Total to Selective Extinction Ratios and Visual Extinctions from Ultraviolet Data

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ABSTRACT

We present determinations of the total to selective extinction ratio $R_V$ and visual extinction $A_V$ values for Milky Way stars using ultraviolet color excesses. We extend the analysis of Gnaciński & Sikorski (1999) by using non-equal weights derived from observational errors. We present a detailed discussion of various statistical errors. In addition, we estimate the level of systematic errors by considering different normalization of the extinction curve adopted by Wegner (2002). Our catalog of 782 $R_V$ and $A_V$ values and their errors is available in the electronic form on the World Wide Web.

Key words: catalogs — dust, extinction — Galaxy: general — ISM: structure — techniques: photometric

1. Introduction

The extinction curve describes how the extinction changes with the wavelength. Extinction is due to the presence of dust grains in the interstellar medium and its characteristics are different in a diffuse interstellar medium as compared to a dense interstellar medium. Thus, the knowledge of extinction curve is necessary to deredden magnitudes and colors of astronomical objects and to understand the physical properties of dust grains.

Cardelli, Clayton, & Mathis (1989, hereafter CCM) derived a mean extinction law (for $0.12 \mu m < \lambda < 3.5 \mu m$) that depends on only one parameter $R_V = A_V/E(B - V)$. They considered the sample used in the ultraviolet (UV) extinction study of Fitzpatrick & Massa (1990) based on International Ultraviolet Explorer extinction curves of 45 reddened Milky Way OB stars. CCM searched for the corresponding optical and near-infrared (UBVRIJHKL) photometry from the literature. Finally they used the intrinsic colors of Johnson (1966) for the appropriate spectral types to determine the extinction. They obtained the following one-parameter family of curves that represents the UV to infrared (IR) extinction law in terms of $R_V$:

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\[
\frac{A_\lambda}{A_V} = a(x) + b(x) \cdot R_V^{-1},
\]
where \( x = 1/\lambda \), and \( a(x) \) and \( b(x) \) are the wavelength-dependent coefficients. Equation (1) is very powerful because it allows one to determine the extinction in some spectral region based on the extinction in a different spectral region, given that one knows \( R_V \).

The \( R_V \) parameter ranges from about 2.0 to about 5.5 (with a typical value of 3.1) when one goes from diffuse to dense interstellar medium. In this formalism \( R_V \) therefore characterizes the dust properties in the region that produces the extinction. Many authors used this parameter to study extinction, e.g.: Jenniskens & Greenberg (1993) searched for a relation between \( R_V \) and other parameters that characterize the extinction curves; Cecchi-Pestellini et al. (1995) studied the role of \( R_V \) as the main regulatory agent of the penetration of radiation inside dark clouds; Fitzpatrick (1999) discussed different methods to deredden the data and obtained a new estimate of the extinction law in terms of \( R_V \). Gnaciński & Sikorski (1999, hereafter GS) applied a \( \chi^2 \) minimization to compute the \( R_V \) values for a sample of stars with UV extinction data using the linear relation (1). A similar method with weights was used by Ducati, Ribeiro, & Rembold (2003) to determine \( R_V \) and \( A_V \) toward a sample of stars with known color excesses in UBVRIJHKL.

Here we extend the method used by GS in order to obtain improved \( R_V \) values for the lines of sight toward a sample of stars with known extinction data in the UV. The structure of this paper is the following. In \( \S 2 \) we discuss the theoretical basis of our \( R_V \) derivation. In \( \S 3 \) we describe our data sources. We present the results and assess the consistency between different samples and theoretical approaches in \( \S 4 \). Finally in \( \S 5 \) we discuss our results and comment on the future work.

2. Theoretical considerations

The interstellar dust grains span a wide range of sizes from a few Angstroms to a few micrometers. In general, they reduce the intensity of the transmitted beam by two physical processes: absorption and scattering. The extinction is the result of these two processes. The apparent magnitude \( m \) of each star as a function of wavelength may be written as

\[
m_{\lambda,\text{red}} = M_{\lambda,\text{red}} + 5 \log \frac{d_{\text{red}}}{10\text{pc}} + A_{\lambda,\text{red}},
\]

\[
m_{\lambda,\text{comp}} = M_{\lambda,\text{comp}} + 5 \log \frac{d_{\text{comp}}}{10\text{pc}} + A_{\lambda,\text{comp}},
\]
where \( M, d \) and \( A \) represent absolute magnitude, distance and total extinction, respectively, and subscripts “red” and “comp” denote ‘reddened’ and ‘comparison’ stars, respectively. The extinction as a function of \( \lambda \) may be obtained by comparing corresponding stars paired according to spectral properties. In principle, the ‘comparison’ star should be of the same spectral classification as the ‘reddened’ star, but with a negligible extinction.
If the reddened star and the comparison star have the same spectral classification it also means that they have very similar intrinsic spectral energy distributions. Thus we have \( M_{\lambda, \text{red}} = M_{\lambda, \text{comp}} \). We also assume that \( A_{\lambda} \equiv A_{\lambda, \text{red}} \gg A_{\lambda, \text{comp}} \). The magnitude difference obtained from equation (2) and (3) is therefore:

\[
\Delta m_{\lambda} = m_{\lambda, \text{red}} - m_{\lambda, \text{comp}} = 5 \log \left( \frac{d_{\text{red}}}{d_{\text{comp}}} \right) + A_{\lambda} \tag{4}
\]

The quantity \( 5 \log (d_{\text{red}}/d_{\text{comp}}) \) is a constant term and may be eliminated by normalizing with respect to extinction difference in two standard wavelengths \( \lambda_1 \) and \( \lambda_2 \):

\[
E_{\text{norm}}(\lambda_1, \lambda_2) = \frac{\Delta m_{\lambda_1} - \Delta m_{\lambda_2}}{\Delta m_{\lambda_1} - \Delta m_{\lambda_2}} = \frac{A_{\lambda_1} - A_{\lambda_2}}{A_{\lambda_1} - A_{\lambda_2}} \tag{5}
\]

Generally, the extinction curves are normalized with respect to the B and V passbands in the Johnson (1966) system:

\[
E_{\text{norm}}(\lambda, B, V) = \epsilon(\lambda - V) = \frac{A_{\lambda} - A_{V}}{A_{B} - A_{V}} = \frac{E(\lambda - V)}{E(B - V)} \tag{6}
\]

where \( E(\lambda - V) = A_{\lambda} - A_{V} = (m_{\lambda} - m_{V}) - (m_{\lambda} - m_{V})_0 \), \( (m_{\lambda} - m_{V}) \) is the observed color and \( (m_{\lambda} - m_{V})_0 \) is the intrinsic color (by construction equal to the color of the 'comparison' star).

It is possible to obtain the absolute extinction by using the total to selective extinction ratio:

\[
R_{V} = \frac{A_{V}}{E(B - V)}. \tag{7}
\]

Then:

\[
\epsilon(\lambda - V) = \frac{E(\lambda - V)}{E(B - V)} = \frac{A_{\lambda} - A_{V}}{E(B - V)} = R_{V} \left\{ \frac{A_{\lambda}}{A_{V}} - 1 \right\}. \tag{8}
\]

CCM, for computational reasons, divided the complete extinction curve (equation 1) into three wavelengths regions and fitted the extinction law as a function of \( x = (1 \mu m)/\lambda \):

- infrared \((0.3 \leq x \leq 1.1)\),
- optical/NIR \((1.1 \leq x \leq 3.3)\),
- ultraviolet and far-ultraviolet \((3.3 \leq x \leq 8.0)\).

For every wavelength, the coefficients \( a(x) \) and \( b(x) \) from equation (1) are fixed and given by an appropriate expression\(^1\). Observations from *International Ultraviolet Explorer* cover a range from

\(^{1}\)In GS one of the coefficients in their equation (2) is incorrect but the results reported in their Table 1 suggest that they used the proper formula.
3.03 < x < 6.45 \, (\lambda / A = 1549, \, 1799, \, 2200, \, 2493, \, \text{and} \, 3294), \, \text{so we use the equations for the coefficients for the last two regions listed above.}

For 1.1 \leq x \leq 3.3 \text{ and } y \equiv (x - 1.82) \text{ we have:}

\begin{align*}
a(x) &= 1 + 0.17699y - 0.50447y^2 - 0.02427y^3 + 0.72085y^4 \\
   &\quad + 0.01979y^5 - 0.77530y^6 + 0.32999y^7; \\
b(x) &= 1.41338y + 2.28305y^2 + 1.07233y^3 - 5.38434y^4 \\
   &\quad - 0.62251y^5 + 5.30260y^6 - 2.09002y^7. \tag{9}
\end{align*}

For 3.3 \leq x \leq 8.0:

\begin{align*}
a(x) &= 1.752 - 0.316x - 0.104/[(x - 4.67)^2 + 0.341] + F_a(x); \tag{10} \\
b(x) &= -3.090 + 1.825x + 1.206/[(x - 4.62)^2 + 0.263] + F_b(x). \tag{11}
\end{align*}

where:

\begin{align*}
F_a(x) &= -0.04473(x - 5.9)^2 - 0.009779(x - 5.9)^3 \\
F_b(x) &= 0.21300(x - 5.9)^2 + 0.120700(x - 5.9)^3 \quad \text{if } 8 \geq x \geq 5.9 \\
F_a(x) &= 0 = F_b(x) \quad \text{otherwise} \tag{12}
\end{align*}

Gnaciński & Sikorski (1999) compute \( R_V \) values using equations (1) and (8) and by minimizing the quantity:

\[ \chi^2 = \sum_{i=1}^{N_{\text{bands}}} \left\{ E(\lambda_i - V) - E(B - V) \cdot [R_V(a(x_i) - 1) + b(x_i)] \right\}^2 \tag{13} \]

The right side of equation (13) is a second order polynomial (parabola) of \( R_V \) with the minimum:

\[ R_V = \frac{\sum_{i=1}^{N_{\text{bands}}} \{(a(x_i) - 1) \cdot [E(\lambda_i - V)/E(B - V) - b(x_i)]\}}{\sum_{i=1}^{N_{\text{bands}}} (a(x_i) - 1)^2} \tag{14} \]

This formula is right when the errors in \( E(\lambda_i - V)/E(B - V) \) are identical for all bands. Our data (see §3) have errors that differ from band to band, so we use an improved \( \chi^2 \), weighted by the observational errors. Ducati et al. (2003) suggested the following \( \chi^2 \) for independent minimization with respect to \( R_V \) and \( A_V \):

\[ \chi^2 = \sum_{i=1}^{N_{\text{bands}}} w_{\lambda_i} \left\{ E(\lambda_i - V) - (a(x_i) - 1)A_V - b(x_i) \frac{A_V}{R_V} \right\}^2 \tag{15} \]

where \( w_{\lambda_i} \) are the weights associated with each band. We use a related but different approach which stems from the fact that in addition to UV bands we also use \( E(B - V) \) as our input data. We normalize our color excesses with \( E(B - V) \) to form \( \epsilon(\lambda - V) \). Since \( A_V = R_V \cdot E(B - V) \), we minimize the following \( \chi^2 \) with respect to \( R_V \) only:

\[ \chi^2 = \sum_{i=1}^{N_{\text{bands}}} w_{\lambda_i} \left\{ \epsilon(\lambda_i - V) - [R_V(a(x_i) - 1) + b(x_i))] \right\}^2 E^2(B - V) \tag{16} \]
Setting $w_{\lambda_i} \equiv 1/\sigma_i^2$ and minimizing equation (16) with respect to $R_V$ we find:

$$R_V = \frac{\sum_{i=1}^{N_{\text{bands}}}(a(x_i) - 1) \cdot [\epsilon(\lambda_i - V) - b(x_i)]/\sigma_i^2}{\sum_{i=1}^{N_{\text{bands}}}(a(x_i) - 1)^2/\sigma_i^2} \quad (17)$$

where:

$$\sigma_i^2 \equiv \sigma^2[\epsilon(\lambda_i - V)] = \left( \frac{\partial \epsilon(\lambda_i - V)}{\partial E(\lambda_i - V)} \sigma[E(\lambda_i - V)] \right)^2 + \left( \frac{\partial \epsilon(\lambda_i - V)}{\partial E(B - V)} \sigma[E(B - V)] \right)^2$$

$$= \left( \frac{E(\lambda_i - V)}{E(B - V)} \right)^2 \left[ \left( \frac{\sigma[E(\lambda_i - V)]}{E(\lambda_i - V)} \right)^2 + \left( \frac{\sigma[E(B - V)]}{E(B - V)} \right)^2 \right] \quad (18)$$

and

$$\sigma^2[E(\lambda_i - V)] \equiv \sigma^2[(m_{\lambda_i} - m_V) - (m_{\lambda_i} - m_V)_0] = \sigma^2[m_{\lambda_i}] + \sigma^2[m_V] + \sigma^2_{\text{mismatch}} \quad (19)$$

The error terms on the right side of equation (19) are described in Table 1. In equation (18) we assumed for simplicity that the errors in $E(\lambda_i - V)$ and $E(B - V)$ are independent. However, the values of $\epsilon(\lambda - V)$ and their errors for different bands are not independent. To get a good idea about the errors in $R_V$, we compute them in two ways. First, we calculate the maximum error in $R_V$, which is the straight sum of errors coming from different sources:

$$\sigma_{\max}(R_V) \equiv \sum_{j=1}^{N_{\text{bands}}} \left[ \frac{\partial R_V}{\partial \epsilon(\lambda_j - V)} \right] \cdot \sigma_j = \frac{1}{\sum_{i=1}^{N_{\text{bands}}}(a(x_i) - 1)^2/\sigma_i^2} \cdot \sum_{j=1}^{N_{\text{bands}}} \left| \frac{a(x_j) - 1}{\sigma_j} \right| \quad (20)$$

Then we obtain the error in quadrature which would properly describe total uncertainty if the errors from different sources were uncorrelated:

$$\sigma_{\text{quad}}(R_V) \equiv \sqrt{\sum_{j=1}^{N_{\text{bands}}} \left[ \left( \frac{\partial R_V}{\partial \epsilon(\lambda_j - V)} \right)^2 \cdot \sigma_j^2 \right]} = \frac{1}{\sum_{i=1}^{N_{\text{bands}}}((a(x_i) - 1)^2/\sigma_i^2)} \cdot \sqrt{\sum_{j=1}^{N_{\text{bands}}} \left( \frac{a(x_j) - 1}{\sigma_j} \right)^2} \quad (21)$$

Neither description (20) nor (21) is strictly correct: the real error in $R_V$ lies likely between these two estimates.

By definition:

$$A_V \equiv R_V E(B - V) = \frac{\sum_{i=1}^{N_{\text{bands}}}(a(x_i) - 1)(E(\lambda_i - V) - b(x_i)E(B - V))/\sigma_i^2}{\sum_{i=1}^{N_{\text{bands}}}(a(x_i) - 1)^2/\sigma_i^2}, \quad (22)$$
where the second equality is a consequence of equation (17). Therefore the maximum error in \( A_V \) is given by²:

\[
\sigma_{\text{max}}(A_V) = \sum_{j=1}^{N_{\text{bands}}} \left| \frac{\partial A_V}{\partial E(\lambda_j - V)} \right| \sigma[E(\lambda_j - V)] + \left| \frac{\partial A_V}{\partial E(B - V)} \right| \sigma[E(B - V)]
\]

\[
= \frac{1}{\sum_{i=1}^{N_{\text{bands}}}(a(x_i) - 1)^2/\sigma_i^2} \left[ \sum_{j=1}^{N_{\text{bands}}} \left| \frac{(a(x_j) - 1)}{\sigma_j^2} \right| \sigma[E(\lambda_j - V)] \right]
+ \left| \sum_{i=1}^{N_{\text{bands}}} \frac{(a(x_i) - 1)(-b(x_i))}{\sigma_i^2} \right| \sigma[E(B - V)]
\]

(23)

The error in quadrature is given by:

\[
\sigma_{\text{quad}}(A_V) = \sqrt{\sum_{j=1}^{N_{\text{bands}}} \left( \frac{\partial A_V}{\partial E(\lambda_j - V)} \right)^2 \sigma^2[E(\lambda_j - V)] + \left( \frac{\partial A_V}{\partial E(B - V)} \right)^2 \sigma^2[E(B - V)]}
\]

\[
= \frac{1}{\sum_{i=1}^{N_{\text{bands}}}(a(x_i) - 1)^2/\sigma_i^2} \left[ \sum_{j=1}^{N_{\text{bands}}} \left( \frac{(a(x_j) - 1)}{\sigma_j^2} \right)^2 \sigma^2[E(\lambda_j - V)] \right]
+ \left( \sum_{i=1}^{N_{\text{bands}}} \frac{(a(x_i) - 1)(-b(x_i))}{\sigma_i^2} \right)^2 \sigma^2[E(B - V)]^{1/2}
\]

(24)

3. Data

We use the data taken from the Savage et al. (1985) catalog of ultraviolet color excesses

\[
E(\lambda - V) = (m_\lambda - m_{AV}) - (m_\lambda - m_{AV})_0
\]

(25)

for stars of spectral types B7 and earlier. The UV measurements are taken from *Astronomical Netherlands Satellite* (ANS) data (Wesselius et al. 1982) and consist of observations in five UV channels with central wavelengths: \( \lambda = 1549, 1799, 2200, 2493, \) and 3294 Å.

The sources of the data used to obtain \( E(\lambda - V) \) as given by equation (25) and their errors are listed in Table 1. We also consider another type of error: a ‘mismatch error’, which is caused by

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²We note that the analysis of GS is equivalent to ours if weights meet the following conditions: \( \sum_{i=1}^{N_{\text{bands}}} \frac{1}{\sigma_i^2} = C \), where \( C \) is a constant. From equation (18) we conclude that this condition is in conflict with \( \sigma[E(\lambda_i - V)] = \sigma[E(B - V)] \) assumed by GS. If we ignore this conflict and force both conditions, then:

\[
\sigma_{\text{max}}(A_V) = \left[ \frac{\sum_{i=1}^{N_{\text{bands}}} (a(x_i) - 1)}{\sum_{i=1}^{N_{\text{bands}}} (a(x_i) - 1)^2} + \left( \frac{\sum_{i=1}^{N_{\text{bands}}} (a(x_i) - 1) \cdot (-b(x_i))}{\sum_{i=1}^{N_{\text{bands}}} (a(x_i) - 1)^2} \right) \right] \cdot \sigma[E(B - V)]
\]

The results reported in Table 1 of GS suggest that they used the above formula rather than their equation (8).
the fact that the reddened star and the comparison star may have slightly different colors. Meyer & Savage (1981) give in their section 2c, Table 1B ultraviolet color excess errors which include errors associated with spectral type misclassification (mismatch error) and errors in the intrinsic colors. We adopt their values for this total additional source of error, and we record them under the name of mismatch error.

Figure 1 shows the histograms of the $E(\lambda_i - V)$ errors for the five ultraviolet bands which we obtain using equation (19). The errors are completely dominated by the mismatch errors which results in a few spikes observed in each panel. The errors adopted by GS and marked by vertical lines are shown for comparison.

From the Savage et al. (1985) catalog we exclude some lines of sight using the same method of selection as GS. It means that we exclude the lines of sight that have $E(B - V) < 0.1$, and the ones with $E(\lambda - V)/E(B - V) > 8$. This selection results in 923 lines of sight considered previously by GS. In addition, we also exclude those stars that do not have spectral type classification, because for them we are not able to assign the mismatch errors. This last cut reduces the number of lines of sight we consider to 782.

Figure 2 shows the sky positions of the stars in our sample. The sample contains stars of spectral type B7 and earlier and this is the reason for which almost all the stars lie in the Galactic plane at low latitudes.

4. Results

4.1. The catalog of $R_V$ and $A_V$ values

By using the method described in §2 we compute for our sample the $R_V$ and $A_V$ values listed in Table 2. Here we present only the first 20 objects from our sample. The complete table is available in electronic form and on the World Wide Web\(^3\). In the first column we list the names of stars, in the second and third the galactic coordinates, then the $E(B - V)$ values taken from Savage et al. (1985) catalog; in the remaining columns we list the $R_V$ and $A_V$ values with their errors obtained using formulae (17)–(24).

Our determination of $R_V$ values with their errors is made using the GS method improved through the consistent treatment of observational errors. Figure 3 shows the good agreement between the $R_V$ values obtained with GS unweighted method and the weighted method applied here. In our case, the $R_V$ values are not so different between the two methods because our adopted errors in $\epsilon(\lambda_i - V)$ are of the same order in the five UV wavelengths. However, it’s important to notice

\(^3\)See [http://dipastro.pd.astro.it/geminale](http://dipastro.pd.astro.it/geminale)
that typical errors in $R_V$ are very different between the two methods (mostly due to the mismatch errors considered here).

Figure 4 shows the same points as in Figure 2, but now different colors mark different values of $R_V$ with $R_V$ increasing from red to blue. As expected most lines of sight have $R_V$ of about 3.1. This may be also seen in Figure 5 which shows $R_V$ values as a function of galactic coordinates. The circular red points are the mean values of $R_V$ for the data binned every 30° and every 1° for the Galactic longitude and latitude, respectively. These mean values do not differ a lot one from another but some sky anisotropy is also quite apparent. Figure 6 shows the histogram of the $R_V$ values derived here. The weighted mean of $R_V$ values is $3.13 \pm 0.02$.

### 4.2. Analysis of systematic errors

We consider systematic errors in extinction curve determination that can result from using biased $E(B - V)$ values. To this aim we use the Wegner’s (2002) calibration of $E(B - V)$ to estimate the effect of the calibration change on the value of $R_V$. Usually, the extinction curve is expressed in terms of a color excesses to $E(B - V)$ ratio. Since $R_V$ value depends on this ratio (see equation 8 or 17), the adopted $E(B - V)$ calibration will influence it. Since we do not know which set of $E(B - V)$ values is more appropriate [Savage et al. (1985) or Wegner (2002)], the difference in obtained $R_V$ values will be a good indicator of a possible systematic error in $R_V$.

Wegner (2002) made a catalog of interstellar extinction curves of OB stars. He used the UV data from Wesselius et al. (1982), but differently from Savage et al. (1985) who used the data sources described in Table 1, he took the visual magnitudes and spectral classification of O and B stars from the SIMBAD database. The maximum error in $E(B - V)$ adopted by Wegner (2002) is 0.04 mag; the error in $m_\lambda$ and $m_V$ is 0.01, and he obtains the intrinsic colors using the ‘artificial’ standard method by Papaj, Krelowski, & Wegner (1993), who found a linear relation between $(m_\lambda - m_V)$ and $(m_B - m_V)$ and used the coefficients of this relation also to compute the linear relation between the intrinsic colors. This method improves the accuracy of the intrinsic colors based on ANS photometry.

There are 190 stars that Wegner (2002) has in common with our sample. For these stars we compute the $R_V$ values using formula (17) weighted by the observational errors given by Wegner (2002).

Figure 7 shows the difference in the $R_V$ values given by different calibrations\textsuperscript{4}. The main effect on $R_V$ comes from the fact that the $E(B - V)$ values from two calibrations differs on average by $0.04$ in the sense that Wegner (2002) color excesses are smaller than the ones used in our primary

\textsuperscript{4}The linear relation between the two set of $R_V$ values is: $R_{V,Wegner} = (-1.856 \pm 0.483) + (1.530 \pm 0.148) \cdot R_{V,GP}$. 

determination.
Table 3 reports results for the lines of sight in common between Wegner’s (2002) sample and our sample. The complete table is given in the electronic form on the World Wide Web\textsuperscript{5}. The first column lists stellar designations, the second and third report the galactic coordinates; in the fourth column we list the $E(B-V)$ values taken by Savage et al. (1985); the fifth column gives our $R_V$ values and the sixth their maximum errors; the seventh contains the $E(B-V)$ values used by Wegner (2002), the eighth provides the $R_V$ values and the ninth their errors computed with our method and using the Wegner’s (2002) ultraviolet data.

5. Conclusion

Using ultraviolet color excesses we find $R_V$ and $A_V$ values and their errors for a sample of 782 lines of sight. We extend the analysis of Gnaciński & Sikorski (1999) by considering various sources of statistical and systematic errors. In a treatment related to the one by Ducati et al. (2003), we introduce the weights associated with the errors in each UV band to our $\chi^2$ minimization procedure. We explicitly give all the formulae we use to compute the $R_V$ and $A_V$ values and their errors. We compute the maximum errors and the errors in quadrature for $R_V$ and $A_V$ taking into account mismatch errors that affect the color excesses to the largest extent. We present the sky distribution of $R_V$ values and show their behavior as a function of galactic coordinates. Finally, we emphasize how $R_V$ values change with different calibrations of $E(B-V)$. Since $R_V$ value may characterize entire extinction curves, extending our study into wavelength regions beyond ultraviolet will provide a check on the universality of CCM law in various parts of the spectrum. We discuss this issue in the forthcoming paper.

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Fig. 1.— Histograms of the errors in the $E(\lambda_i - V)$ for all 782 stars. The vertical lines represent the values adopted by GS for the errors in $E(\lambda_i - V)$. 
Fig. 2.— Sky distribution of the stars in our sample (galactic coordinates).
Fig. 3.— Comparison between the $R_V$ values obtained by GS and the $R_V$ values obtained using our method. The line shows the 1-to-1 relation.
Fig. 4.— Sky distribution of the $R_V$ values (galactic coordinates).
Fig. 5.— $R_V$ values as a function of galactic coordinates. The circular red points represent the unweighted mean values of $R_V$ in different coordinate bins with the rms error bars represented by the vertical lines. The galactic longitudes and latitudes are binned every 30° and 1°, respectively.
Fig. 6.— Histogram of the $R_V$ values computed in this paper and listed in Table 2.
Fig. 7.— The left panel shows $R_V$ values obtained from equation (17) using the Wegner’s (2002) UV data versus the $R_V$ values computed with the same formula, but using our primary data. The line shows a 1-to-1 relationship. The right panel shows the comparison between two different calibrations of $E(B - V)$. The line marks the average difference level.
Table 1. Data sources and adopted errors.

| Quantity | Reference | Error range | Comments |
|----------|-----------|-------------|----------|
| $m_V$    | Nicolet (1978) | $0^m.04$ | We adopt the same conservative errors estimate for all stars. |
| $(m_B - m_V)$ | Nicolet (1978) | $0^m.015$ | We adopt the same conservative errors estimate for all stars. |
| $(m_B - m_V)_0$ | Fitzgerald (1970) | $0^m.02$ | |
| $m_\lambda$ | Wesselius et al. (1982) | $0^m.001$-$0^m.218$ | The error is given for every wavelength band and every line of sight. Typical errors are of the order of tens of millimags. |
| $(m_\lambda - m_V)_0$ | Wu et al. (1980) | $--$ | The error is included in the mismatch error. |
| $E(\lambda - V)$ | Savage et al. (1985) | $0^m.15$-$0^m.40$ | The error given here represents only the mismatch error $\sigma_{\text{mismatch}}$ and it depends on wavelength band and on the spectral type classification of the stars (Meyer & Savage 1981). Although the mismatch error is the dominant contributor, the total error in $E(\lambda - V)$ is expressed by equation (19). |
Table 2. $R_V$ and $A_V$ values with their errors.

| name      | $l$  | $b$  | $E(B-V)$ | $R_V$ | $\sigma_{\text{max}}(R_V)$ | $\sigma_{\text{quad}}(R_V)$ | $A_V$  | $\sigma_{\text{max}}(A_V)$ | $\sigma_{\text{quad}}(A_V)$ |
|-----------|------|------|----------|-------|-----------------------------|-------------------------------|-------|-----------------------------|-------------------------------|
| BD-84617  | 37.0 | 8.4  | 1.22     | 3.23  | 0.24                        | 0.12                          | 3.94  | 0.47                        | 0.34                          |
| BD-84634  | 38.0 | 7.4  | 1.22     | 2.92  | 0.25                        | 0.12                          | 3.56  | 0.48                        | 0.34                          |
| BD-11471  | 213.4| 1.4  | 0.74     | 2.87  | 0.44                        | 0.21                          | 2.13  | 0.50                        | 0.36                          |
| BD+233762 | 60.3 | −0.3 | 1.05     | 3.30  | 0.30                        | 0.15                          | 3.47  | 0.50                        | 0.36                          |
| BD+23771  | 37.2 | −1.4 | 0.93     | 2.65  | 0.35                        | 0.17                          | 2.46  | 0.50                        | 0.36                          |
| BD+243893 | 61.3 | −0.5 | 0.65     | 3.32  | 0.45                        | 0.22                          | 2.16  | 0.47                        | 0.34                          |
| BD+341054 | 173.4| −0.2 | 0.49     | 3.78  | 0.59                        | 0.28                          | 1.85  | 0.47                        | 0.34                          |
| BD+341059 | 173.0| 0.2  | 0.49     | 3.75  | 0.59                        | 0.29                          | 1.84  | 0.47                        | 0.34                          |
| BD+341150 | 175.1| 2.4  | 0.44     | 2.58  | 0.69                        | 0.33                          | 1.13  | 0.47                        | 0.34                          |
| BD+341162 | 175.5| 2.6  | 0.36     | 2.81  | 0.84                        | 0.40                          | 1.01  | 0.47                        | 0.34                          |
| BD+343631 | 69.2 | 6.9  | 0.13     | 4.62  | 2.20                        | 1.05                          | 0.60  | 0.48                        | 0.34                          |
| BD+354258 | 77.2 | −4.7 | 0.29     | 2.39  | 1.07                        | 0.51                          | 0.69  | 0.48                        | 0.34                          |
| BD+361261 | 174.1| 4.3  | 0.52     | 2.75  | 0.62                        | 0.30                          | 1.43  | 0.50                        | 0.36                          |
| BD+363882 | 73.5 | 2.2  | 0.64     | 3.43  | 0.50                        | 0.24                          | 2.19  | 0.50                        | 0.36                          |
| BD+364145 | 77.5 | −2.0 | 0.96     | 2.79  | 0.31                        | 0.15                          | 2.68  | 0.47                        | 0.34                          |
| BD+373945 | 77.3 | −0.2 | 1.07     | 3.24  | 0.30                        | 0.14                          | 3.46  | 0.50                        | 0.36                          |
| BD+374092 | 80.2 | −4.2 | 0.55     | 2.90  | 0.59                        | 0.28                          | 1.60  | 0.50                        | 0.36                          |
| BD+391328 | 169.1| 3.6  | 0.88     | 2.62  | 0.37                        | 0.18                          | 2.30  | 0.50                        | 0.36                          |
| BD+404179 | 79.0 | 1.2  | 0.88     | 3.27  | 0.34                        | 0.16                          | 2.87  | 0.47                        | 0.34                          |
| BD+421286 | 166.1| 4.3  | 0.56     | 3.12  | 0.53                        | 0.26                          | 1.75  | 0.47                        | 0.34                          |

Note. — Columns: [1] star identification number, [2] galactic longitude $l$, [3] galactic latitude $b$, [4] color excess $E(B-V)$, [5] total to selective extinction ratio $R_V$, [6] error in $R_V$ obtained with equation (20), [7] error in $R_V$ obtained with equation (21), [8] visual extinction $A_V$, [9] error in $A_V$ obtained with equation (23), [10] error in $A_V$ obtained with equation (24).
Table 3. Comparison between UV-based $R_V$ values obtained using different calibrations of $E(B - V)$.

| name     | $l$  | $b$  | $E(B - V)_{GP}$ | $R_V_{GP}$ | $\sigma_{\text{max}}[R_V,GP]$ | $\sigma_{\text{quad}}[R_V,GP]$ | $E(B - V)_{Wegner}$ | $R_V$ | $\sigma_{\text{max}}[R_V,Wegner]$ | $\sigma_{\text{quad}}[R_V,Wegner]$ |
|----------|------|------|-----------------|------------|---------------------------------|---------------------------------|---------------------|------|---------------------------------|---------------------------------|
| HD1544   | 119.3| -0.6 | 0.44            | 3.19       | 0.73                            | 0.35                            | 0.37                 | 2.79 | 0.67                            | 0.31                            |
| HD2083   | 120.9| 9.0  | 0.29            | 3.69       | 1.01                            | 0.48                            | 0.26                 | 3.99 | 0.70                            | 0.33                            |
| HD2905   | 120.8| 0.1  | 0.33            | 3.24       | 1.20                            | 0.57                            | 0.30                 | 0.82 | 1.05                            | 0.49                            |
| HD7252   | 125.7| -1.9 | 0.35            | 3.01       | 0.86                            | 0.41                            | 0.32                 | 3.17 | 0.68                            | 0.32                            |
| HD12867  | 133.0| -3.7 | 0.41            | 2.72       | 0.74                            | 0.35                            | 0.38                 | 2.84 | 0.63                            | 0.30                            |
| HD13969  | 134.5| -3.8 | 0.56            | 2.73       | 0.54                            | 0.26                            | 0.54                 | 2.88 | 0.46                            | 0.21                            |
| HD14092  | 134.7| -4.1 | 0.49            | 2.52       | 0.62                            | 0.30                            | 0.46                 | 2.61 | 0.55                            | 0.26                            |
| HD14250  | 134.8| -3.7 | 0.58            | 2.60       | 0.52                            | 0.25                            | 0.55                 | 2.59 | 0.49                            | 0.23                            |
| HD14357  | 135.0| -3.9 | 0.56            | 3.90       | 0.56                            | 0.27                            | 0.49                 | 3.28 | 0.54                            | 0.25                            |
| HD14818  | 135.6| -3.9 | 0.48            | 2.63       | 0.84                            | 0.40                            | 0.46                 | 2.17 | 0.68                            | 0.31                            |
| HD14947  | 135.0| -1.8 | 0.77            | 2.96       | 0.39                            | 0.19                            | 0.76                 | 2.50 | 0.37                            | 0.17                            |
| HD14956  | 135.4| -2.9 | 0.89            | 2.54       | 0.45                            | 0.22                            | 0.88                 | 2.44 | 0.36                            | 0.17                            |
| HD16429  | 135.7| 1.1  | 0.92            | 3.12       | 0.35                            | 0.17                            | 0.86                 | 2.72 | 0.33                            | 0.16                            |
| HD17114  | 137.3| -0.3 | 0.76            | 2.85       | 0.40                            | 0.19                            | 0.73                 | 2.92 | 0.35                            | 0.16                            |
| HD17603  | 138.8| -2.1 | 0.92            | 2.71       | 0.44                            | 0.21                            | 0.92                 | 2.66 | 0.31                            | 0.15                            |
| HD18352  | 137.7| 2.1  | 0.48            | 2.91       | 0.63                            | 0.30                            | 0.45                 | 3.07 | 0.52                            | 0.24                            |
| HD22431  | 148.8| -0.7 | 0.69            | 2.79       | 0.44                            | 0.21                            | 0.65                 | 2.64 | 0.41                            | 0.19                            |
| HD24912  | 160.4| -13.1| 0.29            | 3.45       | 1.36                            | 0.65                            | 0.26                 | 3.78 | 0.75                            | 0.36                            |
| HD30614  | 144.1| 14.0 | 0.30            | 3.01       | 1.33                            | 0.63                            | 0.34                 | 3.07 | 0.74                            | 0.35                            |
| HD34078  | 172.1| -2.3 | 0.52            | 3.44       | 0.57                            | 0.27                            | 0.49                 | 3.20 | 0.49                            | 0.23                            |

Note. — Columns: [1] star identification number, [2] galactic longitude $l$, [3] galactic latitude $b$, [4] color excess $E(B - V)$ taken from Savage et al. (1985), [5] total to selective extinction ratio $R_V$ computed with the calibration from Savage et al. (1985), [6] error in $R_V$ from column 5 obtained with equation (20), [7] error in $R_V$ from column 5 obtained with equation (21), [8] color excess $E(B - V)$ taken from Wegner (2002), [9] total to selective extinction ratio $R_V$ computed with the calibration from Wegner (2002), [10] error in $R_V$ from column 9 obtained with equation (20), [11] error in $R_V$ from column 9 obtained with equation (21).