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# THE VARIATION OF GALACTIC INTERSTELLAR EXTINCTION IN THE ULTRAVIOLET

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## ABSTRACT

The interstellar extinction in the UV ($3.25\ \mu m^{-1} \leq \lambda^{-1} \leq 8.0\ \mu m^{-1}$) has been determined from *IUE* spectra for 29 reddened early-type stars by use of the pair method. The star sample was selected on the basis of highly deviant ratios of the strength of the 4430 Å diffuse interstellar absorption feature to color excess $E(B-V)$ (15 stars) and on the basis of association with reflection nebulae (nine stars). The incidence of peculiar extinction curves among this sample as measured by significant deviations from the mean galactic extinction law is near 70%. Deviations in the strength of the 2175 Å extinction bump appear to occur independently of deviations in the rise of the far-UV extinction at 1250 Å in about 35% of the stars. On the average, stars associated with dense interstellar clouds exhibit weaker UV extinction in the $\lambda < 2500$ Å range than do stars observed through low-density diffuse clouds if normalized to constant $E(B-V)$. At 1250 Å this difference between the averages of the two groups amounts to 27%, measured in units of the average galactic extinction per unit $E(B-V)$ at 1250 Å, but wide dispersion are evident for both groups. Previous studies based on *ANS* and *TD-1* data that show variation in UV extinction characteristics with galactic longitude or with association with specific galactic spiral arms are confirmed.

*Subject headings:* interstellar: matter — stars: early-type — ultraviolet: spectra

## I. INTRODUCTION

It is well known that the wavelength dependence of interstellar extinction is not the same for all stars in our Galaxy. Evidence has been mounting recently suggesting that significant deviations from the *average* galactic extinction law are far more common (Massa, Savage, and Fitzpatrick 1983; Meyer and Savage 1981; Kester 1981; Koornneef 1978) than once suspected (Nandy *et al.* 1976) and that reported isolated cases of "anomalous" extinction (e.g., Seab, Snow, and Joseph 1981; Walker *et al.* 1980; Morales, Andres, and Arbol 1980; Witt, Bohlin, and Stecher 1981; Hecht *et al.* 1982; de Boer 1983) are mere examples of the existing range of extinction laws present in the Galaxy.

With this contribution we are further demonstrating the degree of variation of interstellar extinction in the UV by presenting new extinction measurements toward 29 early-type stars. Our stars should not, however, be considered a random sample. Approximately 15 of them were chosen because they have either an unusually large or an unusually small ratio of the strength of the diffuse interstellar band at 4430 Å to the color excess $E(B-V)$ (Witt, Bohlin, and Stecher 1983). Five stars have a ratio of these quantities near average, and nine additional stars are illuminating reflection nebulae and are hence closely associated with regions of dense interstellar matter, three of them with the Orion molecular cloud. We have already shown (Witt, Bohlin, and Stecher 1983) that the ratio $A(4430)/E(B-V)$ is weakly correlated in a positive sense with the normalized strength of the 2175 Å extinction bump and that a weak negative correlation exists between $A(4430)/E(B-V)$ and the extinction rise at 1250 Å. We may therefore expect a greater number of "anomalous" extinction curves in our sample than would be the case with a purely random sample. Furthermore, stars associated with denser regions of interstellar space such as reflection nebulae are commonly expected to exhibit lower than average far-UV extinction (Mathis and Wallenhorst 1981) although well studied exceptions such as HD 23512 (Witt, Bohlin, and Stecher 1981), HD 200775 (Walker *et al.* 1980) and HD 29647 (Snow and Seab 1980) heve been shown to exist.

The stars in our sample are particularly well suited to explore the range of variation in the extinction curves found among stars already preselected according to dust-related criteria not connected to extinction.

## II. OBSERVATIONS

We observed the UV flux distribution in the 1150–3200 Å wavelength range for our 29 program stars (Table 1) with the *International Ultraviolet Explorer* (*IUE*; Boggess *et al.* 1978). The low-resolution spectrometers were used throughout. Two or more exposures with different exposure levels

[1] Guest Observer with the *International Ultraviolet Explorer* (*IUE*) satellite which is sponsored and operated by the National Aeronautics and Space Administration, the European Space Agency, and the Science Research Council of the United Kingdom.



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1984ApJ...279..698W



TABLE 1

PROGRAM AND STANDARD STARS FOR PAIR METHOD

| No. | Program Star (HD, BD) | MK | $E(B-V)$ | References | Standard Star (HD) | MK | $E(B-V)$ | Remarks[a] |
|---|---|---|---|---|---|---|---|---|
| 1 | 167838 | B5 Ia | 0.54 | 1, 2 | 58350 | B5 Ia | 0.02 | var.? |
| 2 | 166734 | O9 If | 1.41 | 3, 2 | 188209 | O9.5 Ia | 0.21 | D |
| 3 | 170740 | B2 V | 0.27 | 4 | 3360 | B2 IV | 0.04 | RN |
| 4 | +23° 3745 | B0.5 Ib | 0.88 | 5, 2 | 64760 | B0.5 Ib | 0.10 | |
| 5 | 190603 | B1.5 Ia | 0.69 | 4 | 91316 | B1 Iab | 0.05 | RN |
| 6 | 194153 | B1 Iab | 1.25 | 6, 7 | 91316 | B1 Iab | 0.05 | |
| 7 | +41° 3807 | O6f | 1.78 | 8 | 164794 | O5 | 0.34 | |
| 8 | 197512 | B1 V | 0.38 | 9, 10 | 31726 | B1 V | 0.05 | |
| 9 | 204827 | B0 V | 1.11 | 11, 2 | 36512 | B0 V | 0.02 | |
| 10 | +63° 1964 | B0 II | 0.99 | 12, 2 | 188209 | O9.5 Ia | 0.21 | |
| 11 | 225146 | B0 Ibp | 0.61 | 6, 2 | 64760 | B0.5 Ib | 0.10 | |
| 12 | +60° 261 | O7.5 III(n)((f)) | 0.64 | 13, 2 | 93222 | O7 III((ff)) | 0.37 | |
| 13 | 13338 | B1 V | 0.53 | 5, 2 | 31726 | B1 V | 0.05 | |
| 14 | +57° 513 | B1 III | 0.56 | 5, 2 | 74273 | B1.5 V | 0.03 | |
| 15 | 13659 | B1 Ib | 0.76 | 12, 2 | 40111 | B1 Ib | 0.15 | |
| 16 | 14442 | O6f | 0.75 | 14, 2 | 93222 | O7 III((f)) | 0.37 | |
| 17 | 14250 | B1 IV | 0.61 | 15, 2 | 55857 | B0.5 V | 0.02 | |
| 18 | 21291 | B9 Ia | 0.42 | 4, 16 | 202850 | B9 Iab | 0.13 | RN |
| 19 | 34078 | O9.5 Ve | 0.52 | 4 | 38666 | O9.5 IV | 0.01 | RN, var.? |
| 20 | 38131 | B0.5 V | 0.50 | 5, 2 | 55857 | B0.5 V | 0.02 | |
| 21 | 40893 | B0 IV | 0.45 | 17, 2 | 36512 | B0 V | 0.02 | |
| 22 | 37674 | B3 Vn | 0.14 | 4, 18 | 32630 | B3 V | 0.02 | RN, D |
| 23 | 37903 | B1.5 V | 0.38 | 19, 20 | 74273 | B1.5 V | 0.03 | RN |
| 24 | 38087 | B5 V | 0.24 | 19, 18 | 147394/32630 | B5 IV/B3 V | 0.01/0.02 | RN |
| 25 | 46711 | B3 II | 1.07 | 21, 2 | 79447 | B3 III | 0.02 | |
| 26 | 53367 | B0 IVe | 0.73 | 4 | 36512 | B0 V | 0.02 | RN |
| 27 | 53974 | B0.5 IV | 0.33 | 4 | 34816 | B0.5 IV | 0.03 | RN |
| 28 | 114213 | B1 Ib | 1.14 | 22 | 40111 | B1 Ib | 0.15 | |
| 29 | 152408 | O8 If | 0.49 | 23, 24 | 188209 | O9.5 Ia | 0.21 | |

[a] RN: Program star illuminates reflection nebula. D: Double star. var: variability of spectrum or visual brightness possible.

REFERENCES.—If two reference numbers are given, the first refers to the source of the spectral type and the second to the source of photometry. (1) Johnson and Morgan 1953. (2) Hiltner 1956. (3) Jaschek, Conde, and de Sierra 1964. (4) Racine 1968. (5) Baerentzen *et al.* 1967. (6) Morgan, Code, and Whitford 1955. (7) Blanco *et al.* 1968. (8) Hiltner and Johnson 1956. (9) Guetter 1968. (10) Guetter 1974. (11) Münch 1957. (12) Kristenson and Rudkjobing 1965. (13) Walborn 1973. (14) Conti 1973. (15) Slettebak 1968. (16) Johnson 1965. (17) Buscombe 1980. (18) Schild and Chaffee 1971. (19) Guetter 1979. (20) Lee 1968. (21) Walker 1963. (22) Feast *et al.* 1961. (23) Conti and Leep 1974. (24) Lake 1965.

were generally obtained in each of the wavelength ranges of the *IUE* cameras so that the flux level at all wavelengths could be completely included in the limited dynamic range of the detectors. The subsequent normalization and integration of the data into a single spectrum for each star has been described previously (Witt, Bohlin, and Stecher 1981).

The extinction curves were derived via the pair method. We used as flux standards lightly reddened stars of corresponding spectral types and luminosity classes from the *IUE Ultraviolet Spectral Atlas* (Wu *et al.* 1983). The standard stars are listed together with the corresponding program stars in Table 1, where also the respective MK spectral types and color excesses $E(B-V)$ are given for both. The standard stars were dereddened by applying the *average* galactic reddening curve of Savage and Mathis (1979) in proportion to the vaue of $E(B-V)$ shown for the respective stars in Table 1. While in most cases the reddening of the standard stars was small compared to that of the corresponding program stars, instances such as the pairs 12 and 16 should be noted, where the reddening of the standard star HD 93222 is as large as 50% to 60% of the reddening of the program stars. Any anomaly in the extinction of HD 93222 could influence the resulting extinction curves for the two program stars appreciably.

The extinction curves, normalized to unit $E(B-V)$, are shown in Figure 1. On the same scale with each extinction curve we show the *average* galactic extinction law of Savage and Mathis (1979), which allows a quick assessment of the direction and the degree of any deviations from the average law found in each case. Note, that the strong feature near $\lambda^{-1} = 8.2$ results from a mismatch at Ly$\alpha$, which in the fainter program stars is significantly filled in by geocorona emission, simulating weaker extinction. This feature should be ignored. The slight elevation in extinction near $\lambda^{-1} = 6.4$ in the average galactic extinction law is not present in any of our curves. Massa, Savage, and Fitzpatrick (1983) have explained this elevation as resulting from a mismatch error across the C IV feature affecting extinction curves derived from *TD-1* data. These *TD-1* data were included by Savage and Mathis (1979) in determining the average galactic extinction law. Since it is spurious, no importance should therefore be attached to the $\lambda^{-1} = 6.4$ feature.

For a quantitative characterization of the individual reddening curves the extinction parameters $E(\text{Bump})/E(B-V)$, $E(2160-V)/E(B-V)$ and $E(1250-V)/E(B-V)$ of Massa, Savage, and Fitzpatrick (1983) were measured and summarized in Table 2 in order of galactic longitude of the program stars. The first parameter measured the strength of the mid-

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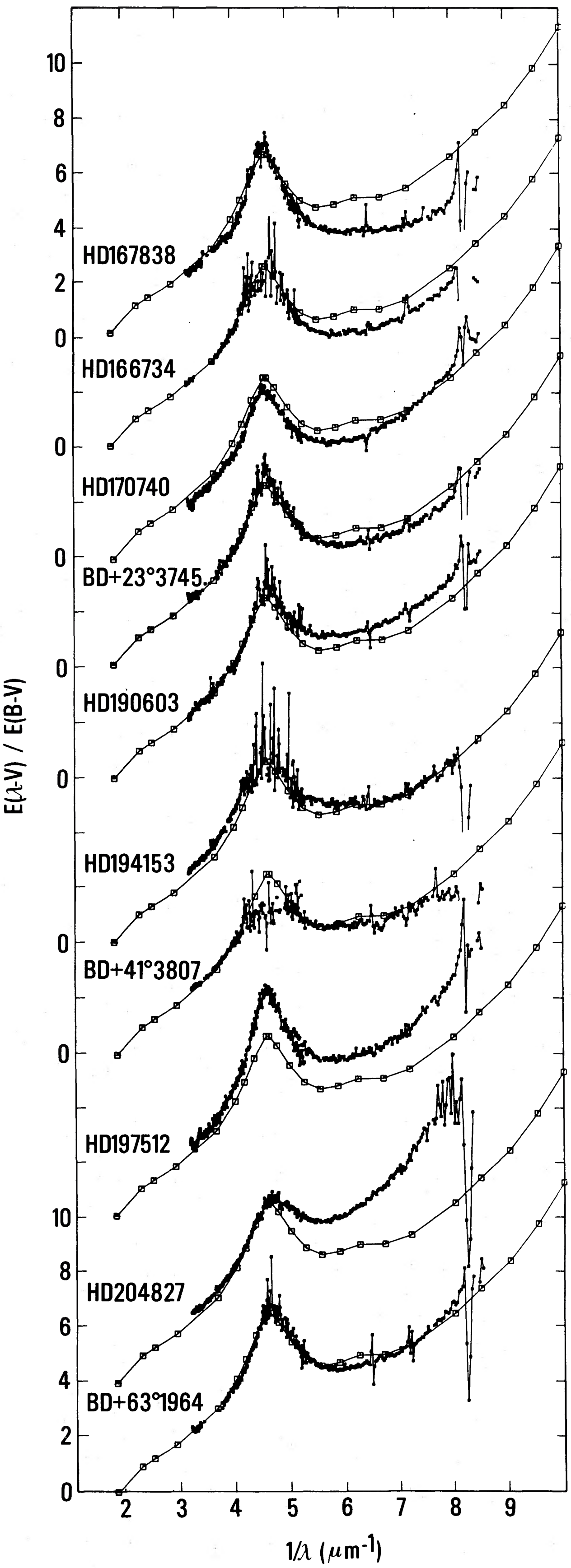


FIG. 1*a*

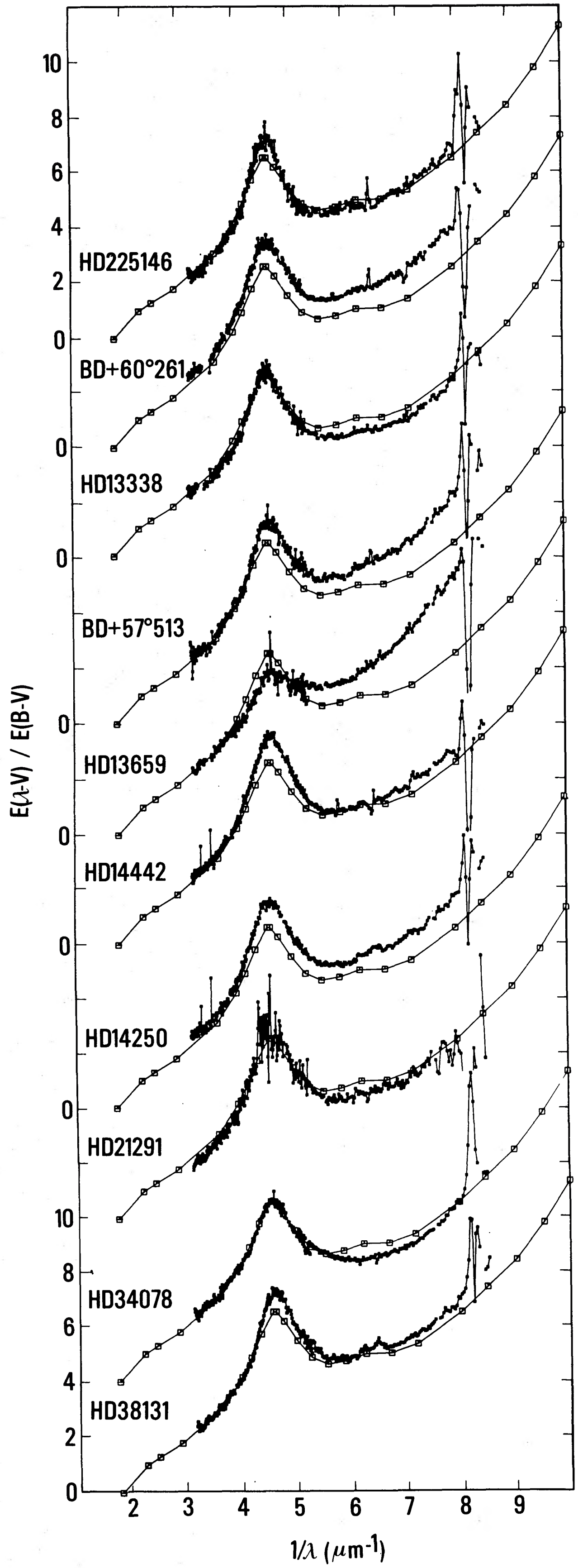


FIG. 1*b*

FIG. 1.—*IUE* extinction curves normalized to $E(B-V) = 1.0$ for our 29 program stars. The mean galactic extinction curve of Savage and Mathis (1979) is given by the open squares connected by solid lines in each case. The arrangement of the stars is in order of increasing galactic longitude as in Table 1.

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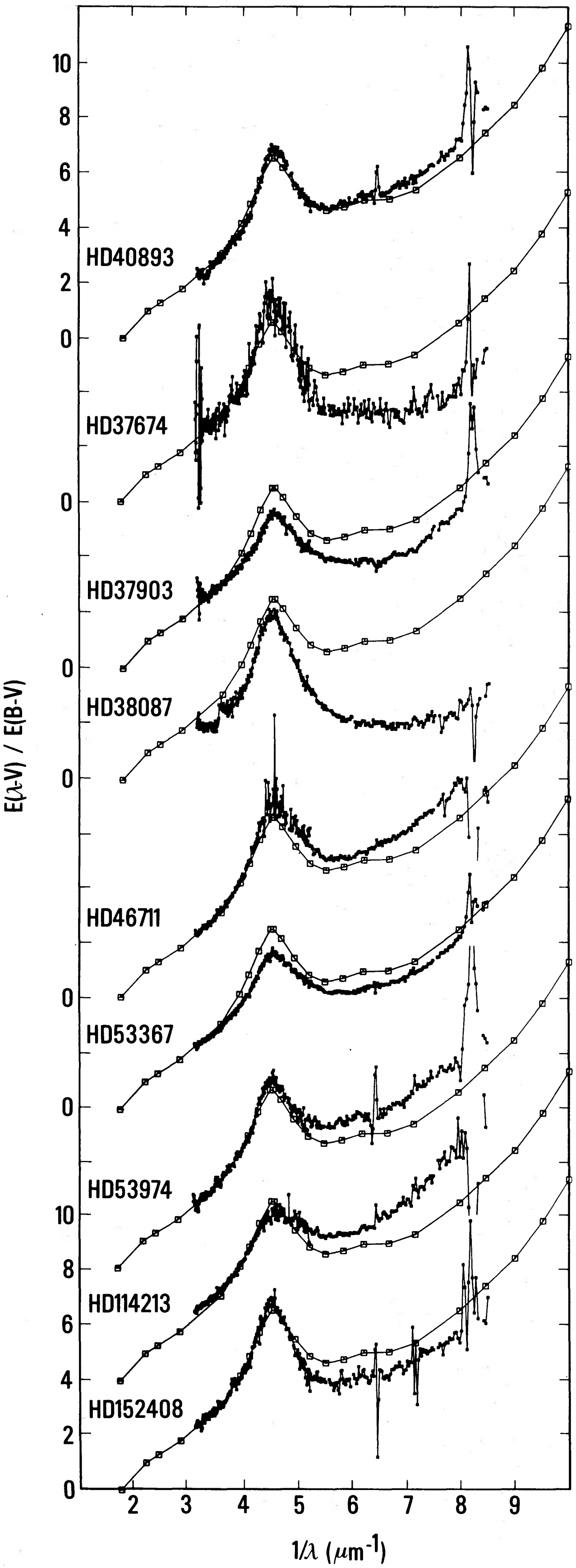


FIG. 1c

UV extinction bump and is defined as the normalized extinction at $\lambda^{-1} = 4.62$ $\mu m^{-1}$ above a linear interpolation of the extinction curve between $\lambda^{-1} = 3.50$ $\mu m^{-1}$ and $\lambda^{-1} = 5.75$ $\mu m^{-1}$. The second and third parameters measure the relative magnitude of extinction in the mid-UV ($\lambda^{-1} = 4.62$ $\mu m^{-1}$) and in the far-UV ($\lambda^{-1} = 8.0$ $\mu m^{-1}$) and are read off directly from the normalized extinction curves.

As discussed by Kester (1981) and by Massa, Savage, and Fitzpatrick (1983), errors in these parameters consist of contributions of random errors as well as systematic errors, which are especially difficult to estimate in the case of stars of luminosity classes I and II. For stars of luminosity classes III–V Massa *et al.* estimate a total error $\sigma = 0.24/E(B-V)$ at $\lambda^{-1} = 6.45$ $\mu m^{-1}$, where $E(B-V)$ is the color excess of the respective program star.

The photometry for each star was checked among independent sources and was found to be within the standard errors of $\Delta V \approx \pm 0.02$ and $\Delta(B-V) \approx \pm 0.01$. In many of our observed cases the deviations between derived extinction curves and the galactic mean curve are substantially larger than can be accounted for in terms of the combined errors. We will, therefore, proceed with the assumption that the major source of deviations between the extinction curves for our program stars and the average galactic extinction law is due to differences in dust properties in different galactic regions.

The parameter $E(\text{Bump})/E(B-V)$, representing a differential measurement over a relatively restricted wavelength interval (2857–1740 Å), is less subject to systematic errors, but is affected by lower signal-to-noise ratios near 2160 Å for some of the more reddened stars, as evident in Figure 1.

In Table 2 we also provide an estimate for the distance of our program stars, based on their observed $V$ magnitude, $E(B-V)$ color excess, and spectral-luminosity type. A value of $R_V = A_V/E(B-V) = 3.1$ and the absolute magnitudes of Balona and Crampton (1974) were adopted for this purpose. Stars associated with reflection nebulae and stars seen in dusty, nebulous regions as apparent on the *Palomar Observatory Sky Survey* (Blue) are identified in Table 2. We have been informed after the submission of this paper that five of our program stars have also been studied for their far-UV extinction in a Ph.D. thesis by Seab (1982).

## III. ANALYSIS

### *a*) *Deviation from the Average Galactic Extinction Law*

The extinction curves for our program stars, arranged in order of increasing galactic longitude in Figures 1*a*, 1*b*, and 1*c*, exhibit various degrees of deviation from the average galactic extinction law. As possible reasons for such deviations we must consider classification errors, stellar spectral peculiarities, secondary star contamination, uncertain visual photometry and, finally, peculiar extinction.

The spectral types given in Table 1 have been compared to those found in independent investigations on each star, and a detailed comparison has been made between the UV spectra of our program stars obtained with *IUE* with those of the respective standard stars. It is our assessment that no gross classification errors in excess of 0.1 to 0.2 of a spectral type exist among our stars. Spectral peculiarities where evident from the visual spectra are so indicated through the MK spectral type. One star, HD 166734, is a



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TABLE 2

DERIVED UV EXTINCTION PARAMETERS

| Program Star (HD, BD) | $l$ | $b$ | $d$(kpc) | $\frac{E(\text{Bump})}{E(B-V)}$ | $\frac{E(2160-V)}{E(B-V)}$ | $\frac{E(1250-V)}{E(B-V)}$ | $R$[a] |
|---|---|---|---|---|---|---|---|
| 167838 | 15°8 | +0°3 | 2.6 | 3.5 | 6.7 | 4.9 | 1 |
| 166734 | 19.3 | +3.0 | 2.1 | 2.5 | 6.2 | 6.0 | 1 |
| 170740 | 21.5 | −1.1 | 0.3 | 2.8 | 6.2 | 6.7 | 2 |
| +23° 3745 | 59.9 | −0.4 | 2.0 | 3.3 | 6.9 | 6.2 | 1 |
| 190603 | 69.9 | +0.1 | 1.3 | 3.0 | 7.0 | 7.3 | 2 |
| 194153 | 76.8 | +0.4 | 1.5 | 2.5 | 6.5 | 6.5 | 1 |
| +41° 3807 | 80.6 | −0.8 | 1.3 | ... | ... | 5.9 | 1 |
| 197512 | 88.2 | +4.5 | 1.1 | 3.8 | 8.3 | 8.7 | |
| 204827 | 99.7 | +5.6 | 0.5 | 2.1 | 6.7 | 10.8 | |
| +63° 1964 | 113.2 | +3.3 | 1.2 | 3.0 | 6.7 | 7.0 | |
| 225146 | 117.6 | −1.0 | 2.9 | 3.5 | 7.3 | 6.9 | |
| +60° 261 | 128.3 | −1.0 | 2.2 | 3.1 | 7.4 | 7.9 | |
| 13338 | 133.5 | −3.3 | 1.3 | 3.1 | 6.7 | 6.5 | |
| +57° 513 | 133.9 | −2.7 | 2.4 | 3.2 | 7.2 | 8.3 | |
| 13659 | 134.2 | −4.1 | 2.3 | 1.9 | 5.9 | 9.5 | |
| 14442 | 134.2 | −1.3 | 2.4 | 3.6 | 7.5 | 6.9 | |
| 14250 | 135.2 | −3.3 | 1.4 | 3.4 | 7.5 | 7.7 | |
| 21291 | 141.9 | +3.3 | 1.0 | 3.1 | 6.6 | 6.3 | 2 |
| 34078 | 172.5 | −1.7 | 0.5 | 2.9 | 6.6 | 6.9 | 2 |
| 38131 | 175.0 | +3.7 | 1.1 | 3.3 | 7.3 | 7.0 | |
| 40893 | 180.1 | +4.3 | 2.3 | 3.0 | 6.9 | 7.2 | |
| 37674 | 206.3 | −15.9 | 0.5 | 4.0 | 7.0 | 4.1 | 2 |
| 37903 | 207.2 | −16.0 | 0.5 | 2.2 | 5.6 | 5.8 | 2 |
| 38087 | 207.4 | −15.7 | 0.5 | 3.5 | 6.3 | 4.1 | 2 |
| 46711 | 209.0 | −2.0 | 1.0 | 2.9 | 6.8 | 8.0 | 1 |
| 53367 | 224.1 | −1.4 | 0.7 | 2.2 | 5.7 | 6.2 | 2 |
| 53974 | 225.3 | −1.3 | 0.5 | 2.9 | 6.9 | 7.6 | 2 |
| 114213 | 305.6 | +1.0 | 1.5 | 2.0 | 6.2 | 8.4 | |
| 152408 | 344.5 | +0.9 | 1.9 | 3.4 | 6.8 | 5.7 | 1 |
| Galactic average[b] | ... | ... | ... | 2.74 | 6.52 | 6.52 | |

[a] (1) Stars in reflection nebulae. (2) Stars seen in dusty, nebulous regions.
[b] Based on Savage and Mathis 1979.

confirmed spectroscopic binary; HD 166734 has two nearly identical components (Conti *et al.* 1980) with a spectral type difference comparable to the spectral type uncertainty of single stars. This fact has been taken into account in the distance estimate (Table 2). Another star, HD 37674, is considered a likely spectroscopic binary (Abt 1970; Guetter 1976). No information concerning possible duplicity among the remaining stars was found despite an extensive search of the literature.

Following Meyer and Savage (1981), the relation of our extinction curves at $\lambda^{-1} = 4.6$ and at $\lambda^{-1} = 8.0$ with respect to the average galactic law can be classified as weak (W), normal (N), or strong (S). Our set of extinction curves contains at least one example for eight of the nine possible combinations. The missing combination is WN, although BD +41°3807 could be such a case. As pointed out by de Boer (1983) in the case of HD 37903, a curve rated WW could well be an example of "normal" UV-extinction but peculiar visual extinction, if the normalization base is shifted from the $B-V$ region to the UV. Similarly, a curve rated SS (e.g., HD 14250) could, when renormalized, be consistent with normal UV extinction but weaker than normal extinction in the visual and IR. On the other hand, curves rated as NS (HD 204827), WS (HD 13659), SN (HD 225146), NW (HD 38087), and SW (HD 37674) should be considered true examples of "peculiar" UV extinction behavior, since they indicate independent variations of the dust components responsible for the 2175 Å bump and the far-UV extinction rise, respectively.

Nine of our 29 stars are considered to exhibit "normal" extinction behavior in the UV: HD 170740, BD +23°3745, HD 194153, BD +41°3807, BD +63°1964, HD 13338, HD 21291, HD 34078, and HD 40893, with a question remaining about the 2175 Å bump in BD +41°3807. Of these, five stars are of luminosity classes I–III, and three are stars in reflection nebulae. Among the 20 remaining cases rated peculiar, 10 are for high-luminosity stars, and six are stars in reflection nebulae. Thus, there is no evidence from our data that peculiar extinction curves are preferentially associated with any particular spectral type or luminosity class, or galactic environment.

### *b) Dense versus Diffuse Cloud Environments*

The distribution of the observed UV extinction parameters for all our program stars is shown in Figure 2, but a distinction is made between stars associated with dense cloud environments and stars reddened by diffuse clouds. While this distinction was made on the basis of the appearance of the star's environment on the *Palomar Sky Survey*, the grouping is confirmed as significant when one evaluates the value of the statistical mean $\langle E(B-V)/d(\text{kpc})\rangle$ for the stars involved. For stars in dense cloud environments we find

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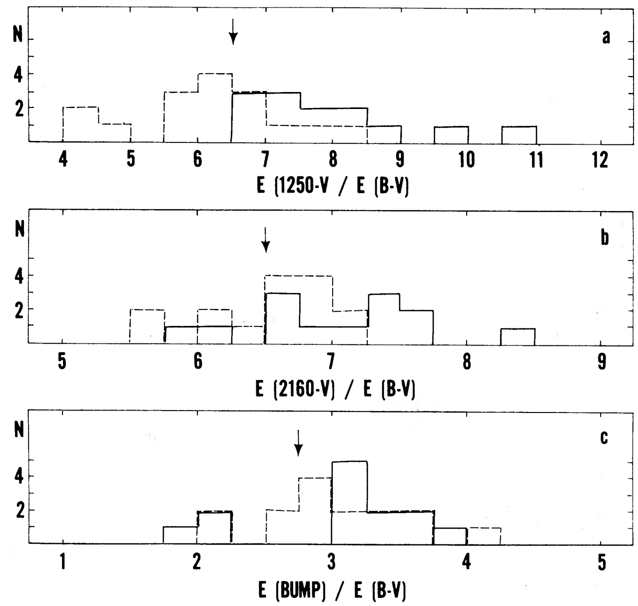


FIG. 2.—The distribution of the program stars over the values of the three UV extinction parameters. Stars associated with dense clouds and nebulous regions are represented by dotted lines; stars reddened by diffuse interstellar clouds are shown by solid lines. The arrows in the three panels indicate the respective galactic mean values based on the mean extinction law of Savage and Mathis (1979).

$\langle E(B-V)/d(\mathrm{kpc})\rangle = 0.69 \pm 0.34$ (s.d.), while the stars seen through diffuse clouds yield $\langle E(B-V)/d(\mathrm{kpc})\rangle = 0.54 \pm 0.54$ (s.d.). The latter result is influenced strongly by HD 204827. If this star is removed from the sample of diffuse cloud stars, $\langle E(B-V)/d(\mathrm{kpc})\rangle = 0.40 \pm 0.18$ (s.d.). The difference between the two samples is then significant at better than a 99% confidence level.

We conducted an analysis of variance (AOV) study on the two samples with regard to their distributions over the possible values of the three UV extinction parameters. The results are given in Table 3. We note, while the two subsamples each have a broad range and substantial overlap with the other, the differences between the means of the two samples with regard to the overall level of continuous UV extinction measured at 1250 Å and at 2160 Å are significant at a high level. Stars reddened by diffuse clouds show stronger UV extinction relative to their $E(B-V)$ color excess, on the average, than stars reddened by more dense clouds. The relative strength of the 2175 Å bump, however, appears to be identical for these two environments, on the average. It should also be noted that in its overall characteristics, our *total* sample does not differ significantly from the "Galactic average" as defined by Savage and Mathis (1979). One needs to re-emphasize, however, that cloud density is only *one* parameter affecting the shape of the extinction curve. In each density environment a wide range of variation does still occur, resulting from other influences, as is illustrated in Figure 2.

### c) *Galactic Longitude Dependence*

While our sample of stars extends fairly evenly over the range of galactic longitudes $15° < l < 345°$, the number density of stars is insufficient to establish the existence of a galactic longitude dependence of UV extinction characteristics independently. It is instructive, however, to examine our sample for consistency with independent results of other authors. Nandy *et al.* (1976), from a study involving *TD-1* observations of more than 100 stars, have identified zones of galactic longitude where the UV extinction curve is steep ($A_{1400}/A_{2740} > 1.8$) compared to others where the curve is less steep ($A_{1400}/A_{2740} < 1.8$), on the average. Of our stars, 15 fall into the regions with steep extinction curves, and we find for them $\langle E(1250-V)/E(B-V)\rangle = 7.49 \pm 1.36$, while the remaining 14 stars in regions reported to have less steep UV extinction curves yield $\langle E(1250-V)/E(B-V)\rangle = 6.33 \pm 1.33$. This difference is significant at better than 95% confidence level. Similarly, when one compares the average $E(1550-V)/E(B-V)$ values found by Meyer and Savage (1981) for different regional groups among the nearly 1400 stars of their *ANS* study with the averages of $\langle E(1250-V)/E(B-V)\rangle$ for subsamples of our stars falling into those regions, a positive correlation with a correlation coefficient $r = 0.98$ results.

Finally, Morgan, McLachlan, and Nandy (1982) report that stars located in the Perseus arm at distances $d \geq 1.7$ kpc show significantly higher extinction shortward of 2000 Å than the galactic average. The stars from BD +60°261 to HD 14250 in Figure 1 fall into the longitude range studied by Morgan *et al.*, and they all show excess UV extinction except for HD 13338, which as the closest of the group with $d = 1.3$ kpc is probably not affected by dust in the Perseus arm. It is important to note that there is no overlap in the samples of stars examined with *IUE* by Morgan *et al.* and by us.

The high degree of consistency between our extinction results and those of other authors, using different instruments and different stars, strongly suggests that the substantial deviations of individual extinction curves from the galactic

TABLE 3

ANALYSIS OF VARIANCE: DENSE VERSUS DIFFUSE CLOUDS

| Item | $\left\langle \frac{E(B-V)}{d(\mathrm{kpc})} \right\rangle$ | $\left\langle \frac{E(1250-V)}{E(B-V)} \right\rangle$ | $\left\langle \frac{E(2160-V)}{E(B-V)} \right\rangle$ | $\left\langle \frac{E(\mathrm{Bump})}{E(B-V)} \right\rangle$ | Sample Size |
|---|---|---|---|---|---|
| Dense cloud stars | 0.69 ± 0.34 | 6.14 ± 1.10 | 6.52 ± 0.44 | 2.98 ± 0.51 | 16 |
| Diffuse cloud stars | 0.54 ± 0.54<br>(0.40 ± 0.18) | 7.91 ± 1.23 | 7.05 ± 0.62 | 3.00 ± 0.62 | 13 |
| Significance of difference | (99%) | 99.9% | 99% | 0 | ... |
| Total sample | 0.62 ± 0.44 | 6.93 ± 1.45 | 6.76 ± 0.59 | 2.99 ± 0.55 | 29 |
| "Galactic average" | 0.6 | 6.52 | 6.52 | 2.74 | ... |

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average found among our sample of 29 stars are real. This result, then, lends support to the important contention of Massa, Savage, and Fitzpatrick (1983) that "peculiar" interstellar extinction in the UV is common.

## IV. CONCLUSIONS

1. New low-resolution spectrophotometric observations have been obtained for 29 early-type stars, which had not previously been examined for ultraviolet interstellar extinction by *IUE* at the time of their observation. Fifteen of these stars are objects for which the strength of the 4430 Å diffuse interstellar band per unit $E(B-V)$ strongly deviates from the galactic mean, and nine additional stars are the illuminating stars of reflection nebulae. Two-thirds of the UV extinction curves derived for these 29 stars deviate significantly from the average galactic extinction law in the UV.

2. Deviations in the strength of the 2175 Å extinction bump and in the steepness of the far-UV rise in extinction occur independently of each other, pointing toward two separate grain constituents for these two features.

3. Stars associated with dense interstellar clouds *on the average* show weaker UV extinction in the $\lambda < 2500$ Å range than do stars reddened by low-density diffuse clouds. However, density of the environment appears to be only one of several important factors. In particular, the average $E(1250-V)/E(B-V)$ of the dense cloud cases is strongly affected by three Orion stars (HD 37674, HD 37903, HD 38087), located closely together in the sky. Without these three stars, the average for the dense cloud stars is close to 6.5, the galactic average. In either case, the two groups of stars show wide dispersions in their UV extinction characteristics, with significant overlap.

4. The average galactic extinction in the UV for diffuse cloud stars, measured by $E(1250-V)/E(B-V)$ and $E(2160-V)/E(B-V)$, was found to be distinctly higher than the galactic average based on the mean galactic extinction law of Savage and Mathis (1979).

5. Previous claims by other authors regarding regional variations of UV extinction characteristics dependent on position in galactic longitude or on location within the Perseus arm have been substantiated by our data, albeit limited.

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## REFERENCES


Abt, H. A. 1970, *Ap. J. Suppl.*, **19**, 387.
Baerentzen, J., Gammelgaard, P., Hilberg, T., Jorgensen, K. F., Kristenson, H., Nissen, P. E., and Rudkjobing, M. 1967, *J. Obs*, **50**, 83.
Balona, L. A., and Crampton, D. 1974, *M.N.R.A.S.*, **166**, 203.
Blanco, V. M., Demers, S., Douglass, G. C., and FitzGerald, M. P. 1968, *Pub. US Naval. Obs., Series 11*, **21**.
Boggess, A., *et al.* 1978, *Nature*, **275**, 327.
Buscombe, W. 1980, *Fourth General Catalog of MK Spectral Classifications* (Evanston: Northwestern University).
Conti, P. S. 1973, *Ap. J.*, **179**, 161.
Conti, P. S., and Leep, E. M. 1974, *Ap. J.*, **193**, 113.
Conti, P. S., Massey, P., Ebbets, D., and Niemela, V. S. 1980, *Ap. J.*, **238**, 184.
de Boer, K. S. 1983, *Astr. Ap.*, **125**, 258.
Feast, M. W., Stoy, R. H., Thackeray, A. D., and Wesselink, A. J. 1961, *M.N.R.A.S.*, **122**, 239.
Guetter, H. H. 1968, *Pub. A.S.P.*, **80**, 197.
———. 1974, *Pub. A.S.P.*, **86**, 795.
———. 1976, *A.J.*, **81**, 537.
———. 1979, *A.J.*, **84**, 1846.
Hecht, J., Helfer, H. L., Wolf, J., Donn, B., and Pipher, J. L. 1982, *Ap. J.* (*Letters*), **263**, L39.
Hiltner, W. A. 1956, *Ap. J. Suppl.*, **2**, 389.
Hiltner, W. A., and Johnson, H. L. 1956, *Ap. J.*, **124**, 367.
Jaschek, C., Conde, H., and de Sierra, A. C. 1964, *Catalogue of Stellar Spectra Classified in the MK System, Obs. Astr. Univ. Nac. La Plata, Ser. Astr.* (*Argentina*), **28**, No. 2.
Johnson, H. L. 1965, *Ap. J.*, **141**, 923.
Johnson, H. L., and Morgan, W. W. 1953, *Ap. J.*, **117**, 313.
Kester, D. 1981, *Astr. Ap.*, **99**, 375.
Koorneef, J. 1978, *Astr. Ap.*, **68**, 139.
Kristenson, H., and Rudkjobing, M. 1965, *J. Obs.*, **48**, 108.
Lake, R. 1965, *M.N.A.S. South Africa*, **24**, 41.
Lee, T. A. 1968, *Ap. J.*, **152**, 913.
Massa, D., Savage, B. D., and Fitzpatrick, E. L. 1983, *Ap. J.*, **266**, 662.
Mathis, J. S., and Wallenhorst, S. G. 1981, *Ap. J.*, **244**, 483.
Meyer, D. M., and Savage, B. D. 1981, *Ap. J.*, **248**, 545.
Morales, C., Llorende de Andres, F., and Ruiz del Arbol, J. A. 1980, *Astr. Ap.*, **85**, 302.
Morgan, D. H., McLachlan, A., and Nandy, K. 1982, *M.N.R.A.S.*, **198**, 779.
Morgan, W. W., Code, A. D., and Whitford, A. E. 1955, *Ap. J. Suppl.*, **2**, 41.
Münch, G. 1957, *Ap. J.*, **125**, 421.
Nandy, K., Thompson, G. I., Jamar, C., Monfils, A., and Wilson, R. 1976, *Astr. Ap.*, **51**, 63.
Racine, R. 1968, *A.J.*, **73**, 223.
Savage, B. D., and Mathis, J. S. 1979, *Ann. Rev. Astr. Ap.*, **17**, 73.
Schild, R. E., and Chaffee, F. 1971, *Ap. J.*, **169**, 529.
Seab, C. G. 1982, Ph.D. thesis, University of Colorado.
Seab, C. G., Snow, T. P., and Joseph, C. L. 1981, *Ap. J.*, **246**, 788.
Sletteback, A. 1968, *Ap. J.*, **154**, 933.
Snow, T. P., and Seab, C. G. 1980, *Ap. J.* (*Letters*), **242**, L83.
Walborn, N. R. 1973, *A.J.*, **78**, 1067.
Walker, G. A. H. 1963, *Ap. J.*, **125**, 141.
Walker, G. A. H., Yang, S., Fahlman, G. G., and Witt, A. N. 1980, *Pub. A.S.P.*, **92**, 411.
Witt, A. N., Bohlin, R. C., and Stecher, T. P. 1981, *Ap. J.*, **244**, 199.
———. 1983, *Ap. J.* (*Letters*), **267**, L47.
Wu, C.-C., Bogges, A., Bohlin, R. C., Holm, A. V., Schiffer, F. H., and Turnrose, B. E. 1983, *IUE Ultraviolet Spectral Atlas*, in preparation.


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