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R_v-DEPENDENT OPTICAL AND NEAR-ULTRAVIOLET EXTINCTION

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ABSTRACT

We have derived extinctions $A(\lambda)/A(V)$ at the wavelengths of the *uvby* filters for 22 stars, with a range of values of R_v, from the sample of Cardelli, Clayton, & Mathis (1989, hereafter CCM). We have fit these extinctions, and also *UBVRIJHKL*, *IUE* and *ANS* extinction measurements, with linear relations $A(\lambda)/A(V) = a + b/R_v$ and fit a and b as a function of $x(=1/\lambda)$ with polynomials to obtain an R_v-dependent mean extinction law $[A(x)/A(V) = a(x) + b(x)/R_v]$ in the optical and near-ultraviolet (1.1 μm$^{-1} \le x \le 3.3$ μm^{-1}.) This law is virtually identical to the CCM extinction law for large values of R_v ($R_v \sim 5$) but is slightly lower in the near-ultraviolet for smaller R_v ($R_v \sim 3$). The extinction law presented here agrees much better with a high-resolution extinction curve for the diffuse interstellar medium ($R_v \sim 3.1$), presented by Bastiaansen (1992), than CCM. The deviations of individual extinction curves from the mean are dominated by observational errors. The wavelength resolution of this work is not high enough to show evidence for or against the existence of very broad structure in optical extinction curves.

Subject headings: dust, extinction

1. INTRODUCTION

Cardelli, Clayton, & Mathis (1989, hereafter CCM) found that $A(\lambda)/A(V)$, the interstellar extinction at wavelength, λ, relative to that at V, could be characterised by one parameter, over a wavelength range from about 1 μm to about 0.1 μm and possibly to shorter wavelengths which have not yet been observed. CCM choose this parameter to be R_v, the ratio of total to selective extinction $[A(V)/E(B-V)]$ and gave expressions for a mean interstellar extinction curve in the form $A(x)/A(V) = a(x) + b(x)/R_v$, where $x = 1/\lambda$, usually measured in inverse microns (μm^{-1}). This formulation reproduces the Savage & Mathis (1979) or Seaton (1979) mean extinction curves with a value $R_v = 3.1$, the average value for the *diffuse* interstellar medium. The expression also reproduces the extinction of sight lines within dense regions, previously considered "peculiar" because they often have larger values of R_v and low far-ultraviolet extinction.

The CCM extinction relation was based upon Johnson-Perry *UBVRIJHKL* photometry in the near-infrared and optical and data from the *International Ultraviolet Explorer* satellite (*IUE*) for $\lambda \le 0.3$ μm. The functions $a(x)$ and $b(x)$ were found by considering the extinctions $A(\lambda)/A(V)$ of a sample of stars with various values of R_v. At each of several wavelengths λ_i, with corresponding wavenumbers x_i, a linear least-squares fit determined the coefficients $a(x_i)$ and $b(x_i)$ in the expression $A(\lambda_i)/A(V) = a(x_i) + b(x_i)/R_v$ for the sample. Then a rational expression was fit through the various values of $a(x_i)$ and $b(x_i)$ to yield a continuous expression for the extinction law.

Our research was motivated by the fact that between $x = 2.25$ μm^{-1} and $x = 3.33$ μm^{-1} there was a "gap" in the CCM law in which the only data point was the Johnson U filter, which might be unreliable for two reasons. First, the U filter spans the Balmer jump, so that extinctions measured in the U band are particularly sensitive to the assumed temperature and luminosity of a star and, therefore, possibly subject to large uncertainties. Second, the U filter has an ill-defined short-wavelength cutoff. Therefore, we extended the CCM mean extinction relation by means of measurements made in the Strömgren *uvby* system, which has well-defined filter responses, especially using v ($x = 2.44$ μm^{-1}) and u ($x = 2.86$ μm^{-1}.) We also used data from the *ANS* (*Astronomical Netherlands Satellite*) extinction excess catalog of Savage et al. (1985) at wavelengths of 3300 Å ($x = 3.03$ μm^{-1}) and 2500 Å ($x = 4.00$ μm^{-1}) (the latter being used for five stars for which *IUE* data were not available.)

In § 2 below, we describe how we selected a sample of stars and derived absolute extinctions $A(\lambda)/A(V)$. In § 3 we present the results of linear least-squares fits to these data and an extinction law based upon them, using the same form as CCM. Differences between this law and CCM are discussed here. A summary is presented in § 4.

2. FITTING THE EXTINCTION LAW

We chose all stars in the CCM sample which were also listed in the *uvby* photometry catalog of Hauck & Mermilliod (1980). We also included in our sample stars from the *ANS* extinction survey (Savage et al. 1985) which were (1) listed in the *uvby* catalog, (2) had measurements of R_v and (3) were in luminosity classes III to V, since intrinsic *uvby* colors are not well known for supergiants. The final sample of 22 stars (of which 16 were in the CCM sample) is listed in Table 1. Color indices $(b-y)$, m_1 and c_1 were obtained for each star by searching the SIMBAD database. Color indices $(v-y)$ and $(u-y)$ were derived from the Strömgren indices m_1, c_1, and $(b-y)$ by the relations

$$(v-y) = m_1 + 2(b-y) ,$$
$$(u-y) = c_1 + 2m_1 + 3(b-y) .$$

Color excesses were obtained for each program star by comparison with the dereddened *uvby* indices of lightly reddened standards (taken from Fitzpatrick & Massa 1990 and Cardelli, Sembach, & Mathis 1992.) Before the comparison was made, a

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TABLE 1

PROGRAM STARS

HD	Comparison	Spectral Type	R_v	$E(B-V)$	$(b-y)$	c_1	m_1	$E(b-y)$	$E(v-y)$	$E(u-y)$	Reference[a]
14250	62747	B1 III	2.85	0.58	0.310	0.122	−0.078	0.440	0.706	1.043	CCM
34078	38666	O9.5 V	3.42	0.52	0.247	−0.011	−0.078	0.379	0.617	0.957	CCM
36982	64802	B2 V	5.6	0.37	0.140	0.147	0.012	0.265	0.431	0.523	CCM
37022	47839	O6 p	5.5	0.31	0.064	−0.161	0.037	0.216	0.392	0.533	CCM
37023	55857	B0.5 V	5.23	0.37	0.126	−0.057	0.023	0.243	0.428	0.631	CCM
37061	55857	B0.5 Vp	5.1	0.55	0.254	−0.048	0.013	0.371	0.674	1.004	CCM
37903	74273	B1.5 V	4.11	0.36	0.129	0.100	0.054	0.244	0.454	0.743	CCM
38087	32360	B3 n	5.3	0.31	0.143	0.327	0.053	0.243	0.431	0.631	CCM
46202	38666	O9 V	3.12	0.48	0.207	−0.037	−0.022	0.339	0.593	0.923	CCM
48099	47839	O7 V	3.52	0.27	0.040	−0.115	0.019	0.192	0.326	0.471	CCM
62542	34759	B5 V	3.2	0.32	0.160	0.396	0.067	0.240	0.420	0.619	CS
144217	55857	B0.5 V	4	0.21	0.006	0.013	0.046	0.123	0.211	0.387	ANS
145502	3360	B3 V	4.1	0.25	0.072	0.150	0.059	0.192	0.347	0.524	ANS
147165	46328	B1 III	3.8	0.39	0.156	0.016	0.004	0.265	0.466	0.708	ANS
147889	64802	B2 V	4.2	1.09	0.643	0.045	−0.112	0.768	1.313	1.682	CCM
149757	38666	O9.5 V	3.09	0.32	0.085	−0.061	0.012	0.217	0.383	0.601	CCM
154445	31726	B1 V	3.15	0.39	0.180	0.087	−0.019	0.317	0.508	0.736	CCM
161056	74273	B1/2 V	3.09	0.63	0.338	0.145	−0.042	0.453	0.776	1.223	ANS
167771	47839	O7 III:(n)((f))	3.48	0.43	0.146	−0.092	−0.025	0.298	0.494	0.724	CCM
184915	119159	B0.5 III	3.1	0.28	0.079	−0.022	−0.014	0.214	0.342	0.512	ANS
193322	38666	O9 V:((n))	3.05	0.41	0.139	−0.036	0.008	0.271	0.487	0.780	CCM
229196	47839	O6 II:(n)(f)	3.12	1.22	0.718	0.021	−0.158	0.87	1.505	2.287	CCM

[a] Spectral type and $E(B-V)$ references; (CCM) Cardelli et al. 1989; (ANS) Savage et al. 1985; (CS) Cardelli & Savage 1988.

small reddening correction was applied to each of the comparison stars to deredden it to $E(b-y) = 0$. Two different methods of dereddening the comparison stars were tried. In the first case, $E(b-y)$ was calculated for each comparison star using the iterative procedure given by Shobbrook (1984). Here an estimate of $(b-y)_0$, the intrinsic color of a lightly reddened star, is obtained from the measured value of c_1 for that star by a polynomial relation between $(b-y)$ and c_1. This leads to a guess for c_0, the unreddened value of c_1, which can then be substituted into the polynomial to obtain a better estimated of $(b-y)_0$. In the second case the relation $E(b-y) = 0.74E(B-V)$ was used to obtain $E(b-y)$ for each of the comparison stars. The values we used for $E(B-V)$ are listed in Table 2 and are taken from Fitzpatrick & Massa (1990), Savage et al. (1985), and Cardelli & Savage (1988).

Once $E(b-y)$ was found, the relations (Crawford 1975)

$$m_0 = m_1 + 0.32E(b-y) ,$$

$$c_0 = c_1 - 0.20E(b-y) ,$$

TABLE 2

COMPARISON STARS

HD	Spectral Type	$E(B-V)$	$(b-y)_0$[a]	c_0	m_0
47839	O7 V ((f))	0.07	−0.152	−0.126	0.077
38666	O9.5 V	0.02	−0.132	−0.113	0.063
55857	B0.5 V	0.02	−0.117	−0.075	0.081
119159	B0.5 III	0.20	−0.135	−0.064	0.072
31726	B1 V	0.05	−0.137	0.050	0.107
46328	B1 III	0.02	−0.109	−0.025	0.068
74273	B1.5 V	0.04	−0.115	0.021	0.088
62747	B1.5 III	0.06	−0.130	0.051	0.096
64802	B2 V	0.05	−0.125	0.221	0.111
3360	B2 IV	0.04	−0.120	0.128	0.096
32630	B3 V	0.02	−0.100	0.315	0.108
34759	B5 V	0.01	−0.080	0.377	0.127

[a] Calculated by assuming $E(b-y) = 0.74E(B-V)$.

were used to obtain m_0 and c_0, the dereddened values of m_1 and c_1, for each of the comparison stars. There was a mean difference of 0.018 mag between the values of $(b-y)_0$ produced by the two procedures, with Shobbrook's procedure giving larger values than the procedure based upon $E(B-V)$. Table 2 lists the comparison stars, $E(B-V)$ and the intrinsic colors $(b-y)_0$, c_0, and m_0 which were derived from $E(B-V)$.

Color excesses were then calculated for each of the program stars by subtracting the dereddened colors of a comparison star from the color indices of each program star. In the case of the CCM stars we used the same comparison star as was used by Fitzpatrick & Massa (1990) to derive the ultraviolet (UV) extinction curve for each program star, whereas for the *ANS* stars we selected comparison stars on the basis of the spectral types given in the *ANS* extinction catalog. The comparison star used with each program star is listed beside the star in Table 1. Since Shobbrook's dereddening procedure tended to produce larger intrinsic colors than the procedure based upon $E(B-V)$, the color excesses for the program stars which were calculated from intrinsic colors based upon Shobbrook's procedure were systematically lower. We calculated the ratio $E(b-y)/E(B-V)$ for the color excesses generated from each set of intrinsic colors, ignoring stars with $E(b-y) > 0.6$ since a linear relation between $E(b-y)$ and $E(B-V)$ may not hold for those (Crawford 1975). Shobbrook's colors gave $E(b-y)/E(B-V) = 0.67 \pm 0.05$ as opposed to 0.71 ± 0.05 for the colors estimated from $E(B-V)$ of the comparison stars. The ratios are in agreement with one another but are somewhat lower than the value of 0.74 found by Crawford (1975). Since $E(B-V)$ provides a direct measurement of the amount of reddening along a sight line, the reddenings $E(b-y)$ for the program stars which we found from $E(B-V)$ are probably more reliable than those found from Shobbrock's procedure. In any case, we carried out the analysis described below for both sets of intrinsic colors and found that the results were not significantly affected by the choice of dereddening procedure for the comparison stars. The intrinsic colors presented in Table 2 and the results presented below are the intrinsic colors derived from $E(B-V)$ and the color excesses and extinctions which were derived from them.

In Table 1 we list the *uvby* color excesses that were derived for each of the program stars. Of the 22 stars, 16 were taken from CCM; UV extinction curves ($\lambda < 3000$ Å) for all of these stars are given by Fitzpatrick & Massa (1990). In these cases we used the same comparison stars as were used by Fitzpatrick and Massa. Fitzpatrick and Massa chose these comparison stars by inspecting *IUE* spectra for each of the stars to find good spectral matches to the program stars. Of the remaining six stars, Cardelli & Savage (1988) derived an UV extinction curve for HD 62542 from *IUE* data. We use the same the comparison star as Cardelli & Savage, which they chose by matching spectral features in the *IUE* spectra of the two stars. The above 17 program/comparison star pairs have each been carefully matched in temperature and luminosity and, therefore, the *uvby* color excesses which we find for them should be reliable. The remaining five stars (HD 144217, HD 145502, HD 147165, HD 161056, and HD 184915) are taken from the *ANS* catalog (Savage et al. 1985) and comparisons for these stars were chosen from Table 2 on the basis of the spectral types given in the *ANS* catalog. Two (HD 144217 and HD 147165) are noted in that catalog as being binaries. HD 147165 (σSco) is also noted as being variable and is discussed by Clayton & Hanson (1993), who derive an UV extinction curve for this star from *IUE* data. It is a B1 III β Cepheid variable with an O9.5 V companion, which is about two magnitudes fainter at V than the primary star. Clayton & Hanson show that there is no sign of O9.5 V spectral features in the *IUE* spectrum of HD 147165 and argue that the companion has no significant effect on their extinction curve. Since we are interested in longer wavelengths we expect it to have even less effect on our color excesses. Finally, we note that for the most part the deviations of the *ANS* stars from our mean extinction curve are no larger than those of the CCM stars. Of the entire sample, HD 38087 and HD 145502 do show large deviations from the mean behavior (see below) and were not used in the final derivation of a mean extinction law.

In order to derive values of $A(\lambda)/A(V)$ from the *uvby* color excesses, we had to transform excesses measured relative to y, $E(b-y)$, $E(v-y)$ and $E(u-y)$, to excesses measured relative to V. We made the assumption that $A(y) = A(V)$ so that $E(b-y) = E(b-V)$ and so on for v and u. Relyea and Kurucz (1978) calculated V and y magnitudes from their model atmospheres and found that $V-y$ is constant for $T_{\rm eff}$ greater than about 10,000 K. All of the stars in our sample have $T_{\rm eff}$ greater than about 13,000 K. However, the cooler stars in our sample may be reddened to a degree that the effective wavelength of y differs from that of V and a correction must be made to $E(b-y)$ in order to get $E(b-V)$. Relyea & Kurucz (1978) give $V-y$ as a function of $T_{\rm eff}$, from which we estimated that for a B2 V star $[(B-V)_0 = -0.24]$ with a reddening $E(B-V) = 0.4$, $E(b-y) \simeq E(b-V) - 0.005$. This correction is much less than the probable errors in the color excesses. A calculation of the effective wavelength of y, as compared with that of V, also found no appreciable difference when measuring the flux from at 10,000 K blackbody than when measuring the flux from a 30,000 K blackbody (assuming rectangular filter response functions.) From this we concluded that, to within the observational errors, it was reasonable to adopt the relationship $E(b-y) = E(b-V)$.

The extinction at wavenumber x was then calculated from the color excess at that wavenumber, $E(x-V)$, from the relation

$$\frac{A(x)}{A(V)} = \frac{E(x-V)}{E(B-V)}\frac{1}{R_v} + 1 .$$

TABLE 3

Coefficients and Standard Deviations of Fits to Our Data

Filter	x (μm^{-1})	$a(x)$	$b(x)$	$\sigma_a(x)$	$\sigma_b(x)$	$\sigma(x)$	$\sigma_{\rm CCM}(x)$
L	0.290	0.043	0.159	0.085	0.321	0.062	0.060
K	0.460	0.148	−0.099	0.054	0.195	0.042	0.040
H	0.630	0.225	−0.243	0.055	0.196	0.033	0.034
J	0.800	0.421	−0.458	0.043	0.153	0.031	0.030
I	1.110	0.661	−0.555	0.036	0.130	0.028	0.027
R	1.430	0.855	−0.309	0.028	0.102	0.023	0.017
B	2.270	1.000	1.000	0.000	0.000	0.000	0.000
U	2.780	0.958	1.898	0.032	0.114	0.025	0.022
b	2.130	0.974	0.803	0.015	0.054	0.013	...
v	2.440	0.980	1.284	0.020	0.071	0.017	...
u	2.860	0.913	2.140	0.035	0.123	0.029	...
ANS	3.030	0.770	2.705	0.115	0.389	0.071	...
FM	3.330	0.576	3.988	0.061	0.217	0.048	...
FM	3.700	0.371	5.296	0.067	0.240	0.053	...
FM	4.000	0.197	6.702	0.094	0.335	0.078	0.117

The wavenumbers at which the extinction law was determined from the sample are listed in Table 3. The Strömgren filters (*ubv*) and the *ANS* data at 3300 Å ($x = 3.03$ μm^{-1}) were not used by CCM. As well as the Strömgren data, we used Johnson-Perry data from Clayton & Mathis (1988) and Clayton & Cardelli (1988), *IUE* data (Fitzpatrick & Massa 1990), and *ANS* data (Savage et al. 1985).

CCM found that plots of $A(\lambda)/A(V)$ against $1/R_v$ are close to linear and expressed their mean extinction curve in the form $A(\lambda)/A(V) = a(x) + b(x)/R_v$. Following them, we made linear least-squares fits to our derived extinctions at each wavelength. Table 3 lists the values of $a(x)$ and $b(x)$ that were found from these fits and Figure 1 shows the data for the Strömgren filters and also at 3300 and 2500 Å. The standard deviations of these values, $\sigma(a)$ and $\sigma(b)$, are also listed in Table 3 and were calculated from the scatter in the data in Figure 1 about a linear fit, neglecting observational errors in $A(\lambda)/A(V)$ and R_v, and hence are underestimated. At B, $a(x) = b(x) = 1.000$ by the definition of R_v, so the standard deviations there are zero. The 3300 Å data are all from the *ANS* extinction catalog. The 2500 Å data are a mixture of *IUE* data and *ANS* data. The stars HD 38087 and HD 145502 (shown as stars in Fig. 1) were not included in the linear fits since both showed large deviations from a linear relationship at the shorter wavelengths. HD 37022 and HD 37061 were not included in the fit at 3300 Å ($x = 3.03$ μm^{-1}) since their extinction at this wavelength was considerably lower than might be expected from measurements at adjacent wavelengths (see Fig. 3 below). Both stars are associated with reflection nebulosity and it is likely that measurements at this wavelength, which were made by *ANS* with a 2'.5 × 2'.5 aperture, have been contaminated by nebulosity. One should note from Figure 1 that since two stars with high values of R_v were not included in the linear fit at 3300 Å, and since the scatter in the remaining data at 3300 Å is large, the values of $a(x)$ and $b(x)$ we derived at this wavelength have large uncertainties and do not constrain the mean extinction curve very well.

Also listed in Table 3 are our values of $\sigma(x)$, the standard deviation at each wavenumber x of the distribution of $A(x)/$

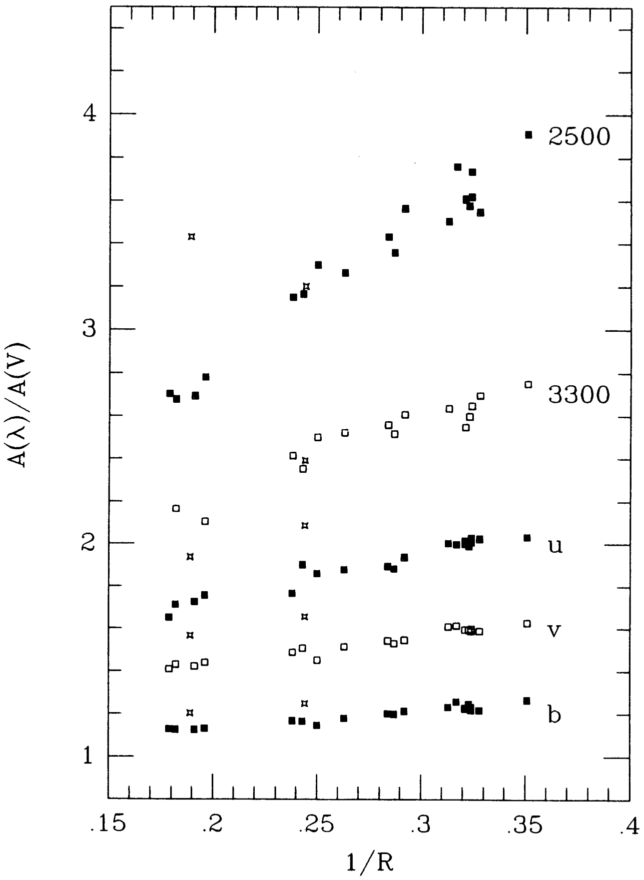

FIG. 1.—Extinctions $A(\lambda)/A(V)$ (*solid and open squares*) as a function of $1/R_v$ at the wavelengths of the b, v, and u filters and also at 3300 Å (calculated from the color excesses given in the *ANS* extinction catalog of Savage et al. 1985) and at 2500 Å (from Fitzpatrick & Massa 1990). To avoid confusion the points have been vertically offset by the following amounts; b, 0.0; v, 0.2; u, 0.4; 3300 Å, 1.0; 2500 Å, 1.3. The stars mark HD 38087 and HD 145502, which were not included in the linear fits (see text). The fit at 3300 Å did not include HD 37022 and HD 37061, which showed large deviations from the mean at this wavelength, although data for these stars are included in the figure (see text.)

$A(V)$ about the mean value $a(x) + b(x)/R_v$. This provides an estimate of the reliability of the mean extinction law at a particular wavelength. The standard deviations found by CCM, $\sigma_{\rm CCM}(x)$, are listed for comparison at those wavenumbers for which CCM tabulated standard deviations. The two agree quite closely for filters longward of U ($x < 2.78\ \mu m^{-1}$), where we expect the scatter in the data to be dominated by photometric errors and by mismatches in spectral type between program and comparison stars, but disagree at 2500 Å ($x = 4.00\ \mu m^{-1}$), where our sample has a much smaller scatter than the CCM sample. At wavelengths as short as this, real deviations of actual extinction curves from the mean dominate the scatter in the data. The CCM sample, which is twice as large as ours, presumably contains stars with more extreme deviations from the mean UV extinction law at 2500 Å than our sample does.

3. RESULTS

The CCM extinction law was based on Johnson photometry and we found that $a(x)$, $b(x)$ and the standard deviation of observations about the mean extinction for our sample, which is basically a subset of the CCM sample, are in excellent agreement with the same quantities tabulated by CCM (Table 3). The Strömgren filters u, v, and b were not used to define the CCM mean extinction curve but we also found reasonably good agreement between our extinctions at these wavelengths and the predictions of CCM. The best agreement was at u, where $a(x)$ and $b(x)$ were both consistent with CCM. This is perhaps not too surprising, since CCM used U in the derivation of their extinction curve and the effective wavelengths of the two filters are quite close. This indicates that the problems of extinctions measured at U related to the Balmer jump and the short wavelength cutoff are smaller than we had supposed. At v ($x = 2.44\ \mu m^{-1}$) we found that $a(x)$ was in good agreement with CCM but $b(x)$ was slightly lower than predicted and $A(v)/A(V)$ was generally much lower than one would expect from the CCM law (a mean difference of -0.029 ± 0.017 over our sample, excluding HD 38087 and HD 145502.) Our values of $A(v)/A(V)$ support the sharp change in the slope of the extinction curve at about $x = 2.25\ \mu m^{-1}$ found by other authors (Ardeberg & Virdefors 1982; Whiteoak 1966; Whitford 1958), which is not present in the CCM curve and which would give a lower extinction at $x = 2.44\ \mu m^{-1}$ than predicted by CCM. Finally, we found the largest deviations of $a(x)$ and $b(x)$ from the CCM relation at b ($x = 2.13\ \mu m^{-1}$), where $a(2.13\ \mu m^{-1})$ is too small and $b(2.13\ \mu m^{-1})$ is too large. The errors presented in Table 3 are, however, underestimated and the extinctions $A(b)/A(V)$ which we found are in agreement with the CCM law so we do not regard the discrepancies in $a(2.13)\ \mu m^{-1}$) and $b(2.13\ \mu m^{-1})$ as serious.

Reddening ratios in the Strömgren system have been measured observationally by other authors. These could be used to check our mean extinctions. The ratios $E(c1)/E(b-y)$, $E(m1)/E(b-y)$ and $E(u-b)/E(b-y)$ for $R_v = 3.1$ (appropriate for mean interstellar extinction along diffuse sight lines), obtained from the values of $a(x)$ and $b(x)$ in Table 3, are in very good agreement with observational values for mean interstellar reddening found by Ardeberg & Virdefors (1982) and Crawford (1975) (Table 4). We conclude from this that our mean extinctions are quite accurate at the wavelengths of the Strömgren filters.

We have fitted the data, for $1.1\ \mu m^{-1} \le x \le 3.3\ \mu m^{-1}$ (the optical/near-infrared regime as defined by CCM) with eight-order polynomials, including the four new points at $x = 2.13$, 2.44, 2.86, and 3.03 μm^{-1} and requiring that $a(x)$, $b(x)$, $da(x)/dx$, and $db(x)/dx$ match the CCM relation at the endpoints of the fits. We obtained the following analytic expressions for the coefficients $a(x)$ and $b(x)$:

$$
\begin{aligned}
a(x) = 1 &+ 0.104y - 0.609y^2 + 0.701y^3 + 1.137y^4 \\
&- 1.718y^5 - 0.827y^6 + 1.647y^7 - 0.505y^8 , \\
b(x) = 1.952y &+ 2.908y^2 - 3.989y^3 - 7.985y^4 \\
&+ 11.102y^5 + 5.491y^6 - 10.805y^7 + 3.347y^8 ,
\end{aligned}
$$

where $y = x - 1.82\ \mu m^{-1}$. These expressions may be used in place of equations (3a) and (3b) in CCM.

Figure 2 compares a recent high-resolution extinction curve (Bastiaansen 1992), based on narrow-band photometry (*open squares*), with our curve (*solid line*, $R_v = 3.1$) and the CCM curve (*dashed line*, $R_v = 3.1$). The normalization is Bastiaansen's and the crosses show the wavelengths at which we made our fit. The agreement between our curve and Bastiaansen's data is excellent and our curve provides a much better fit than the CCM curve at the shorter wavelengths ($x \ge 2.3\ \mu m^{-1}$). The

TABLE 4

COLOR EXCESS RATIOS

Ratio	Crawford (1975)	Ardeberg & Videfors (1982)	This Work ($R = 3.1$)
$\frac{E(m_1)}{E(b-y)}$	−0.32	−0.27	−0.31
$\frac{E(c_1)}{E(b-y)}$	0.20	0.23	0.21
$\frac{E(u-b)}{E(b-y)}$	1.5	1.7	1.59

agreement is much better than we would have expected given that our curve is based on data at only a few wavelengths. Figure 3 compares extinction data for four stars in our sample (*open squares*) with the CCM law (*dashed line*) and our fit (*solid line*). The stars were chosen to represent a range of values of R_v. One can see from the figure that the CCM law is in good agreement, in general, with the *uvby* data. However, the data point at $x = 2.44\ \mu\text{m}^{-1}[A(v)/A(V)]$ for HD 14250 is lower than expected from the CCM law. This difference is present for other extinction curves with $R_v \sim 3$ in our sample and is also seen in higher resolution data (Fig. 2). From this we conclude that extinctions, $A(\lambda)/A(V)$, are somewhat smaller than given by the CCM law for $x \sim 2.5\ \mu\text{m}^{-1}$ for lines of sight with $R_v \sim 3$ (i.e., lines of sight through the diffuse interstellar medium.) We would expect from the agreement between our extinction law and that of Bastiaansen (1992) that the near-UV extinction law for these lines of sight resembles the law found by Whitford (1958) and, more recently, Ardeberg & Virdefors (1982), although we do not have data at enough wavelengths to confirm this. This latter extinction law consists of two linear segments which join abruptly at $x = 2.25\ \mu\text{m}^{-1}$, unlike the CCM law, which turns over smoothly for the optical into the UV and hence overestimates extinctions at $x \sim 2.5\ \mu\text{m}^{-1}$. Interestingly, there is no sign of an abrupt change in slope of the extinction law in the large-R_v extinction curves, but our curve is based on a limited number of data points and would tend to smooth out such a feature if it did not occur close to one of our selected wavelengths.

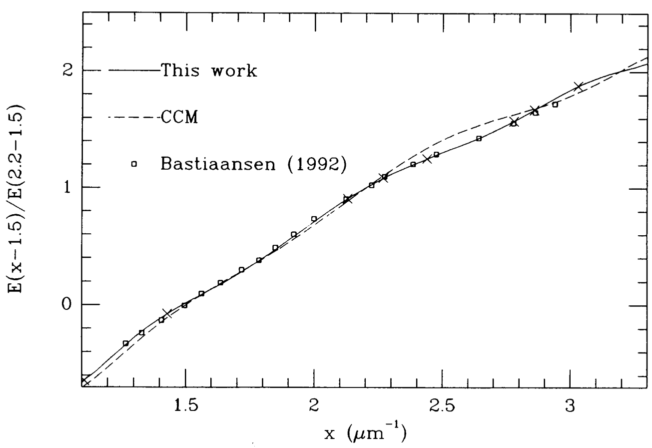

FIG. 2.—Comparison of our $R_v = 3.1$ extinction curve (*solid line*) and that of CCM (*dashed line*) with the mean extinction curve of Bastiaansen (1992) (*open squares*). The crosses represent the wavelengths at which our fit was made. Our extinction curve is in much better agreement with Bastiaansen's data, for $x > 2.3\ \mu\text{m}^{-1}$, than the CCM curve.

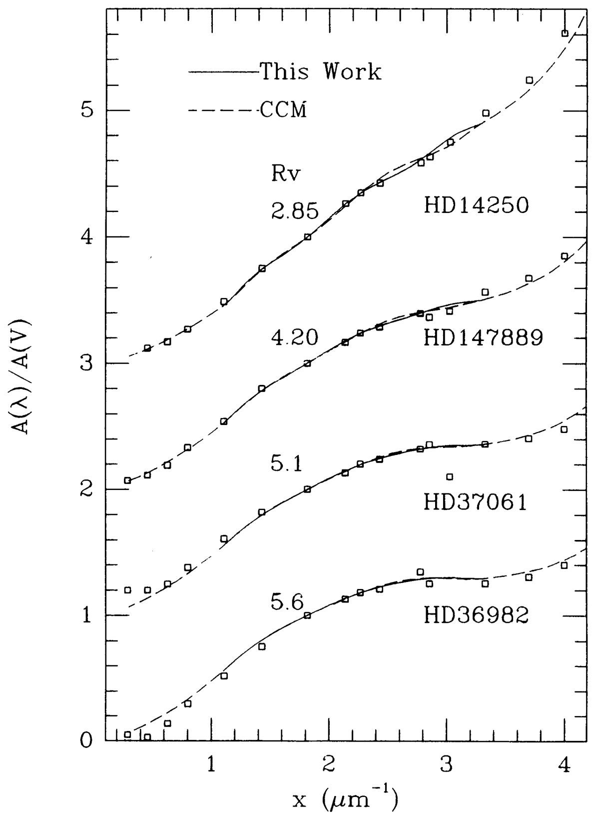

FIG. 3.—Extinction data (*open squares*) compared with the CCM law (*dashed line*) and our mean extinction law (*solid line*) for four lines of sight with a range of values of R_v. Note that the data point at 3300 Å ($x = 3.03\ \mu\text{m}^{-1}$) for HD 37061, which was taken from *ANS* measurements, is lower than expected and was not included in the determination of the mean extinction law (see text.)

One should also note that there is a slight kink in the extinction curve for HD 14250 at $x \sim 3\ \mu\text{m}^{-1}$. This is not real but is an artifact of our fitting procedure caused by our requiring the extinction curve from the ground-based data to join smoothly onto the curve based upon *IUE* data.

Mathis & Cardelli (1992) examined the deviations of individual UV extinction curves from the mean CCM extinction curve and found correlations between deviations within the far-UV rise and also over a narrow range of x ($4\ \mu\text{m}^{-1} \leq x \leq 5\ \mu\text{m}^{-1}$) within the 2175 Å bump. Adopting their method, we calculated the deviations of our individual extinction curves from the mean law given above and looked for correlations between those deviations. We found no such correlations (i.e., the deviation from the mean at one filter, for an individual line of sight, cannot be used to reliably predict the deviation from the mean at another filter) and conclude that real deviations of individual extinction curves from the mean optical/UV curve, which would show up as correlations between extinctions at different wavelengths, are smaller than the errors in the extinction curves caused by spectral type mismatch and by intrinsic errors in the photometry.

A number of authors have reported very broad structure (VBS) in the extinction curve in the visible, in the form of a broad, shallow dip between about $x = 1.6\ \mu\text{m}^{-1}$ and $x = 2.2\ \mu\text{m}^{-1}$, relative to a linear interpolation of the extinction curve between those points. There may be a variation with line of sight or with R_v (van Breda & Whittet 1981) but the number of sight lines that have been examined is small and so broad conclusions are hard to draw. Our data points are spaced too far apart for our analysis of deviations from the mean extinction law to show any evidence of VBS. Higher resolution observations of the CCM sample to determine the extinction curve in the spectral region between R and B would be very useful in order to investigate this structure and any possible variation with environment or with R_v.

4. SUMMARY

We have derived extinctions $A(\lambda)/A(V)$ from Johnson-Perry *UBVRIJHKL* data, Strömgren *uvby* data, *ANS* data, and *IUE* data for 20 stars (mostly taken from the CCM sample) and have performed linear fits to these data as a function of $1/R_v$. Eighth-order polynomials were fit to the coefficients, for wavenumbers in the range $1.1\ \mu\text{m}^{-1} < x < 3.3\ \mu\text{m}^{-1}$, to obtain the intercept and slope, $a(x)$ and $b(x)$, as a function of wavelength, and hence obtain a mean interstellar extinction curve $A(\lambda)/A(V) = a(x) + b(x)/R_v$. Our curve gives a much better match to the higher resolution extinction curve of Bastiaansen (1992), in the near-UV, than CCM. At small values of R_v our extinction law gives a somewhat smaller value of $A(v)/A(V)$ than one would expect from the CCM law. This result is in agreement with the extinction law found by Whitford (1958) and Ardeberg & Virdefors (1982) in which there is an abrupt change in the slope of the extinction curve at around $x = 2.25\ \mu\text{m}^{-1}$. For larger values of R_v we find a curve like that of CCM, which curves over more gradually from the optical into the UV. However, an abrupt change in slope for these latter curves may be masked by our only having data at a limited number of wavelengths. We have examined deviations of the extinctions of individual stars from the predicted mean and found no significant correlation of the deviations at any one wavelength with those at another, leading us to conclude that real deviations from our mean extinction curve are generally smaller than the errors in the curve.

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REFERENCES

Ardeberg, A., & Virdefors, B. 1982, A&A, 115, 347
Bastiaansen, P. A. 1992, A&AS, 93, 449
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245 (CCM)
Cardelli, J. A., Sembach, K. R., & Mathis, J. S. 1992, AJ, 104, 1916
Cardelli, J. A., & Savage, B. D. 1988, ApJ, 325, 864
Clayton, G. C., & Cardelli, J. A. 1988, AJ, 96, 695
Clayton, G. C., & Hanson, M. M. 1993, AJ, 105, 1880
Clayton, G. C., & Mathis, J. S. 1988, ApJ, 327, 911
Crawford, D. L. 1975, PASP, 87, 481
Crawford, D. L., & Mandwewala, N. 1976, PASP, 88, 917
Fitzpatrick, E. L., & Massa, D. 1990, ApJS, 72, 163
Hauck, M., & Mermilliod, M. 1980, A&AS, 40, 1
Mathis, J. S., & Cardelli, J. A. 1992, ApJ, 398, 610
Relyea, L. J., & Kurucz, R. L. 1978, ApJS, 37, 45
Savage, B. D., Massa, D., Meade, M., & Wesselius, P. R. 1985, ApJS, 59, 397
Savage, B. D., & Mathis, J. S. 1979, ARA&A, 17, 73
Seaton, M. J. 1979, MNRAS, 187, 73P
Shobbrook, R. R. 1984, MNRAS, 211, 659
van Breda, I. G., & Whittet, D. C. B. 1981, MNRAS, 195, 79
Whiteoak, J. B. 1966, ApJ, 144, 305
Whitford, A. E. 1958, AJ, 62, 201