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THE CORRELATION BETWEEN THE ULTRAVIOLET λ 2200 FEATURE AND THE DIFFUSE λ 4430 BAND

K. Nandy and G. I. Thompson

Royal Observatory, Edinburgh

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SUMMARY

Observations of the ultraviolet feature which occurs close to 2200 Å are presented for over 60 stars for which interstellar λ 4430 data are available in the literature. Observational material used here is obtained from the ultraviolet spectra taken with the Sky Survey telescope (S2/68) in the ESRO TD1 satellite. The equivalent widths of the λ 2200 feature have been determined from ultraviolet extinction at 2190 and 2500 Å, and the relation between the equivalent width of the ultraviolet feature and the central depth of the λ 4430 band has been determined. It is found that they are well correlated and the correlation coefficient, including allowance for errors, is greater than 0·9; this indicates that the carriers for the λ 2200 feature and diffuse band λ 4430 coexist in the interstellar medium.

1. INTRODUCTION

Recent stellar ultraviolet measurements have extended our knowledge of interstellar extinction into the region 3000–1200 Å. Of particular interest is the feature which appears as a peak in the extinction curve near 2200 Å, first reported by Stecher (1969) and confirmed by later satellite observations. Recently Nandy *et al.* (1975) have measured the equivalent width of this ultraviolet feature for about 100 stars and have found that the feature is well correlated with colour excess E_{B-V}, the correlation coefficient being 0·8; the equivalent width of this feature is found to be 450 Å per unit colour excess E_{B-V}. This feature thus removes light by several order of magnitudes more from stellar spectra than the light absorbed by unidentified diffuse interstellar features in the visible region. The origin of the diffuse features is still unknown. It has been suggested that the λ 2200 feature may originate from very small graphite particles of 200 Å radius (Wickramasinghe & Nandy 1974; Wickramasinghe *et al.* 1974). Since diffuse features in the optical region may be produced by dust, the correlation studies between the strength of the ultraviolet feature and the strength of other diffuse features in the visible will be of considerable interest.

Of 100 stars which were studied earlier very few stars have measurements of diffuse features in the visible. As a part of the general programme of the studies of interstellar extinction laws in the ultraviolet in different galactic regions from S2/68 data, we have extended the observations to much fainter and more reddened stars than those studied before. The measurements of interstellar extinction will be presented in a separate paper. In this paper we shall present the observations of the λ 2200 feature for those stars for which interstellar λ 4430 data are available and study the correlation between them. The λ 4430 band is the strongest of the diffuse features in the visible and most widely studied; the observational data of this band are taken from Baerentzen *et al.* (1967) and Herbig (1975).

2. OBSERVATIONS AND REDUCTIONS

Observational material presented in Table I is obtained from the ultraviolet spectra taken with the S2/68 Ultraviolet Sky Survey telescope in the European satellite TD1. The number of observations per star is four or more. The telescope and the spectrometer have been described by Boksenberg *et al.* (1973). The wavelength coverage is from 1350 to 2550 Å.

TABLE I

List of stars observed

HD number	Spectral type	V	E(U3–U2)	$W_{\lambda\,2200}$ (Å) from equation (1)	A_c (λ 4430) (%)
2083	B1 V	6·89	0·66	106	2·7
3360	B2 V	3·64	0·04	6	0·2
13267	B5 Ia	6·39	0·88	141	3·0
14489	A2 Ia	5·47	1·04	166	3·2
14818	B2 Ia	6·25	1·63	261	5·8
19243	B1 V	6·72	1·65	264	6·0
21291	B9 Ia	4·23	1·36	218	3·9
21389	A0 Ia	4·53	0·96	154	6·3
21803	B2 IV	6·40	0·86	138	3·6
21856	B1 V	5·91	0·59	94	2·7
22928	B5 III	3·03	0·11	18	1·1
23180	B1 III	3·82	0·76	122	3·9
23478	B3 IV	6·65	0·60	96	2·0
24131	B1 V	5·78	0·80	128	4·1
24398	B1 Ib	2·83	0·69	110	2·8
24431	O9 IV–V	6·72	1·85	296	5·8
24640	B2 V	5·48	0·68	109	2·5
30614	O9·5 Ia	4·29	0·94	150	2·8
30836	B2 III	3·69	0·18	29	2·3
31327	B2 Ib	6·06	1·61	258	3·2
32630	B3 V	3·16	0·02	3	0
33461	B2 V	7·78	1·04	166	2·7
33604	B2 V	7·33	0·71	114	2·7
34921	B0 IV	7·51	1·07	171	6·8
35468	B2 III	1·64	0·06	10	0·8
36822	B0 IV	4·40	0·31	50	3·6
36879	O6	7·58	1·84	294	5·8
39746	B1 II	7·04	1·44	230	6·8
39970	A0 Ia	6·02	1·23	197	5·4
40111	B1 Ib	4·83	0·60	96	3·4
40589	B9 Iab	6·05	1·23	197	4·4
40894	B2 V	7·56	0·41	66	2·7
41117	B2 Ia	4·63	1·33	213	6·0
41690	B1 V	7·71	1·37	219	5·6
42379	B1 II	7·37	1·47	235	6·6
42400	B5 II	6·84	0·93	149	3·6
43384	B3 Iab	6·28	0·89	182	5·6
43818	B0 II	6·92	1·36	218	8·0

TABLE I—*continued*

HD number	Spectral type	V	E(U3–U2)	$W_{\lambda\,2200}$ (Å) from equation (1)	A_c (λ 4430) (%)
47240	B1 Ib	6·15	0·90	144	5·3
91316	B1 Ib	3·85	0·31	50	2·2
103287	A0 V	2·43	0·04	6	0·2
147394	B5 IV	3·89	0·06	10	0·4
155763	B6 III	3·17	0·09	14	1·0
160762	B3 V	3·80	0·19	30	0·6
166937	B8 Ia	3·86	0·61	98	4·5
175544	B3 V	7·35	0·98	157	3·2
178129	B3 Ia	7·41	1·83	293	8·2
186980	O7·5	7·48	1·23	197	4·3
190066	B1 Iab	6·48	1·06	170	7·0
190603	B1·5 Ia	5·60	2·20	352	8·2
193443	O9 III	7·23	2·10	336	7·0
197770	B2 IV	6·32	1·38	220	3·6
198183	B5 V	4·54	0·14	22	0·2
198478	B3 Ia	4·82	1·35	216	7·2
199579	O6	5·96	0·81	130	4·1
202860	B9 Iab	4·22	0·50	80	1·7
204172	B0 Ib	5·93	0·49	78	3·6
204710	B8 Ib	6·95	0·82	131	4·6
207198	O9 II	5·96	2·08	333	6·5
210072	B2 V	7·65	1·53	245	6·1
210809	O9 Ib	7·56	0·87	139	3·6
224151	B0·5	6·00	1·09	174	4·8

Since the broad extinction feature near 2200 Å is nearly symmetrical (Bless & Savage 1972; Nandy *et al.* 1975) and extends from 1700 to 2500 Å, the peak occurring near 2160 Å, the difference in extinction E(2190–2500) is linearly related to the strength of the feature, as will be shown. Because of strong extinction near 2190 Å, the fluxes of faint and strongly reddened stars at this wavelength are weak. In order to achieve greater photometric accuracy the magnitudes at 2500 and 2190 Å are obtained from sets of three consecutive spectral data points centred at 2190 and 2500 Å respectively. These magnitudes designated as U2 and U3 have an effective passband of 75 Å. The mean photometric error of the ultraviolet colour (U3–U2) obtained in this way is $\pm 0{\cdot}05$ for stars brighter than $V = 5^{m}{\cdot}0$ rising to $\pm 0{\cdot}15$ for fainter stars.

The intrinsic colour (U3–U2) has been obtained from the study of a large number of unreddened or slightly reddened stars; corrections were applied for small amounts of reddening by using the mean extinction law derived from the S2/68 data (Nandy *et al.* 1975). The intrinsic colour (U3–U2) for main sequence and supergiants is shown in Fig. 1. There are insufficient unreddened stars of luminosity of class II and III, and $(U3–U2)_0$ for these luminosity classes is taken as the same as for the corresponding main sequence stars. However, the luminosity effect on the ultraviolet colour (U3–U2) is clearly present. The colour index $(U3–U2)_0$ changes very slowly with spectral type, and therefore the colour excess E(U3–U2) is not very sensitive to uncertainty of MK spectral type. The colour excess E(U3–U2), computed from the observed colour is given in column 4 of Table I.

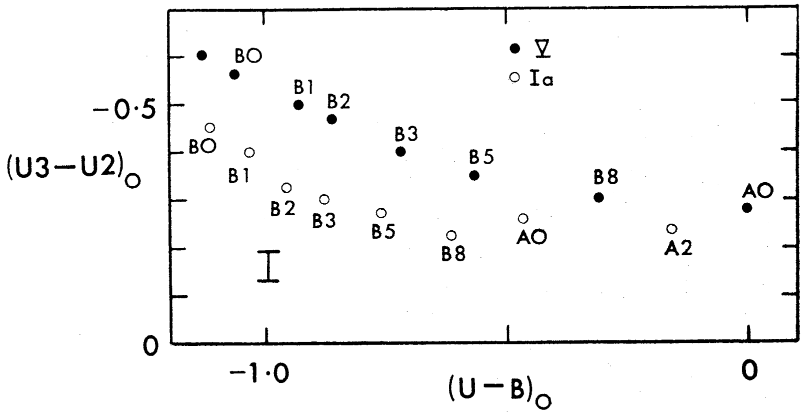

FIG. 1. *Intrinsic ultraviolet colour* $(U3-U2)_0$ *vs* $(U-B)_0$*;* $(U-B)_0$ *has been taken from Johnson* (1966).

The relation between the equivalent width of the λ 2200 feature and the colour excess E(U3–U2) has been established in the following way:

The central depth of the λ 2200 band has been measured from the extinction curve for the visible to ultraviolet wavelength range derived from the comparison of the reddened and slightly reddened star. This comparison method removes the difficulty of ascertaining a stellar continuum over the extent of the band which is about 1000 Å. Using the visible data from the literature and ultraviolet observations

TABLE II

Pairs of stars compared

HD number	Spectral type	V	HD number	Spectral type	V	ΔE_{U3-U2}	$W_{\lambda\,2200}$ (Å)
21856	B1 V	5·91	36512	B0 V	4·60	0·50	80
23793	B3 V	5·06	3360	B2 V	3·66	0·09	21
25558	B3 V	5·32	3360	B2 V	3·66	0·34	50
27192	B2 IV	5·54	3360	B2 V	3·66	0·70	125
30614	O9·5 Ia	4·29	37128	B0 Ia	1·70	0·68	130
32990	B2 V	5·50	3360	B2 V	3·66	0·84	137
36819	B3 V	5·36	3360	B2 V	3·66	0·28	50
41117	B2 Ia	4·63	40111	B1 Ib	4·80	1·10	166
41690	B1 V	7·72	36959	B1 V	5·67	1·30	209
42088	O6	7·54	36861	O8	3·39	0·84	127
46966	O8	6·86	36861	O8	3·39	0·51	94
47129	O8	6·06	36861	O8	3·39	0·77	107
48099	O6	6·37	36861	O8	3·39	0·72	100
48434	B0 III	5·91	36512	B0 V	4·62	0·56	62
54662	O6	6·21	36861	O8	3·39	0·82	127
142096	B3 V	5·02	35299	B2 V	5·71	0·35	65
149757	O9 V	2·56	36512	B0 V	4·60	0·57	67
175876	O6	6·95	36861	O8	3·39	0·32	78
188209	O9·5 III	5·62	36861	O8	3·39	0·40	60
190603	B1·5 Ia	5·60	40111	B1 Ib	4·80	1·80	286
192639	O8	7·11	36861	O8	3·39	1·74	250
193322	O8	5·84	36861	O8	3·39	0·90	150
199579	O6	5·95	36861	O8	3·39	0·56	104
204172	B0 Ib	5·93	37128	B0 Ia	1·70	0·33	54
209481	O9 V	5·56	36512	B0 V	4·62	0·90	138
212593	B9 Ia	4·56	34085	B8 Ia	0·08	0·35	68

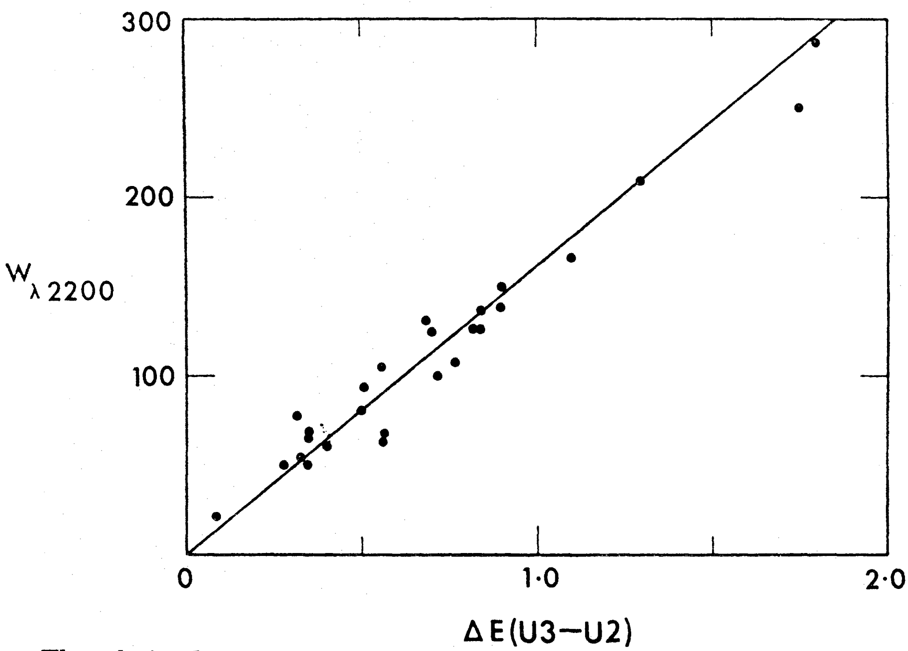

FIG. 2. *The relation between the ultraviolet colour excess E(U3–U2) and the equivalent width of the λ 2200 feature.*

from TD1 for the same pairs of stars, the extinction curves in the wavelength range from near infrared to 1350 Å have been obtained for 26 pairs as listed in Table II. The selection of comparison stars depends on the availability of data, and no corrections have been applied for spectral type mismatch. In each extinction curve a third order polynomial has been fitted to all the points excluding the wavelength region 2550–1700 Å over which the band occurs. The absorption at the centre of the band magnitude A is measured with respect to this polynomial, and the central depth r_c (λ 2200) $= 1-10^{-0.4A}$. The error of centre absorption A due to uncertainty of polynomial fitting is not more than $0^m.1$.

The equivalent width, $W_{\lambda\,2200}$, is obtained by multiplying the central depth, r_c (λ 2200), by the half width of the feature, which is 360 ± 20 Å (Nandy *et al.* 1975). The plot of colour excess difference between the reddened and comparison star, E(U3–U2) and the equivalent width in Ångströms of the λ 2200 feature (*cf.* column 2 and 3 of Table II) is shown in Fig. 2, and giving equal weight to each point, the relation between E(U3–U2) and $W_{\lambda\,2200}$ is given by

$$W_{\lambda\,2200} = 160 . E(\mathrm{U3{-}U2})\ \text{Å mag}^{-1}. \qquad (1)$$

The resulting error of $W_{\lambda\,2200}$ due to photometric error of (U3–U2) and uncertainty of the central depth is less than ± 25 Å.

For each of the stars of Table I the equivalent width $W_{\lambda\,2200}$ is obtained from (1) and is given in column 4. The central depth of the λ 4430 band is taken from Herbig (1975) and Baerentzen *et al.* (1967). The catalogue of Baerentzen *et al.* gives photoelectrically determined intensities of the strength of the λ 4430 band; the zero-point of the index has been determined by Gammelgard (1968). From the stars common to the studies of Herbig and Baerentzen *et al.*, the relation between their measures of the central depth A_c (λ 4430) is obtained, and the λ 4430 indices of Baerentzen *et al.* reduced to Herbig's scale are given in column 5 of Table I.

3. RESULTS

The correlation between the strength of the λ 4430 band and visual colour excess E_{B-V} has been studied by various authors. From a detailed investigation, Herbig (1975) has shown that the strength of the λ 4430 band is well correlated with E_{B-V}, the correlation coefficient being 0·92 ± 0·02; the correlation coefficient between the λ 4430 band and the other principal diffuse features in the visible is 0·8 or higher.

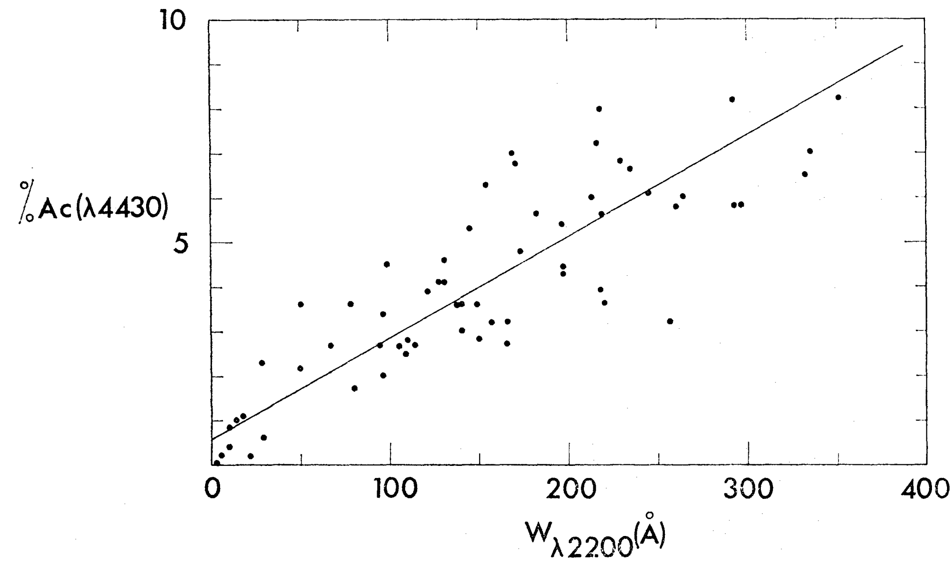

FIG. 3. *The relation between the equivalent width of the* λ 2200 *feature and the central depth of the* λ 4430 *band.*

In this paper we shall study the correlation between $W_{\lambda 2200}$ and A_c (λ 4430) using the statistical model outlined by Deeming (1968). Fig. 3 shows the plot of $A_{c(4430)}$ *vs* $W_{\lambda 2200}$. The slope of the best line fit is given by

$$m = \{(\sigma_y{}^2 - \epsilon_y{}^2)/(\sigma_x{}^2 - \epsilon_x{}^2)\}^{1/2} \tag{2}$$

and

$$c = \bar{y} - m.\bar{x} \tag{3}$$

where σ_x and σ_y are the variances from the mean $\bar{A}_c$ (λ 4430) and $W_{\lambda 2200}$ respectively, $\epsilon_x{}^2$ and $\epsilon_y{}^2$ are the mean square values of the errors of A_c (λ 4430) and $W_{\lambda 2200}$ respectively. The correlation coefficient including allowance for errors is given by

$$R = \frac{\text{cov}\,(x, y)}{\{(\sigma_y{}^2 - \epsilon_y{}^2)(\sigma_x{}^2 - \epsilon_x{}^2)\}^{1/2}} \tag{4}$$

where $\text{cov}\,(x, y) = \bar{x}\bar{y} - \bar{x}.\bar{y}$.

The error of $W_{\lambda 2200}$ is obtained from directly computed standard errors of (U3–U2) for a number of observations. The error of individual measurements of λ 4430 strength is given by the authors. The best straight line fit through the plotted data in Fig. 3 is shown by the solid line and the correlation coefficient between $W_{\lambda 2200}$ and A_c (λ 4430) including allowance for errors is 0·93.

Present results differ from those of Wu (1972) who found a much smaller correlation between λ 4430 and $E(2175–3500)$; this may be partly due to his small sample of stars.

CONCLUSIONS

The strengths of the λ 4430 and λ 2200 interstellar features are well correlated. This correlation does not necessarily indicate that both features are produced by the same agent but that their carriers coexist in interstellar medium.

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