969; Knacke, et al., 1969; Ney and Allen, 1969; Stein and Gillett, 1969; Woolf and Ney, 1969) which are able to condense into particles (Hoyle and Wickramasinghe, 1962) and then be ejected into the interstellar medium by radiation pressure.

By comparing the spectral distribution of a large number of reddened and unreddened early type stars, observed by means of the OAO-II spectrometers, Bless and Savage (1972) derived the wavelength dependence of the law in the range $\lambda\lambda$ 3600-1100 Å. The features obtained confirm the earlier results by Stecher (1965, 1969) and demonstrate the constant existence of a pronounced maximum around 2175 Å. The broad minimum between $\lambda\lambda$ 1800 - 1350 Å and the rapid rise towards the shorter wavelengths are generally found to vary from star to star. We used the OAO set of broad-band photometers to study faint stars of a single spectral type to provide additional data. The present results concern the behavior of the interstellar reddening law, as deduced from 16 stars classified on the MK system as B0.

II. THE OBSERVATIONAL DATA

Broad band photometry at ten effective wavelengths was obtained for stars in the visual magnitude range 1.70 to 6.65 and having (B-V) color-excesses from 0.02 to 0.51. The original signal from a star, in terms of count rate was reduced in the way described by Code et al., (1970). Within the spectral type considered, the shape of the bandpasses remain constant and the differential influences of the strongest lines like C IV and Si IV are expected to be negligible relative to the effective width of the bands ($\simeq$ 250 Å). The stars observed are listed in Table 1. The UBV data are from the catalogs of Lesh (1968) and Hiltner et al. (1969). Color excesses have been derived from intrinsic colors given by Johnson (1963). The observations are listed in Table 2. In those cases in which the star was observed in more than one orbit, the mean value has been taken. Generally the deviation was a few hundredths of a magnitude. Three stars are classified as B0.5 in the adopted sources although they have been classified as B0 by several observers. As a first step we shall assume that this uncertainty results in a negligible difference in the intrinsic energy distribution of the stars. We shall investigate the influence of a misclassification in the next section.

III. THE RESULTS

Determination of the reddening law by comparison of the flux distributions of pairs of stars is sensitive to instrumental fluctuations and to the UBV characteristics of the stars. To minimize these effects a statistical study may be made of stars of the same spectral type, thus intrinsically the same in $(B-V)_o$, but differing in (B-V). We have used a least-squares fit of the observed UV colors to a straight line in a color- E(B-V) diagram in order to define the slope and probable error of the mean reddening line for each ultraviolet color $(m_\lambda - V)$. The intercept of the mean line with

$E(B-V) = 0.0$ gives the most probable intrinsic color $(m_\lambda - V)_o$ for the wavelength while the standard deviation indicates the scatter of the points and the error around the intrinsic color. Diagrams of $(m_\lambda - V)$ vs $E(B-V)$ for two representative effective wavelengths are shown in Figure 1. The statistical properties of the reddening lines, computed (i) for all the stars and (ii) by separating the stars into two groups: luminosity classes V and IV and luminosity classes Ia and Ib, are listed in Table 3. Stars of luminosity Class III have been left out for the reasons developed later. Each set of results does not have the same weight since all the stars were not available for each wavelength. The number of stars used in each solution is given in columns 6, 10, and 14 of Table 3. The wavelength dependence of the interstellar reddening law resulting from the three solutions is shown in Figure 2.

First, the average reddening law computed from filter photometry with no regard to the luminosity of the star is in satisfactory agreement with the average curve deduced by Bless and Savage from spectrum scans of different early-type stars. This agreement is very good in the near UV for $\lambda >$ 1910 Å ($5.24\ \mu^{-1}$) except for the filter centered at 2030 Å ($4.93\ \mu^{-1}$). Here we suspect the photometric accuracy of the filter and we note also the small number in the sample at this wavelength. From the visible to the short wavelengths the standard deviation increases strongly and at λ eff = 1550Å the scatter of the points about the mean reddening line is $0\overset{m}{.}27$. By translating the supergiants towards the main-sequence stars in the color-color excess diagrams so that the little reddened stars coincide, an analogous computation leads to a similar value of the standard deviation. Therefore, the large computed value is not a consequence of the apparent intrinsic faintness of the supergiants compared to the main-sequence stars, but does support the idea that large fluctuations occur in the interstellar reddening and in the flux distributions of the stars.

Second, using a different approach, when the stars are separated according to luminosity the computed standard deviation turns out to be significantly lower than in the previous case. It is found that both groups obey approximately the same reddening law on the long wavelength side of the 2175Å maximum, the supergiants systematically showing slightly lower values. Towards the far UV the differences between the two groups become large. Indeed, for the filter centered at 1550Å, slopes of the reddening lines for main-sequence stars and for supergiants differ by 12 probable errors. Thus, a peculiar behavior of the reddening law seems to occur. The curve derived from main-sequence stars is consistent with the upper limit of the law found by Bless and Savage for ζ Oph (O9.5 Vnn) and close to the extrapolation of the $1/\lambda$ law used by Carruthers (1971) and by Smith (1967). The extinction derived from the supergiants turns out to be clearly weaker.

To emphasize the meaning of the observations, we shall discuss the case at 1550Å in detail. We have the following properties: for the more luminous stars, the standard deviation about the mean reddening line is $0^{m}.11$ and the slope is 3.54 ± 0.2. For the dwarfs the standard deviation is $0^{m}.08$ and the slope is 5.93 ± 0.15. The size of the standard deviations of the points about the straight lines and the probable errors of the slopes indicate that individual reddening laws deduced by comparing pairs of stars may be expected to lie mostly within 2 or 3 p.e. of the average extinction curve. Such a scattering is illustrated in Figure 1b for supergiants. Consequently, to know whether or not this scattering is representative of a physical effect becomes of importance. The determination of reddening by the method of color-color diagrams assumes that all the stars have the same intrinsic energy distribution and that a linear relationship between the ultraviolet and B-V color excesses exists. According to these hypotheses, the scatter of the observed values can be attributed to ultraviolet and UBV photometric inaccuracies, differences in the spectral distributions due to misclassification or peculiarities and changes in the physical properties of the interstellar medium. We have noted an uncertainty in the position of each point of about $0^{m}.05$ due to instrumental fluctuations. In addition, it is improbable that all the stars used are exactly type B0, the likely range in type being from 09.5 to B0.5. In Lesh's classification υ Ori and τ Sco, HD 209339, HD 48434 are standard stars for luminosity classes

V, IV, and III, respectively. Figure 3 illustrates what differences may appear in the spectral distribution between a B0.5 star (λ Lep, Standard) and a B0 star (υ Ori). It follows that a mean error of $0^{m}.1$ at 1550Å may be due to uncertainties in the spectral classification at type B0. Statistically this error and the instrumental fluctuations should introduce a standard deviation of $0^{m}.11$ which is equal to or larger than the computed standards deviations. It may be concluded that within the sample of stars considered here, the observed scattering is consistent with the expected instrumental fluctuations plus classification uncertainties. Therefore, intrinsic variations in the spectral distribution due to peculiarities or variations in the reddening law may exist but cannot be distinguished. Regarding the main-sequence stars plotted in Figure 1b, we note that of the two classified B0.5 V (Φ^1 Ori , E(B-V) = .13 and δ Sco, E(B-V) = .19), the former is consistent with a B0.5 flux distribution ($\simeq 0^{m}.2$ fainter), the latter gives results in agreement with type B0. The supergiants scatter more widely about a straight line, possibly owing to a less well-defined classification.

The three stars of luminosity class III are intermediate in their properties. Two are slightly reddened, E(B-V) $\leq$ 0.09, and one is moderately reddened. It follows that a mean reddening line for this class cannot be reliably deduced. However, from Figure 1b we see that a reddening line through the observed giants would be displaced from that for class V stars. This may result either from systematic observing errors or be of intrinsic significance. Within the three observations involved, the amount of displacement appears to be greater than the expected instrumental errors. On the other hand, slopes of the reddening lines determined for the giants by using an unreddened comparison star of class V would give an unusually large amount of far UV extinction. The derived values would be about 10 and 7 for the two stars which are little reddened and for HD 48434 at E(B-V) = .28, respectively.

A different alternative consists in considering the three giants are deficient in their far UV flux compared to that of the main-sequence stars. Accordingly, we excluded these stars from the computed average reddening law for main-sequence stars, but we did use this law to correct them for reddening.

Finally, the derived mean intrinsic colors, $(m_\lambda - V)_o$, for each luminosity class III, Ia and Ib, relative to those of classes V and IV are plotted in Figure 4. The large deficiency in the far ultraviolet flux of supergiants is evident. The results reported by Bless and Savage and by Carruthers (1969) confirm this observation although they do not find the smaller deficiency for giants. The spectral distribution of supergiants relative to main-sequence stars has been found by Mihalas (1970) to be in good agreement with the theoretical influence of the usually admitted gravity differences between dwarfs and supergiants, allowance being made for supergiants to be systematically cooler. From this viewpoint, the observed deficiency for giants is also consistent.

IV. DISCUSSION

Several attempts have been made to explain the wavelength dependence of the interstellar reddening law in the ultraviolet. Recent reviews of the suggestions have been given by Bless and Savage (1970, 1972) and by Gilra (1971). The original proposal of Stecher and Donn (1965) and of Wickramasinghe and Guillaume (1965) regarding graphite particles as suitable for causing the observed hump around 2200Å is supported by Bless and Savage who deduced from the invariable presence of this hump, its constant position and relative narrowness that small particles of graphite are required. To explain the rise of the extinction towards the far UV, the photo-dissociation of molecules such as H_2^+ (Stecher and Williams, 1969) or grains including silicates have been proposed by Wickramasinghe and Nandy (1971) in multi-component models of grains. Small particles cause the amount of extinction to increase rapidly as the wavelength decreases.

The two different shapes of the extinction law derived in Section III, the nearly common curve before the 2175Å maximum with the large difference appearing after, and the clear change in the slopes of the curves suggest that a different component is responsible for the far and for the near ultraviolet extinction. On the basis of a multi-component model of grains, the smaller extinction observed in the case of supergiants implies a larger than average size distribution of grains. The multicomponent model including a silicate-like wavelength dependence of the extinction becomes consistent with the present observations since we have also found smaller values of the extinction for supergiants in the near UV. Since the peak absorption produced by small particles of graphite is nearly independent of the size distribution (Gilra 1971), variations of the interstellar reddening law could be attributed chiefly to variations in the amount of extinction due to the component responsible for the far UV extinction. Then the ratio $E(m_\lambda - V)/E(B-V)$ computed for 2175Å should be correlated with that for 1550Å.

From the results presented here, it cannot be determined whether or not the apparent dependence of the reddening law upon the luminosity class is peculiar to the small sample of stars we have studied. Results reported by Bless and Savage, concerning stars not belonging to the class B0, contain indeed contradictory examples. In addition, some of the stars described here may also have a peculiar flux distribution, such as HD 168021, 202214, 209339 which are spectroscopic binaries. In view of these peculiarities, the small scattering in the data must be emphasized, indicating that the fluxes radiated by the companions of these stars do not disturb appreciably their ultraviolet colors.

All the stars are within $+22\overset{\circ}{.}5$ -21° of the galactic plane and most of them, including both luminosity classes I and V are located in areas of nebulosities. The main-sequence stars: HD 36822, 202214, 143275 are exciting stars of H II regions and turn out to be reddened about the same way as the main-sequence star ζ Oph, which represents the case of the upper limit of the interstellar reddening law known so far. This star is also an exciting star. HD 167264 (Ia) is in nebulosity and HD 204172 (Ib) excites an H-II region.

It can be concluded that the sample of supergiants differs apparently from the sample of main-sequence stars only in regard to their distances. It is found however, that the supergiants have less extinction. Then, an extinction proportional to the distance, under the assumption of a uniformly distributed interstellar medium must be ruled out. In the reverse situation, one could expect a non-uniformly distributed medium to produce a large scattering in the data unrelated to the luminosity of the stars. This is not observed. The remaining possibility consists of an extinction partially due to materials located in the vicinity of the star, as argued several times in the past and recently by Nandy and Wiskramasinghe (1971), where the nature and/or the size distribution of the particles might be related to the luminosity of the star.

V. CONCLUSIONS

We have presented results deduced from filter photometry obtained of 16 BO stars representing about 75 percent of the total number of such stars available in the Bright Star Catalogue.

It is of interest to note that the method used here gives an average reddening law in good agreement with the independently-obtained earlier results reported by Bless and Savage.

Our attempt in relating the shape of the law with the luminosity of the star appears to be positive within the present results. Nevertheless, further investigations using a larger body of obsevations seem to be needed to verify our conclusions. OAO-II satellite's observations including both the Wisconsin Experiment Package and the Celescope Experiment will certainly help in solving this question.

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TABLE 1

The Observed Stars

HD	Name or Constellation	Sp	V	B–V	E(B–V)	Ref.
36512	υ Ori	B0V	4.61	–0.28	0.02	L(A)
36822	ϕ^1 Ori	B0.5V	4.41	–0.17	0.13	L(A)
37128	ϵ Ori	B0Ia	1.70	–0.19	0.05	L(A)
48434	Mon	B0III	5.86	–0.02	0.28	L(A)
74753	Vel	B0III	5.15	–0.21	0.09	H
75821	Vel	B0III	5.09	–0.22	0.08	H
122879	Cen	B0Ia	6.41	+0.11	0.35	H
143275	δ Sco	B0.5V	2.30	–0.11	0.19	H
149038	μ Nor	B0Ia	4.89	+0.08	0.32	H
149438	τ Sco	B0V	2.82	–0.25	0.05	H
150898	Ara	B0.5Ia	5.56	–0.08	0.16	H
167264	15 Sgr	B0Ia	5.38	+0.07	0.31	H
168021	Sgr	B0Ib	6.63	+0.27	0.51	B
202214	Cep	B0V	5.64	+0.10	0.40	L(A)
204172	69 Cyg.	B0Ib	5.94	–0.10	0.14	L(A)
209339	Cep	B0IV	6.65	+0.07	0.37	L(A)

L: Lesh (1968)(A) Crawford

H: Hiltner *et al.* (1969)

B: Blanco *et al.* (1968)

TABLE 2

The Observed Magnitudes, m_λ

FILTERS	ST1 F3	ST1 F1	ST1 F4	ST2 F2	ST2 F5	ST2 F1	ST3 F2	ST3 F1	ST4 F1	ST4 F3
HD	4250	3320	2980	2940	2390	2030	2460	1910	1550	1430
36512	-4.08	-3.10	-3.36	-3.56	-3.32	-3.14	-2.33	-1.23	-0.90	-0.91
36822	-4.16	-3.15	-3.24	-3.46	-3.01	-2.73	-2.08	-0.82	-0.32	-0.34
37128							(-4.80)	-3.27	-2.87	-2.97
48434	-2.68	-1.55	-1.52	-1.77	-0.96	-0.45	-0.05	+1.59	+2.28	+2.42
74753	-3.44	-2.53	-2.66		-2.56		-1.62	-0.13	+0.37	+0.38
75821	-3.54	-2.61	-2.73		-2.66		-1.70	-0.22	+0.28	+0.34
122879	(-1.88)	-0.82	-0.70	-1.04	+0.12	+0.53	+0.88	+2.53	+2.98	+3.16
143275							-3.90	-2.58	-2.32	-2.32
149038	-3.52	-2.42	-2.34	-2.60	-1.62	-1.12	-0.74	+0.84	+1.38	+1.43
149438							-3.93	-2.86	-2.60	-2.57
150898	-2.96	-1.87	-1.91	-2.32	-1.69	-1.21	-0.72	+0.82	+1.43	+1.44
167264	-3.00	-1.87	-1.86		-1.23		-0.44	+1.19	+1.65	+1.63
168021	-1.59	-0.28	-0.13		+0.94		+1.63	+3.40	+3.82	+3.84
202214	-2.80	-1.48	-1.34	-1.62	-0.44	-0.02	+0.37	+1.94	+2.38	+2.37
204172	-2.73	-1.66	-1.69	-1.95	-1.32	-0.85	-0.46	+1.14	+1.99	+2.07
209339	-1.74	-0.51	-0.43	-0.63	+0.34	+0.69	+1.12	+2.68	+3.19	+3.14

TABLE 3

Statistical Properties of the Observed Reddening Lines

Case (A): V, IV, III, Ia, Ib
Case (B): V, IV
Case (C): Ia, Ib

		Case A				CASE B				CASE C			
λ_{eff}(Å)	$\lambda^{-1}(\mu^{-1})$	St. Dev.	$\frac{E(m_\lambda - V)}{E(B-V)}$	p.e.	No. in Sample	St. Dev.	$\frac{E(m_\lambda - V)}{E(B-V)}$	p.e.	No. in Sample	St. Dev.	$\frac{E(m_\lambda - V)}{E(B-V)}$	p.e.	No. i Sampl
4250	2.35	0.06	0.86	0.07	13	0.03	0.70	0.06	4	0.06	1.03	0.13	6
3320	3.01	0.04	1.74	0.06	13	0.02	1.76	0.03	4	0.05	1.65	0.11	6
2980	3.36	0.06	2.49	0.07	13	0.03	2.68	0.06	4	0.04	2.19	0.09	
2940	3.40	0.05	2.33	0.09	9	0.02	2.43	0.04	4	0.00	2.22	0.01	
2460	4.07	0.09	4.00	0.11	16	0.05	4.17	0.09	6	0.07	3.53	0.12	
2390	4.18	0.07	4.74	0.09	13	0.03	4.78	0.07	4	0.05	4.36	0.11	6
2030	4.93	0.11	5.10	0.20	9	0.04	5.28	0.09	4	0.02	4.49	0.08	4
1910	5.24	0.17	4.93	0.21	16	0.03	5.50	0.06	6	0.08	3.92	0.14	7
1550	6.45	0.27	5.04	0.32	16	0.08	5.93	0.15	6	0.11	3.53	0.20	7
1430	6.99	0.29	5.15	0.34	16	0.07	5.83	0.13	6	0.15	3.78	0.27	7

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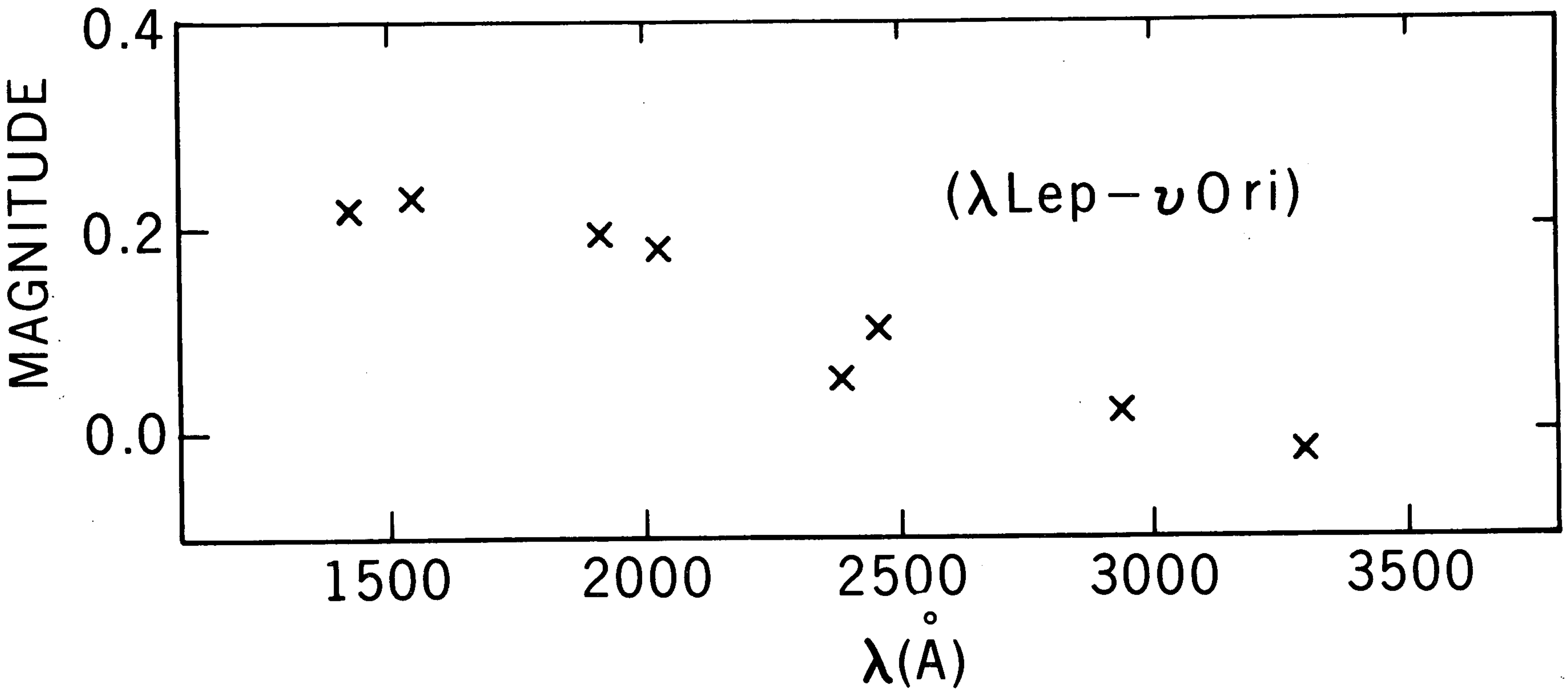
FIGURE CAPTIONS

Fig. 1 - $(m_\lambda - V)$ vs $E(B-V)$ for two representative effective wavelengths. Dots ● -- main-sequence stars; open circles ○ -- subgiants; crosses + -- giants; triangles △ -- supergiants, Ia; inverted triangles ▽ -- supergiants, Ib.

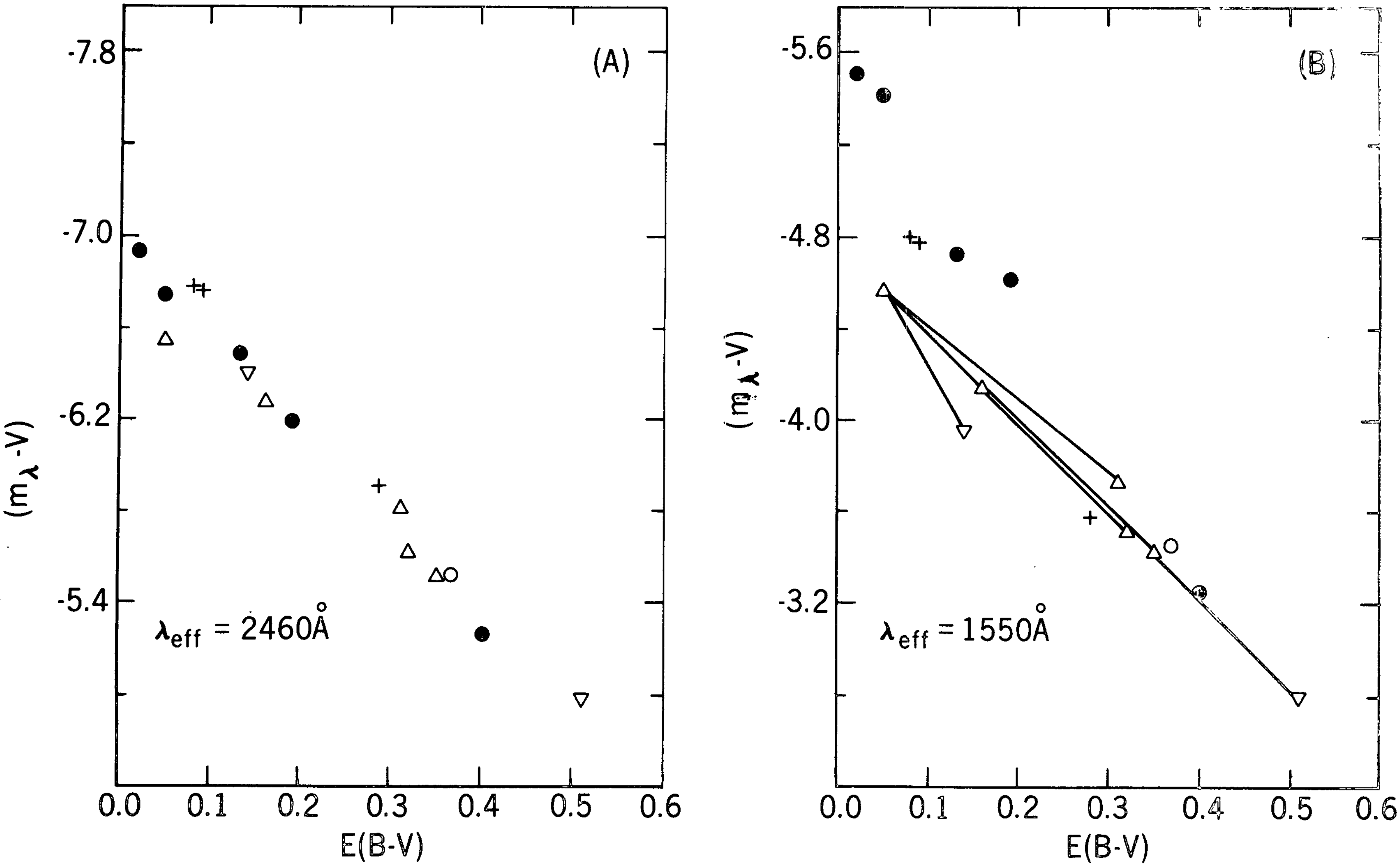
Fig. 2 - The wavelength dependence of the interstellar reddening law computed according to the luminosity classes. Open circles ○ -- classes V and IV; triangles △ -- classes Ia and Ib; the dashed line represents the average extinction from Bless and Savage (1972); Dots represent the average extinction deduced from all the stars. Vertical bars indicate the probable error.

Fig. 3 - A comparison of the flux distribution relative to the V magnitude between λ Lep (B0.5IV) and υ Ori (B0 V).

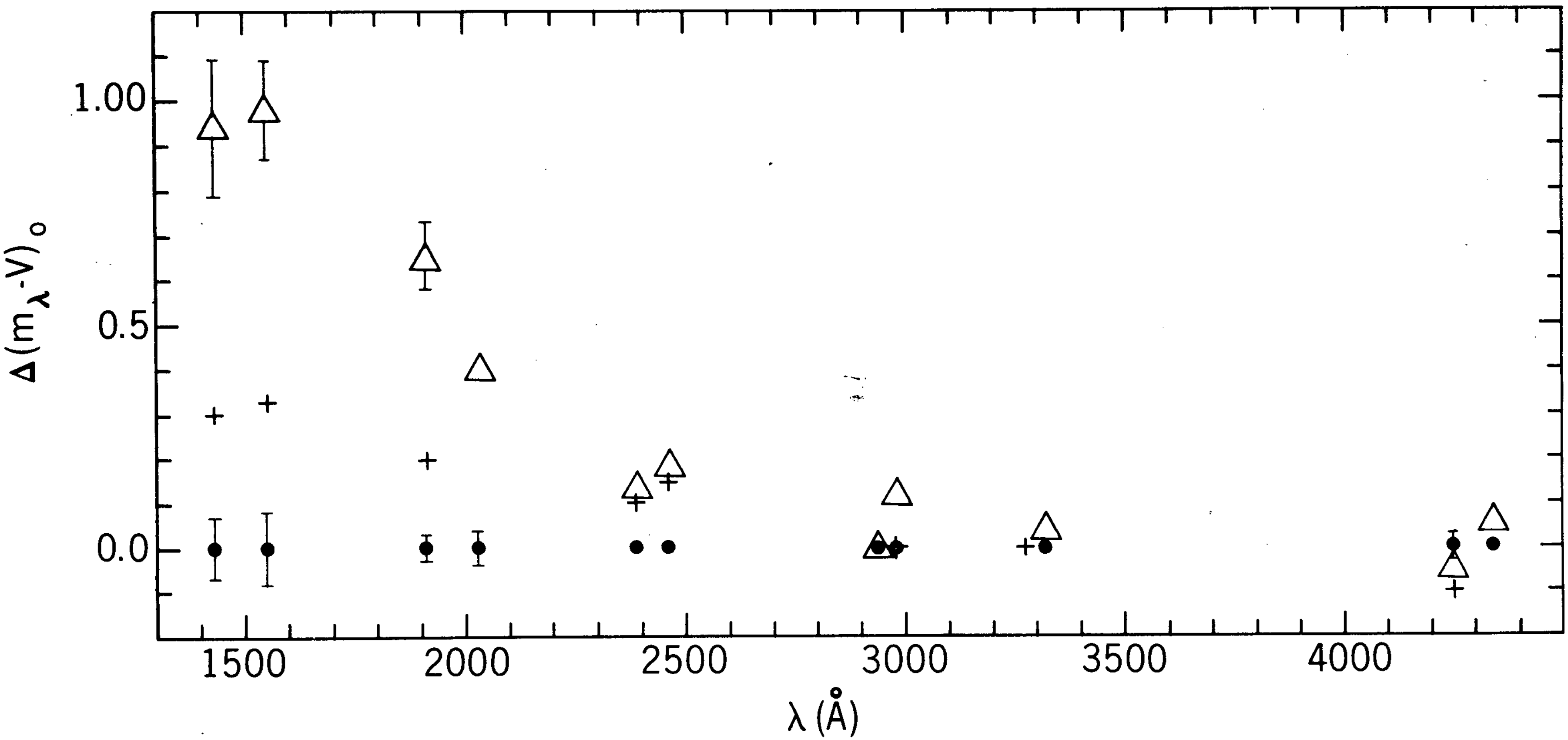
Fig. 4 - A comparison of the intrinsic colors $(m_\lambda - V)_0$ for main-sequence stars (dots), supergiants (triangles) and giants (crosses).



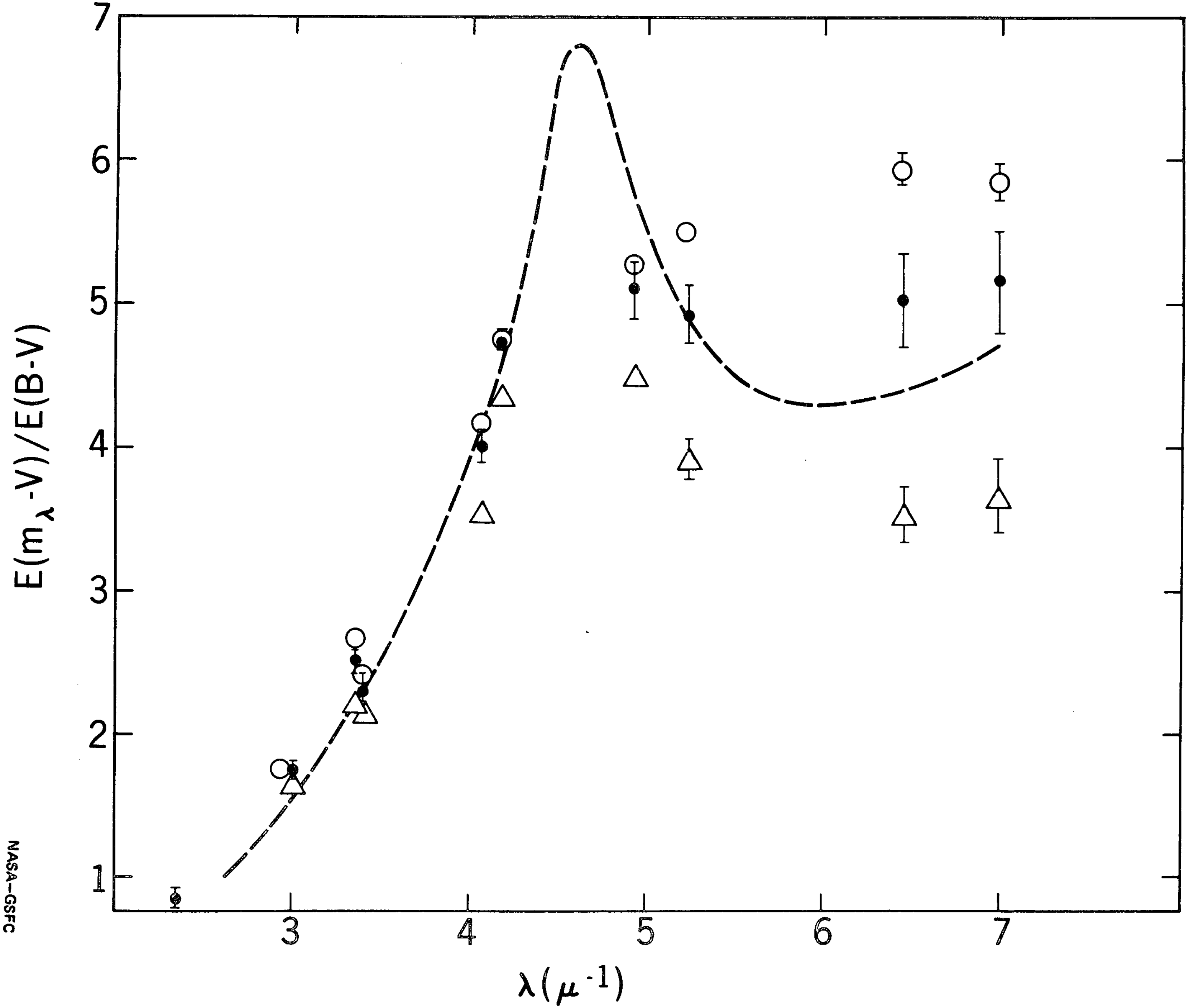
0.4
0.2
0.0
MAGNITUDE
(λ Lep − υ Ori)
1500
2000
2500
3000
3500
λ(Å)



(A)
-7.8
-7.0
-6.2
-5.4
$(m_\lambda\text{-V})$
λ_{eff} = 2460Å
0.0 0.1 0.2 0.3 0.4 0.5 0.6
E(B-V)
(B)
-5.6
-4.8
-4.0
-3.2
$(m_\lambda\text{-V})$
λ_{eff} = 1550Å
0.0 0.1 0.2 0.3 0.4 0.5 0.6
E(B-V)



1.00
0.5
0.0
$\Delta(m_\lambda - V)_0$
1500
2000
2500
3000
3500
4000
λ (Å)



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