PRELIMINARY RESULTS ON INTERSTELLAR REDDENING AS DEDUCED FROM FILTER PHOTOMETRY

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ABSTRACT

Filter photometry has been used to derive the interstellar reddening law from stars through the study of a single spectral type, B0. The deficiency in the far ultraviolet flux of a supergiant relative to a main sequence star is compared with the difference in the flux distribution due to a change of one spectral class. Individual interstellar reddening curves show the general feature reported by Stecher (1969) and by Bless and Savage (1970). There is a large amount of scatter in the far ultraviolet which may be partially due to a real difference in interstellar extinction and partially due to observational inaccuracy. The mean ratio $E(m_\lambda-V)/E(B-V)$ computed from the color-color diagrams using a least squares fit to the reddening line shows an increasing probable error from long wavelength to short wavelength which cannot be explained by the expected mean instrumental error.

I. INTRODUCTION

The study of a single spectral type with the set of broad-band photometers on board the OAO-2 satellite is an appropriate means to observe the interstellar extinction from faint

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stars which cannot be observed by the spectrum scanners. This type of observation provides additional data to recent results reported from relatively high resolution scans by Stecher (1969) and by Bless and Savage (1970) and allows us a statistical approach.

In this paper preliminary results are given about the interstellar reddening deduced from the study of twelve stars classified on the MK system as type B0. The visual magnitude ranges from 1.70 to 6.65; the maximum difference in B-V is 0.38. The choice of type B0 for this study is compatible with the following considerations: (i) a sufficient number of stars, including faint stars, was available to the satellite, (ii) the differential influence within the spectral type B0 of the strongest lines such as C IV and Si IV could be expected to be negligible in comparison to the FWHM of the band passes (about 250 Å), and (iii) problems of identifying correctly the effective wavelength are minimized. The effective wavelengths of the photometers are defined in terms of a uniform spectral intensity distribution.

II. THE OBSERVATIONAL DATA

The original signal for each star, in terms of number of counts, has been reduced in the way described by Code et al. (1970). In those cases in which the star was observed on more than one orbit, the mean value has been taken. Generally, the deviation was a few hundredths of a magnitude, but this remark does not refer to the filters ST4F1 (1550 Å) and ST4F3 (1430 Å) which have been corrected for a change in transmission with time. These corrections were made using information published by Holm (1972) and values derived from those stars observed several times in the course of several months. It appears that for filter ST4F3, in particular, the correction is large and uncertain. Filters ST4F5 (1680 Å) and ST4F4 (1330 Å) have not been used for the present work because of unreliable results which are suspected in ST4F5 and because ST4F4 covers the region of the L_α interstellar absorption line.

The ultraviolet extinction results are sensitive to the UBV characteristics of the star as well as to the spectral classification. In order to have a homogeneous set of stars we have used classifications by Lesh (1968), when available, or by Hiltner, Garrison and Schild (1969). Color excesses have been derived using the intrinsic colors of Johnson (1963). The data for all the stars used are summarized in Table 1, including the sources used. The observations are given in Table 2. Three stars are classified as B0.5 in the adopted sources although previously they were classified as B0. We shall assume that this difference has a negligible effect on the calculations presented in the next section.

Table 1. The Stars Observed

HD	Name	Sp	V	B-V	Ref	Remark
36512	υ Ori	B0 V	4.61	-0.28	L(A)	
36822	ϕ^1 Ori	B0.5 V	4.41	-0.17	L(A)	Spectral peculiarities noted by Lesh
37128	ε Ori	B0 Ia	1.70	-0.19	L(A)	
48434		B0 III	5.86	-0.02	L(A)	Monoceros. Spectral peculiarities noted by Lesh
122879		B0 Ia	6.41	+0.11	H	Centaurus
143275	δ Sco	B0.5 V	2.30	-0.11	H	
149038	μ Nor	B0 Ia	4.89	+0.08	H	
149438	τ Sco	B0 V	2.82	-0.25	H	
150898		B0.5 Ia	5.56	-0.08	H	Ara
202214		B0 V	5.64	+0.10	L(A)	Cepheus: Binary Δm_V=1
204172	69 Cyg	B0 Ib	5.94	-0.10	L(A)	Triple, Δm_V = 3
206773		B0 Vpe	6.93	+0.20		Cepheus
209339		B0 IV	6.65	+0.07	L(A)	Cepheus: Binary Δm_V=2

L: Lesh (1968). (A): Crawford. H: Hiltner *et al*. (1969).

Table 2. *The Observed Magnitudes* m_λ

HD	ST1F3 4250	ST1F1 3320	ST1F4 2980	ST2F2 2940	ST2F5 2390	ST2F1 2030	ST3F2 2460	ST3F1 1910	ST4F1 1550	ST4F3 1430
36512	-4.18	-3.29	-3.46	-3.69	-3.44	-3.26	-2.37	-1.25	-0.94	-0.93
36822	-4.28	-3.27	-3.36	-3.57	-3.11	-2.82	-2.11	-0.84	-0.38	(-0.36)
37128							(-4.91)	-3.31	-2.93	-2.99
48434	-2.69	-1.56	-1.54	-1.80	-1.00	-0.48	-0.06	(+1.10)	(+1.10)	(+1.13)
122870	-2.35	-0.94	-0.82	-1.04	+0.05	+0.45	+0.84	+2.49	+2.94	+3.1
143275							-3.92	-2.61	-2.25	-2.03
149038	-3.57	-2.42	-2.34	-2.57	-1.61	-0.92	-0.64	+0.88	+1.39	+1.46
149438							(-4.06)	-2.85	-2.54	-2.63
150898	-3.03	-2.03	-2.06	-2.35	-1.72	-1.24	-0.72	+0.74	+1.44	+1.43
202214	-2.86	-1.55	-1.41	-1.68	-0.49	-0.07	+0.38	+1.8	+2.15	+2.40
204172	-2.78	-1.71	-1.73	-1.97	-1.35	-0.88	(-0.23)	+0.90	+1.97	+2.05
209339	-1.88	-0.65	-0.57	-0.73	+0.20	+0.55	+1.09	+2.64	+3.15	+3.10

III. THE COLOR-COLOR DIAGRAMS

Diagrams of $(m_\lambda - V)$ vs. $(B-V)$ for representative effective wavelengths are shown in Figure 1. Mean reddening lines have

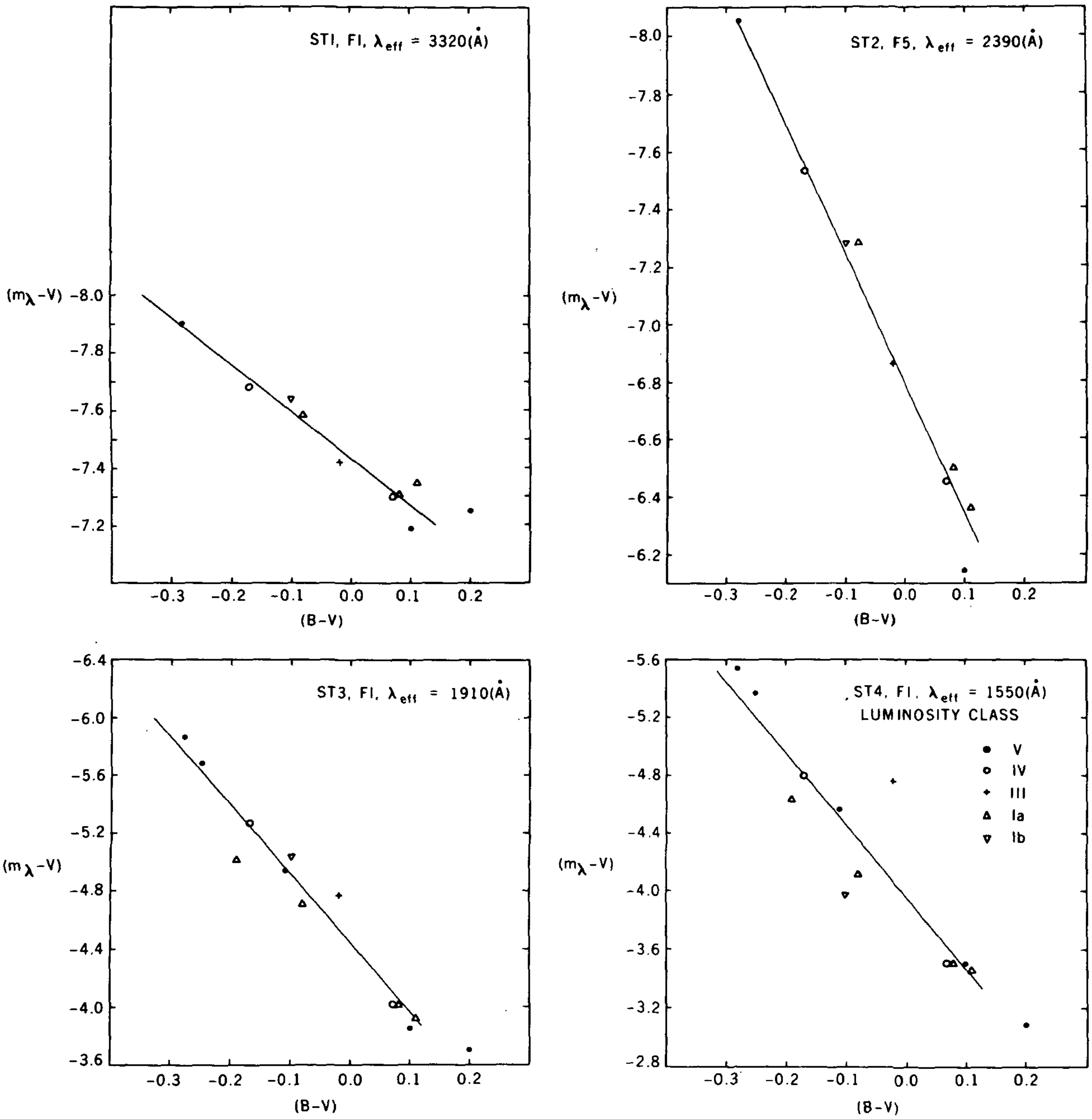

Figure 1.—Color-color diagrams for representative effective wavelengths. Note the increase of the scatter around the reddening line with decreasing wavelength.

been obtained by a least squares fit of a straight line to the observed points. The slopes of the reddening lines and their probable errors are listed in Table 3 together with the standard deviations. The scatter of the points is due to instrumental errors, possible errors in V and in (B-V), differences in the interstellar extinction and in the intrinsic properties of the stars themselves. The slope of the straight line represents a mean ratio $\Delta(m_\lambda - V)/\Delta(B-V)$ which can be used to estimate the ultraviolet extinction when the E(B-V) is known. The star HD 206773 (B0 Vpe) has been left out of the calculations.

Table 3. Statistical Properties of the Observed Reddening Lines

λ_{eff} (Å)	Stand. Dev.	$\frac{\Delta(m_\lambda - V)}{\Delta(B-V)}$	p.e.	λ^{-1} (μ^{-1})
4250	0.03	0.81	0.06	2.35
3320	0.05	1.63	0.08	3.01
2980	0.05	2.36	0.09	3.36
2940	0.06	2.41	0.10	3.40
2460	0.08	4.03	0.12	4.07
2390	0.09	4.62	0.15	4.18
2030	0.10	5.23	0.18	4.93
1910	0.14	4.71	0.21	5.24
1550	0.28	4.96	0.42	6.45
1430	0.30	5.29	0.44	6.99

The large standard deviations obtained for the filters with effective wavelengths shorter than 2000 Å may be due to intrinsic differences in the far ultraviolet spectra of the program stars. Bless and Savage have shown that for stars of the same spectral type but luminosity classes in the range II to V, the spectral distribution is closely the same. In order to investigate what differences may appear in the filter photometry, differences in magnitude between a supergiant and a main sequence star (ε Ori, υ Ori) and between two main sequence stars (τ Sco, υ Ori) all of type B0 are shown in Figure 2. The differences are normalized to zero at the effective wavelength of the V pass band. The difference between types B0.5 V and B0 V is shown by the pair (λ Lep, ν Ori). Each of these stars has E(B-V) < 0.05, thus differential reddening is minimal.

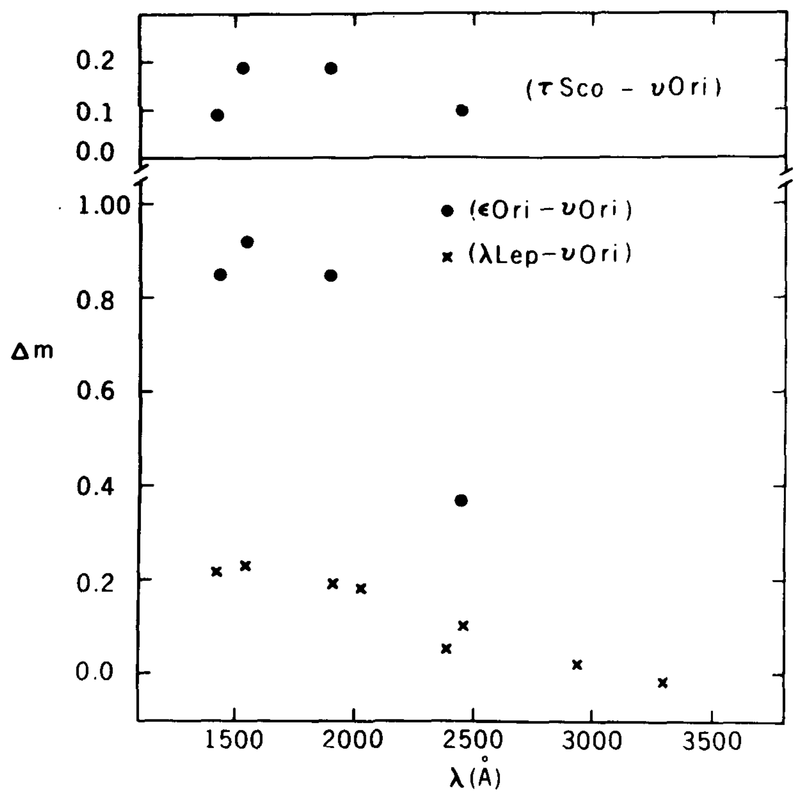

Figure 2.—Differences in magnitudes of the ultraviolet energy distribution of stars of similar spectral types relative to the visual magnitude.

The supergiant shows a large ultraviolet deficiency in comparison to a main sequence star. A similar deficiency was found by Carruthers (1969) at 1115 Å for ε Ori. Mihalas (1970) has commented upon this in terms of a decrease in the surface gravity and in effective temperature from main sequence to supergiant stars.

IV. THE WAVELENGTH DEPENDENCE OF THE INTERSTELLAR EXTINCTION

By comparing the spectral distribution of a reddened star with that of an unreddened star of the same spectral type and luminosity class, one can deduce the wavelength dependence of the interstellar extinction in the different directions of the stars. This method assumes that stars of the same spectral type and luminosity class have identical flux distributions.

Figure 3 illustrates five reddening curves obtained by comparing four main sequence stars to the reference star υ Ori and one supergiant to ε Ori. The data are normalized to a difference in (B-V) = 1 mag for the pairs of stars considered and for ΔV = 0. The observed values of ϕ^1 Ori and δ Sco have been corrected from B0.5 to B0 using values given in Figure 2 for the pair (λ Lep, υ Ori). The shadowed area represents the probable error around the mean values computed in § III.

On the whole, the points show a maximum between 4.18 and 4.93 μ^{-1} and a minimum between 5.24 and 6.45 μ^{-1}. The profile of the maximum has been given by Stecher (1965,1969) and Bless and Savage (1970). The first explanations that the maximum is

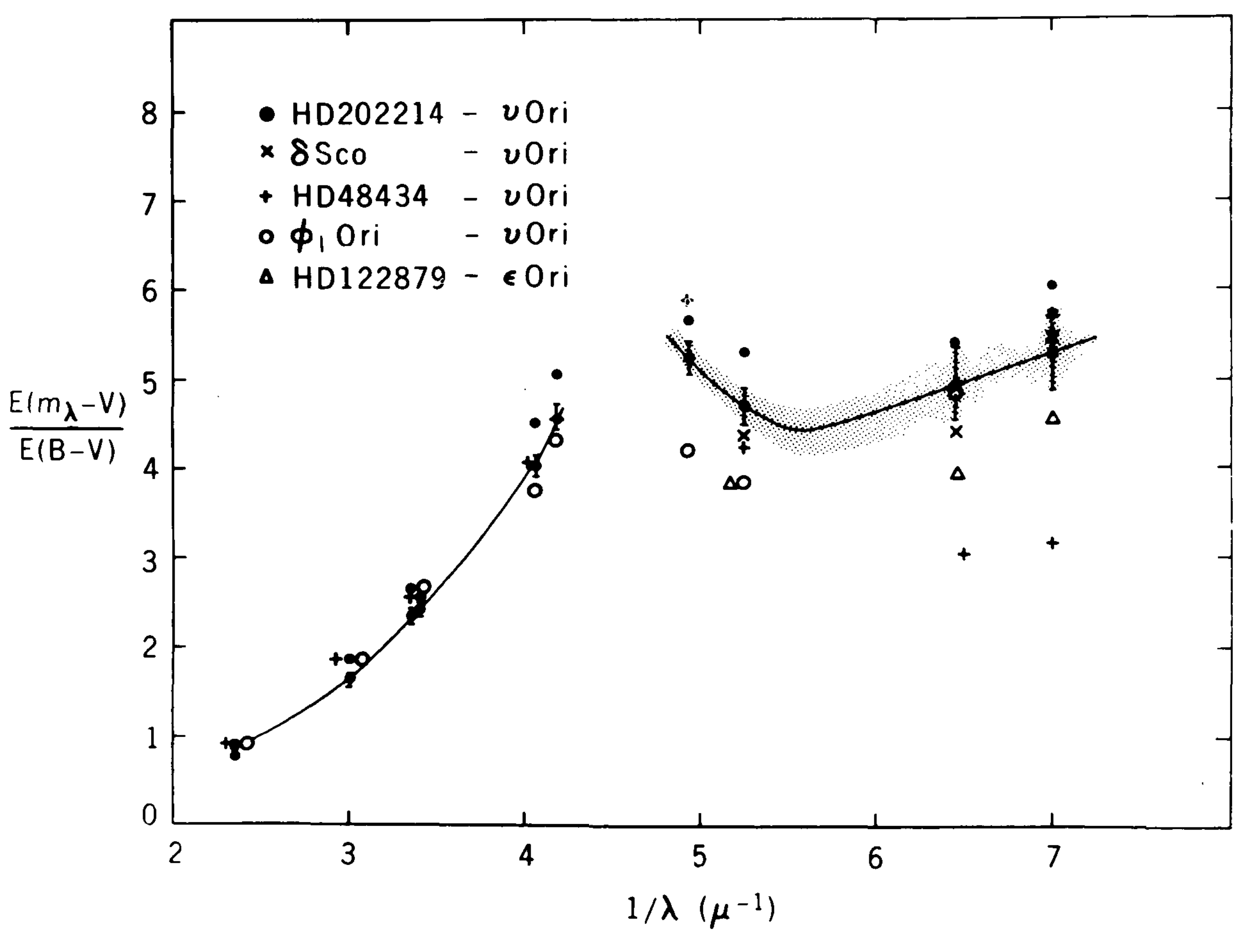

Figure 3.—Interstellar reddening found for HD 209339 compared with that for ζ Oph (Gilra 1971).

due to graphite particles were given by Stecher and Donn (1965) and by Wickramasinghe and Guillaume (1965).

The interstellar extinction law is known to vary in the visible and in the infrared (Johnson 1968). Figure 3 shows for representative pairs of stars that in the range 4.93 to 7 μ^{-1} the interstellar extinction seems to differ significantly from the average value. It is therefore of importance to find out whether or not this scatter is a real effect which can be attributed to an intrinsic property of the interstellar medium.

For such a purpose we must note first that a probable error of 0.1 mag in the difference between two stars is on the average magnified by a factor of 4 because $\langle \Delta(B-V) \rangle = 0.25$, and secondly, that points lying within 2 or 3 probable errors cannot be interpreted as basically deviant from the mean curve.

It follows that the case obtained for the star HD 48434 is significantly peculiar. However, it cannot be considered to be representative of a low interstellar extinction because of an uncertainty, difficult to evaluate, in the technical reduction of the far ultraviolet data.

The star HD 202214 is slightly above the mean curve but it cannot be considered to be different. This star is double with a companion 1 mag fainter than the primary component.

The stars ϕ^1 Ori and HD 122879 present an intermediate case. The uncertainties in the data in the far ultraviolet fall in the area corresponding to 2 or 3 p.e., while in the region 4.93 to 5.24 μ^{-1} a real deviation seems to be present, indicating that for these two cases the values of the interstellar extinction may be below the average.

The curve obtained for the star HD 209339, shown in Figure 4, has a peculiar profile which deserves additional comments. Indeed, the values obtained are within 2 p.e., indicating that this profile is not statistically different from the mean. But apparently there is no minimum in the range 4.93 to 7 μ^{-1}. The star HD 209339 is double with a companion 0.6 arc sec distant and 2 mag fainter. In addition, since this star is a standard B0 IV star in the Lesh classification system it is unlikely that the observed differences in the reddening curve are due to misclassification. It cannot be excluded that the wavelength dependence of the interstellar extinction in the direction of HD 209339 might be unusual, presenting some similarities with the results found for ζ Oph by Bless and Savage (1970).

V. DISCUSSION

In the case considered here, there are two ways in which to deduce the wavelength dependence of the interstellar reddening profiles:

1. Individual profiles deduced from the comparison of

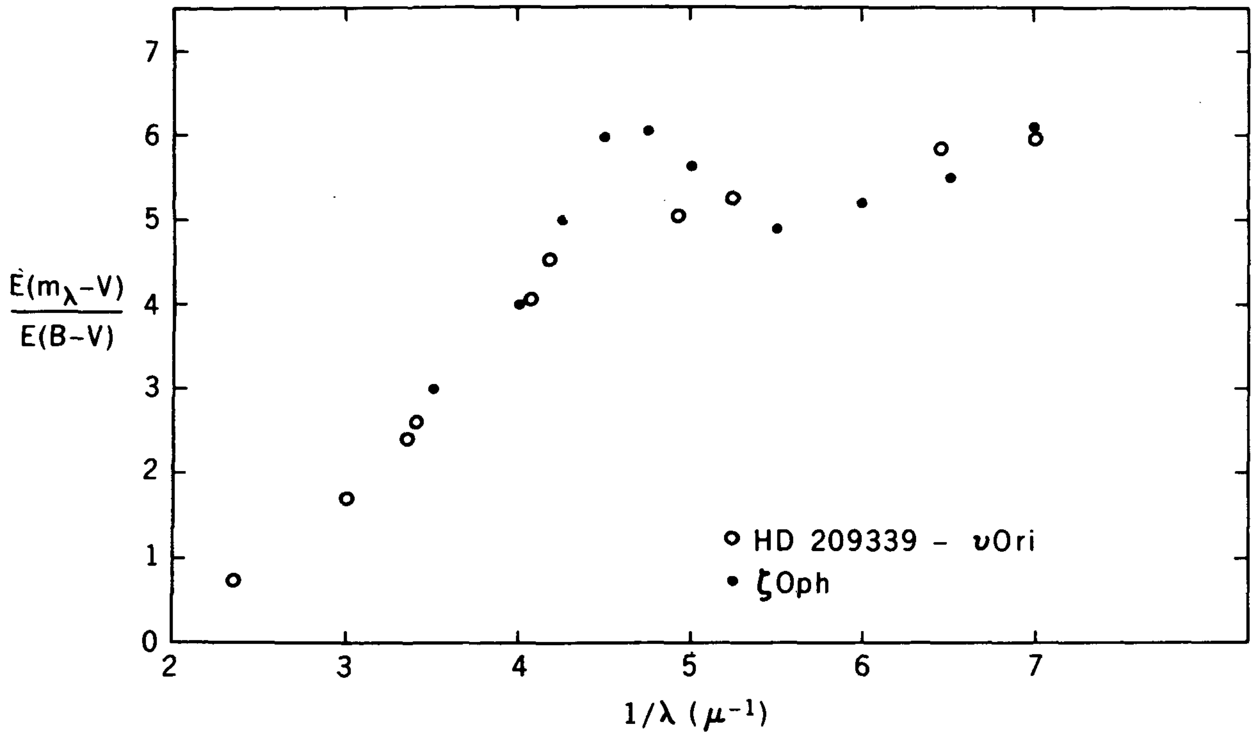

Figure 4.—The wavelength dependence of the interstellar reddening obtained from pairs of stars and from a statistical method.

pairs of stars. In this case each curve is sensitive to the accuracy of V, (B-V) and m_λ. The largest uncertainty is in Δm_λ between the two stars. The stars used generally have been observed at different epochs and it is difficult at present to give an upper limit to the expected accuracy at each time.

2. A statistical approach, considering all the stars as a whole, without any discrimination of luminosity class. The least squares fit to the straight line

$$m_\lambda - V = a(B-V) + b$$

is used at each wavelength. We can evaluate the error in m_λ from the mean error found by considering the results for several stars observed several times at different epochs.

We have pointed out in § IV that the first method gives peculiar results significantly different from the mean, and that among the sample of stars used it is difficult to evaluate whether or not these differences indicate real differences in the reddening law.

An attempt to understand the constant increase from long wavelength to short wavelength of the standard deviation and of the probable error around the mean value found in case 2 can be made by estimating the statistical errors. We shall take the probable error of 0.42 computed for the 1550 Å filter as representative.

At this step we must briefly review the hypotheses used:

(1) All the stars have the same intrinsic spectral distribution.

(2) There is a linear relationship between (m_λ-V) and (B-V). The slope is the same for any luminosity class, and is characteristic of the interstellar medium.

(3) The method of least squares fit can be applied for twelve stars and the probable error of the derived slope is independent of intrinsic differences between main sequence stars and supergiants. This is confirmed by the fact that the probable errors computed separately in the sample case are respectively ±0.48 and ±0.33 for main sequence stars and supergiants.

Under these hypotheses, mean errors of ±0.1 mag in m_λ, ±0.04 on the correction added to allow for the variation of the sensitivity with time, and ±0.02 on V and (B-V) give an expected total probable mean instrumental error of ±0.11 mag in the derived mean slope.

It turns out that the instrumental error cannot explain the total probable error found. We conclude that a "natural" scatter of the data exists which can be attributed to a local change in the physical properties of the interstellar medium.

I am grateful to Prof. A. D. Code of the University of Wisconsin for the opportunity to make these observations with the OAO-2 as part of the Goddard Space Flight Center Guest Observer Program.

Also, I would like to thank Dr. A. B. Underhill, Dr. A. Boggess and Mr. L. Dunkelman for helping me in the completion of this work.

My thanks are extended to the National Academy of Science for the grant of a Research Associateship tenable at Goddard Space Flight Center.

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