Empirical extinction coefficients for the *GALEX*, SDSS, 2MASS and WISE* passbands

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ABSTRACT

By using the ‘standard pair’ technique of pairing stars of almost nil and high extinction but otherwise with almost identical stellar parameters from the Sloan Digital Sky Survey (SDSS), and combining this information with photometry from the SDSS, *GALEX*, Two Micron All Sky Survey (2MASS) and Wide-field Infrared Survey Explorer (WISE) photometry ranging from the far ultraviolet (UV) to the mid-infrared (mid-IR), we measure dust reddening in the $FUV - NUV$, $NUV - u$, $u - g$, $g - r$, $r - i$, $i - z$, $z - J$, $J - H$, $H - K_s$, $K_s - W1$ and $W1 - W2$ colours for thousands of Galactic stars. The measurements, together with the $E(B - V)$ values given by Schlegel et al., allow us to derive the observed, model-free reddening coefficients for these colours. The results are compared with previous measurements and with the predictions of various Galactic reddening laws. We find that (i) the dust reddening map of Schlegel et al. overestimates $E(B - V)$ by about 14 per cent, consistent with the recent work of Schlafly et al. and Schlafly & Finkbeiner; (ii) after accounting for the differences in reddening normalization, the newly deduced reddening coefficients for colours $FUV - NUV$, $NUV - u$, $u - g$, $g - r$, $r - i$, $i - z$, $z - J$, $J - H$ and $H - K_s$ differ by respectively $-1640, 15.5, 12.6, -0.8, 3.4, -0.7, 3.5, 2.5$ and 1.4 per cent from the predictions of the Fitzpatrick reddening law for an assumed total-to-selective extinction ratio $R(V) = 3.1$, and by respectively $-1730, 13.0, 8.1, 10.0, 8.0, -13.5, -1.7, -6.7$ and $-17.1$ per cent from the predictions of the CCM reddening law; and (iii) all the new reddening coefficients, except those for $NUV - u$ and $u - g$, favour the $R(V) = 3.1$ Fitzpatrick reddening law over the $R(V) = 3.1$ CCM and O’Donnell reddening laws. Using the $K_s$-band extinction coefficient predicted by the $R(V) = 3.1$ Fitzpatrick law and the observed reddening coefficients, we deduce new extinction coefficients for the $FUV$, $NUV$, $u$, $g$, $r$, $i$, $z$, $J$, $H$, $W1$ and $W2$ passbands. We recommend that the new reddening and extinction coefficients should be used in the future and that the Fitzpatrick reddening law in the UV should probably be updated. We stress, however, that the $FUV$- and $NUV$-band coefficients should be used with caution, given their relatively large measurement uncertainties. Finally, potential applications of the ‘standard pair’ technique with the upcoming LAMOST Galactic surveys are discussed.

Key words: stars: general – dust, extinction.

1 INTRODUCTION

Dust grains produce extinction and reddening of stellar light from the ultraviolet (UV) to the infrared (IR) (Draine 2003). An accurate determination of the reddening to a star is vital for reliable derivation of its basic stellar parameters, such as distance, effective temperature and intrinsic spectral energy distribution (SED).

Using *IRAS* and DIRBE data, Schlegel, Finkbeiner & Davis (1998, hereafter SFD) generated a whole-sky 2D dust-reddening map of $E(B - V)$ based on the dust thermal emission. The map has been widely used to correct for extinction and reddening of extra-galactic as well as Galactic sources. However, the SFD dust reddening map delivers the total amount of reddening along a sightline at a spatial resolution of about 6 arcmin, and thus it may overestimate the real values for Galactic sources. The extinction of a given passband $a$ and the colour excess (reddening) of a given colour $a - b$ are usually estimated by $A(a) = R(a) \times E(B - V)$ and $E(a - b) = R(a - b) \times E(B - V)$, respectively. Here $R(a)$, defined as extinction in the...
The paper is organized as follows. In Section 2, we introduce the data sets and the method used to measure the reddening in various colours. The reddening coefficients for various colours and extinction coefficients for various passbands are presented in Section 3 and compared with previous studies and the predictions of various Galactic reddening laws. The results are discussed in Section 4, along with the potential applications of the ‘standard pair’ technique in several ongoing and forthcoming large-scale spectroscopic surveys. A brief summary then follows in Section 5.

2 DATA AND METHOD

Extinction curves are usually measured using the ‘standard pair’ technique (Stecher 1965; Massa et al. 1983) by comparing the photometric and/or spectrophotometric measurements of two stars of the same spectral type, one of which has negligible foreground dust while the other is highly reddened. Comparison of the SEDs of the two stars, together with the assumption that the dust extinction goes to zero at very long wavelengths, allows one to determine the extinction $A_\lambda = 2.5 \log (F_\lambda/F_\lambda^0)$ as a function of wavelength $\lambda$, where $F_\lambda$ is the observed flux and $F_\lambda^0$ is the flux in the absence of extinction. The method has been used to measure extinction curves for many sightlines, in many cases over a wavelength range extending from the vacuum UV to the mid-IR. We use a similar ‘standard pair’ method to measure reddening and then derive the reddening coefficient of a given colour. This method requires a target sample of highly reddened stars and a control sample of stars of matching spectral types that are unreddened or have extremely low reddening. Control stars of matching spectral type are used to estimate the intrinsic colours of the target stars. In order to maximize the numbers of target and control stars for different passbands, different selection criteria have been used here. This section describes selections of target and control stars for measuring reddening coefficients of the SDSS, GALEX, 2MASS and WISE passbands.

2.1 Data for the SDSS passbands

Both the target and control samples are selected from the SDSS Data Release 7 (DR7; Abazajian et al. 2009). SDSS DR7 provides accurate photometry of about 100 million stars in the $u, g, r, i$ and $z$ bands, and spectra of more than 300 000 stars. We select target stars as those with a line-of-sight extinction $E(B - V) > 0.1$, a spectrum of signal-to-noise ratio S/N > 40, and having basic stellar parameters of effective temperature $T_{\text{eff}}$, surface gravity log $g$ and metallicity [Fe/H] that are well determined with corresponding uncertainties given by the SSPP for $0.25$ dex and $0.23$ dex, respectively. Values of $E(B - V)$ used here are from SFD. Values of $T_{\text{eff}}$, log $g$ and [Fe/H] are from the SSPP. Note that the SSPP estimates $T_{\text{eff}}$, log $g$ and [Fe/H] of each star using a variety of methods. Some of the methods are photometry-based and thus have some sensitivity to reddening corrections, while others, such as the NGS1, ki13, ANNR and ANNSR methods, do not rely on photometry. To avoid uncertainties introduced by reddening corrections, we use the mean values of $T_{\text{eff}}$, log $g$ and [Fe/H] derived only from the NGS1, ki13, ANNR and ANNSR methods for the purpose of the current work. However, the errors estimated by the SSPP are still used. Typical uncertainties given by the SSPP for $T_{\text{eff}}$, log $g$ and [Fe/H] are 180 K, 0.25 dex and 0.23 dex, respectively, dominated by the systematic errors (Schlesinger et al. 2010; Smolinski et al. 2011). In this work, we are interested mainly in the relative ranking of stars in the $T_{\text{eff}}$, log $g$ and [Fe/H] parameter spaces, and thus systematic uncertainties are not important. In total, 9202 target stars are selected. Their
Figure 1. Spatial distributions of target samples for measuring reddening coefficients of the SDSS (top left), GALEX (top right), 2MASS (bottom left) and WISE (bottom right) passbands. The total numbers of stars of the individual samples are also marked.

Spatial and $T_{\text{eff}}$ versus log $g$ distributions are shown in the top left panels of Figs 1 and 2, respectively. It is seen that the target stars are composed mainly of FGK dwarfs, with a small fraction being A dwarfs and KM giants. These targets are from different SDSS spectroscopic plates, so they are spatially clustered by plate.

For the control sample, we select stars with a line-of-sight extinction $E(B-V) < 0.03$ and a spectrum of S/N > 20. The err cuts on $T_{\text{eff}}$, log $g$ and [Fe/H] are the same as target stars. In total, 50,053 stars are selected.

2.2 Data for the GALEX passbands

GALEX (Martin et al. 2005) is a space telescope providing imaging in the far-UV (1344–1786 Å, centred at 1528 Å) and near-UV (1771–2831 Å, centred at 2271 Å) bands, with a 6–8 arcsec angular resolution (80 per cent encircled energy) and 1-arcsec astrometry. GALEX is carrying out a number of surveys of different sizes of sky coverage and detection depths. The catalogues of unique UV sources from two of GALEX’s surveys, namely AIS (the All-Sky Imaging Survey of depths of AB magnitudes of 19.9 and 20.8 in the far- and near-UV bands, respectively) and MIS (the Medium-depth Imaging Survey of depths of 22.6 and 22.7, respectively) from the GALEX fifth data release, have been matched to the SDSS DR7 catalogues by Bianchi et al. (2011), using a match radius of 3.0 arcsec.

The target and control samples for the GALEX passbands are selected from the corresponding samples for the SDSS passbands by requiring that the sources are well detected in the two GALEX bands with photometric errors [error(FUV) and error(NUV)] smaller than 0.2. Given the relatively low angular resolution of GALEX, a GALEX source may have multiple SDSS matches. Sources with multiple matches within a search radius of 4.2 arcsec are removed. In total, 1396 targets and 16,405 control stars were collected. The spatial and $T_{\text{eff}}$ versus log $g$ distributions of the targets are shown in the top right panels of Figs 1 and 2, respectively. The target stars are also spatially clustered, and most of them are FG dwarfs.

2.3 Data for the 2MASS passbands

2MASS (Skrutskie et al. 2006) has made uniformly calibrated imaging observations of the whole sky in the $J$ (1.24 μm), $H$ (1.66 μm) and $K_s$ (2.16 μm) near-IR bands. The 2MASS Point Source Catalog contains positions and photometry for 470,992,970 objects, and is complete down to $J = 15.8$, $H = 15.1$ and $K_s = 14.3$ mag.

The target and control samples for the 2MASS passbands are also selected from the corresponding samples for the SDSS passbands, by requiring that the sources are well detected and have photometric errors smaller than 0.1 mag in all three 2MASS bands. In total, 7357 targets and 34,548 control stars were collected. The spatial and $T_{\text{eff}}$ versus log $g$ distributions of the targets, which are very similar to those of the targets for the SDSS passbands, are plotted in the bottom left panels of Figs 1 and 2, respectively.

2.4 Data for the WISE passbands

The satellite WISE (Wright et al. 2010) has imaged the whole sky in four bands at 3.4, 4.6, 12 and 22 μm (named W1, W2, W3 and W4, respectively) with a corresponding angular resolution of 6.1, 6.4, 6.5 and 12.0 arcsec. The WISE Source Catalog contains positions and photometry for over 563 million point-like and resolved objects. The positions are calibrated against the 2MASS, achieving an accuracy of ~200 mas on each axis with respect to the 2MASS reference
Figure 2. $T_{\text{eff}}$ versus log $g$ distributions of target samples for measuring reddening coefficients of the SDSS (top left), GALEX (top right), 2MASS (bottom left) and WISE (bottom right) passbands. The total numbers of stars of the individual samples are also marked.

frame for sources with S/Ns better than 40. Photometry is performed using techniques of point-source profile-fitting and multi-aperture photometry, achieving 5σ photometric sensitivities of 0.068, 0.098, 0.86 and 5.4 mJy (equivalent to 16.6, 15.6, 11.3 and 8.0 Vega mag) at 3.4, 4.6, 12 and 22 µm, respectively, in unconfused regions in the ecliptic plane. Given the low sensitivities of the W3 and W4 bands and the poor angular resolution of the W4 band, the extinction coefficients for these two bands are not measured in this work. We focus only on the W1 and W2 bands.

The target and control samples for the WISE W1 and W2 passbands are selected from the corresponding samples for the 2MASS passbands, requiring that the sources are well detected in the W1 and W2 bands and have photometric errors smaller than 0.05 mag in both bands. The samples for the 2MASS passbands are matched to the WISE sources with a match radius of 3.0 arcsec. Considering the low angular resolutions of WISE, WISE sources with multiple matches within a search radius of 10.0 arcsec are excluded. Sources that are affected by known artefacts or are likely variables are also removed. In total, 3885 targets and 10 842 control stars were collected. The spatial and $T_{\text{eff}}$ versus log $g$ distributions of the targets are plotted in the bottom right panels of Figs 1 and 2, respectively. Most of the targets are GK dwarfs and giants.

2.5 Method

The ‘standard pair’ technique used in this work is very similar to the template subtraction method used by Yuan & Liu (2012) to detect and measure DIBs in the SDSS spectra. For each star in the target sample, the control stars are selected from the control sample as those having values of $T_{\text{eff}}$, log $g$ and [Fe/H] that differ from those of the target by less than 50 K, 0.25 dex and 0.1 dex, respectively. The reddening of the target in a given colour is measured as the difference between the observed and intrinsic colours. The latter is derived assuming that the intrinsic colours of the target and its control stars vary linearly with $T_{\text{eff}}$, log $g$ and [Fe/H]. The assumption is valid considering the small ranges of values of $T_{\text{eff}}$, log $g$ and [Fe/H] being considered. The control stars are dereddened using an initial set of reddening coefficients and $E(B-V)$ values from SFD. Then a new set of reddening coefficients is derived by comparing the estimates of reddening relative to $E(B-V)$ for the target sample. Iterations are carried out until the derived set of reddening coefficients is consistent with the one used for dereddening the control sample.

After obtaining reddening coefficients for colours of two adjacent bands, the extinction coefficients for all bands can be computed by assuming an extinction coefficient value for a given passband.

3 RESULTS

3.1 $R(u-g), R(g-r), R(r-i)$ and $R(i-z)$

We first determine the reddening coefficients for the $u-g, g-r, r-i$ and $i-z$ colours for the sample of the SDSS passbands. The left panels in Fig. 3 show reddening (i.e. colour excess, defined as the difference of the observed and intrinsic colours) $E(u-g), E(r-i)$ and $E(i-z)$ versus $E(g-r)$. All those derived are independent of possible uncertainties in the SFD map. The right panels in Fig. 3 show the same set of reddening plus $E(g-r)$ plotted against $E(B-V)$ given by SFD. The black pluses denote results from the individual target stars, whereas the large red pluses represent median values of individual data points grouped into eight bins in the $x$-axis, with a bin size of 0.1 mag. A 3σ clipping has been applied in calculating the medians. The red lines represent linear regressions passing through
Figure 3. Reddening coefficients of the $u - g$, $g - r$, $r - i$ and $i - z$ colours deduced using the samples for the SDSS passbands. (Left) Reddening of $u - g$, $r - i$ and $i - z$ colours versus that of $g - r$. (Right) Reddening of $u - g$, $g - r$, $r - i$ and $i - z$ colours versus $E(B - V)$ from SFD. Black pluses denote data deduced for individual stars. Large, red pluses represent median values by binning the data points into eight groups with a bin size of 0.1 on the x-axis. The red lines are linear regressions passing through the origin to the red pluses, with each plus carrying equal weight. As already noted, the SFD map delivers the total amount of extinction integrated along a given line-of-sight to infinity, has a limited spatial resolution of about 6 arcmin and fails at low Galactic latitudes ($|b| \leq 5^\circ$); thus, the $E(B - V)$ values from the SFD map may not represent the true values of the targets. However, as is discussed in Section 4, these effects are not important for the targets in this work.
The bottom right panel of Fig. 3 yields an $R(g - r)$ value of 0.99 ± 0.015, which is consistent with those obtained by S10 and SF11, confirming their earlier findings that $E(B - V)$ values from SFD are overestimated by about 14 per cent. The value of 14 per cent is consistent with the fact that an $R(V) = 3.1$ Fitzpatrick law predicts $R(g - r) = 1.139$. Adopting the relation $E(g - r) = 0.99 E(B - V)$, values of $R(u - g)$, $R(r - i)$ and $R(i - z)$ can then be derived from the data plotted in the left panels of Fig. 3. The results are found to agree well with those derived from the data plotted in the right panels. The values of $R(u - g)$, $R(g - r)$, $R(r - i)$ and $R(i - z)$ deduced in this work are listed in the 2nd and 3rd columns of Table 1. The 4th, 5th and 6th columns give predictions of the $R(V) = 3.1$ Fitzpatrick, CCM and O’Donnell extinction laws, respectively, assuming that SFD overpredict $E(B - V)$ by 14 per cent. For comparison, relations predicted by the Fitzpatrick, CCM and O’Donnell laws are over-plotted in Fig. 3 in purple, blue and cyan, respectively. The predicted values are calculated by convolving a synthetic stellar spectral model from Castelli & Kurucz (2004) of $T_{\text{eff}} = 7000$ K, log $g = 4.5$ and [Fe/H] = 1 without and with dust extinction of $E(B - V) = 0.4$. The SDSS filter curves are from the SDSS DR7 website. Values obtained by SF11, S10 and SFD are also listed in Table 1.

Note that the extinction and reddening coefficients predicted by the extinction laws do have some dependence on the source spectrum. For example, for a temperature range of 5000–7000 K, which covers most targets in this work, the variations of $R(a)$ predicted by the $R(V) = 3.1$ Fitzpatrick law [except $R(FUV), R(NUV), R(g)$ and $R(r)$] in this work caused by such dependence are found to be well below 0.01. The predicted $R(FUV), R(NUV), R(g)$ and $R(r)$ increase respectively by $-0.95, 0.76, 0.069$ and 0.016 when the source temperature increases from 5000 to 7000 K. Therefore, the dependence of $R(a)$ and consequently of $R(u - b)$ on the source spectrum can be safely ignored in most cases. Similarly, the extinction and reddening coefficients also depend on the amount of extinction. The predicted $R(FUV), R(NUV), R(u), R(g)$ and $R(r)$ decrease respectively by 0.02, 0.45, 0.015, 0.047 and 0.016 when $E(B - V)$ increases from 0.2 to 1.0. For other bands considered in this work, however, the corresponding variations for $E(B - V)$ between 0.2 and 1.0 are well below 0.01. Thus again it is reasonable to assume constant extinction and reddening coefficients for the purpose of this work.

As in the case of $R(g - r)$, values of $R(r - i)$ and $R(i - z)$ yielded by our data are consistent with those of S10 and SF11. A comparison of values of $R(g - r), R(r - i)$ and $R(i - z)$ from the current work with those predicted by different extinction laws favours the $R(V) = 3.1$ Fitzpatrick reddening law over those of CCM and O’Donnell, again consistent with the findings of S10 and S11. However, $R(u - g)$ is the worst predicted. The value of $R(u - g)$ in the 2nd column of Table 1, derived in this work, is respectively 7 and 15 per cent higher than those from S10 and S11, and is respectively 14, 10 and 14 per cent higher than those predicted by the $R(V) = 3.1$ Fitzpatrick, CCM and O’Donnell laws. Based on a colour–colour fit, SF11 obtained a relation $E(u - g) = 1.01 E(g - r)$. Checking the data plotted in the left panel of Fig. 7 of SF11, we find that their above relation underpredicts $E(u - g)/E(g - r)$ by about 10 per cent at high extinctions. The same problem exists in the left panel of Fig. 16 of S10. The top panels of Fig. 3 also show a similar trend, namely that $R(u - g)$ tends to be larger at higher extinctions. Thus all the data, those of this work and of SF11 and S10, are consistent, and the differences in the derived reddening coefficients, such as $R(u - g)$ and $R(i - z)$, are probably caused largely by the different fitting procedures.

### 3.2 $R(NUV - u)$ and $R(NUV - V)$

Fig. 4 shows the reddening of $NUV - u$ and $NUV - V$ colours versus that of $g - r$ and $E(B - V)$ of the target sample for the GALEX passbands. The symbols and lines are similar to those in Fig. 3. Owing to the large (even systematic) photometric uncertainties of GALEX data, the small size of the target sample, the relatively

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**Table 1.** $R(a - b)$ for various colours.

| Colour                  | This work$^a$ | This work$^b$ | Fitzpatrick$^c, d$ | CCM$^d, e$ | O’Donnell$^d, f$ | SF11$^g$ | S10$^h$ | SFD$^i$ |
|-------------------------|--------------|--------------|-------------------|-----------|----------------|----------|---------|-------|
| $NUV - NUV$             | $-2.35 \pm 0.58$ | $-2.69 \pm 0.50$ | 0.164             | 0.154     |                |          |         |       |
| $NUV - u$               | $2.85 \pm 0.070$ | 2.71 $\pm 0.22$ | 2.406             | 2.460     |                |          |         |       |
| $u - g$                 | $1.08 \pm 0.010$ | 1.04 $\pm 0.018$ | 0.945             | 0.984     | 0.950          | 1.01 $\pm 1.01$ | 1.362   |       |
| $g - r$                 | $0.99 \pm 0.015$ | 0.99 $\pm 0.015$ | 0.999             | 0.901     | 0.936          | 0.98 $\pm 1.01$ | 1.042   |       |
| $r - i$                 | $0.60 \pm 0.010$ | 0.60 $\pm 0.011$ | 0.582             | 0.557     | 0.514          | 0.55 $\pm 1.01$ | 0.665   |       |
| $i - z$                 | $0.43 \pm 0.004$ | 0.43 $\pm 0.005$ | 0.426             | 0.496     | 0.513          | 0.44 $\pm 1.01$ | 0.607   |       |
| $z - J$                 | $0.56 \pm 0.011$ | 0.56 $\pm 0.013$ | 0.544             | 0.554     |                |          |         |       |
| $J - H$                 | $0.26 \pm 0.005$ | 0.26 $\pm 0.011$ | 0.254             | 0.279     |                |          |         |       |
| $H - Ks$                | $0.16 \pm 0.006$ | 0.16 $\pm 0.005$ | 0.158             | 0.188     |                |          |         |       |
| $Ks - W1$               | $0.12 \pm 0.008$ | 0.12 $\pm 0.010$ | 0.120             | 0.149     |                |          |         |       |
| $W1 - W2$               | $0.026 \pm 0.004$ | $0.036 \pm 0.007$ | 0.063             | 0.075     |                |          |         |       |

$^a$ $R(a - b)$ derived by fitting $E(a - b)$ against $E(g - r)$, assuming $R(g - r) = 0.99$.
$^b$ $R(a - b)$ derived by fitting $E(a - b)$ against $E(B - V)$ from SFD.
$^c$ Predictions by an $R(V) = 3.1$ Fitzpatrick extinction law at $E(B - V) = 0.4$ for a 7000-K source spectrum, assuming that SFD overestimate $E(B - V)$ by 14 per cent.
$^d$ The filter curves for GALEX, SDSS, 2MASS and WISE passbands are from Morrissey et al. (2005), the SDSS DR7 website, Cohen et al. (2003) and Wright et al. (2010), respectively.
$^e$ Predictions by an $R(V) = 3.1$ CCM extinction law at $E(B - V) = 0.4$ for a 7000-K source spectrum, assuming that SFD overestimate $E(B - V)$ by 14 per cent.
$^f$ Predictions by an $R(V) = 3.1$ O’Donnell extinction law at $E(B - V) = 0.4$ for a 7000-K source spectrum, assuming that SFD overestimate $E(B - V)$ by 14 per cent.
$^g$ $R(a - b)$ derived from fitting SFD by SF11 using stars with spectra without applying zero-point offsets.
$^h$ $R(a - b)$ derived from fitting SFD by S10 with the ‘blue tip’ method.
$^i$ Original SFD prescription.
strong sensitivity for the temperature of the targets and possibly stellar chromospheric activities of solar-type stars, the values of $R(NUV - u)$ and $R(FUV - NUV)$ deduced suffer large uncertainties, especially for $R(FUV - NUV)$. However, the values derived from the data plotted in the left and right panels of Fig. 4 are still consistent within the error bars, as listed in Table 1. Relations predicted by the $R(V) = 3.1$ Fitzpatrick and CCM laws are also listed. The GALEX filter curves are from Morrissey et al. (2005). Both the Fitzpatrick and the CCM law seem to have underpredicted $R(NUV - u)$ by about 12 per cent and to have overpredicted $R(FUV - NUV)$ dramatically.

### 3.3 $R(z - J), R(J - H)$ and $R(H - Ks)$

Fig. 5 shows the reddening of $z - J, J - H$ and $H - Ks$ colours versus that of $g - r$ and $E(B - V)$ of the target sample for the 2MASS passbands. The symbols and lines are similar to those in Fig. 3. Again owing to the relatively large photometric uncertainties of 2MASS for faint sources, the scatters in Fig. 5 are larger than those in Fig. 3. The values of $R(z - J), R(J - H)$ and $R(H - Ks)$ deduced are compared with the predictions of the $R(V) = 3.1$ Fitzpatrick and CCM laws in Table 1. The 2MASS filter curves are from Cohen, Wheaton & Megeath (2003).

Values of $R(z - J), R(J - H)$ and $R(H - Ks)$ obtained from data plotted in the left panels of Fig. 5, consistent with those deduced from data plotted in the right panels, differ by 3.5, 2.5 and 1.4 per cent respectively from those predicted by the $R(V) = 3.1$ Fitzpatrick law, and by $-1.7$, $-6.7$ and $-17.1$ per cent respectively from those predicted by the $R(V) = 3.1$ CCM law. Our measured values of $R(z - J), R(J - H)$ and $R(H - Ks)$ favour the $R(V) = 3.1$ Fitzpatrick law over that of CCM.

### 3.4 $R(Ks - W1)$ and $R(W1 - W2)$

Fig. 6 shows the reddening of $Ks - W1$ and $W1 - W2$ colours versus that of $g - r$ and $E(B - V)$ of the target sample for the WISE passbands. The symbols and lines are similar to those in Fig. 3. We obtained $R(Ks - W1) = 0.12 \pm 0.008$ and $R(W1 - W2) = 0.026 \pm 0.004$ from data plotted in the left panels, and $R(Ks - W1) = 0.12 \pm 0.010$ and $R(W1 - W2) = 0.036 \pm 0.007$ from those in the right panels. The numbers are listed in Table 1, along with predictions of the Fitzpatrick and CCM reddening laws. The WISE filter curves are from Wright et al. (2010). Note that the Fitzpatrick law is valid only from 0.1 to 3.5 $\mu$m, and the CCM law is valid only from 0.125 to 3.5 $\mu$m. Beyond 3.5 $\mu$m, the extinction laws are extrapolated to calculate the predictions for the WISE passbands, which may cause incorrect results. Again, the results favour the $R(V) = 3.1$ Fitzpatrick law over the CCM law. Unsurprisingly, both the Fitzpatrick and the CCM law overpredict $R(W1 - W2)$ significantly. However, the observed small values of $R(W1 - W2)$ are consistent with previous studies of mid-IR extinction laws (e.g. Gao, Jiang & Li 2009).

### 3.5 Extinction coefficients for the GALEX, SDSS, 2MASS and WISE passbands

To derive the extinction coefficients for the GALEX, SDSS, 2MASS and WISE passbands from the reddening coefficients for colours of
adjacent bands presented above, the $R(\alpha)$ value for a given band is needed. Ideally, if one of the bands studied has a long enough wavelength, say in the far-IR, then one can always assume that $R(\alpha)$ for that band is zero. This, however, is not the case for the current study. As such, we have adopted $R(K_s) = 0.306$, predicted by the $R(V) = 3.1$ Fitzpatrick law assuming that SFD overpredict $E(B - V)$ by 14 per cent, as the reference point. Here the $R(V) = 3.1$ Fitzpatrick law is used because it is favoured by the observations in this work.

The resultant extinction coefficients for the GALEX, SDSS, 2MASS and WISE passbands are given in Table 2. Also listed in Table 2 are extinction coefficients predicted by the $R(V) = 3.1$ Fitzpatrick, CCM and O'Donnell laws assuming that SFD overpredict $E(B - V)$ by 14 per cent, and those adopted in the literature for comparison.

Table 2 shows that the two sets of $R(\alpha)$ values based on the reddening coefficients deduced from the data plotted in the left and right panels of Figs 3–6 agree with each other within 2.5 per cent, except for $R(FUV)$ and $R(W2)$, for which the results differ by about 10 per cent. Table 2 also shows that the derived $R(\alpha)$ values overall agree better with the $R(V) = 3.1$ Fitzpatrick law than with the $R(V) = 3.1$ CCM and O'Donnell laws. Both the $R(V) = 3.1$ Fitzpatrick and CCM laws overpredict $R(FUV)$ by 40–50 per cent and underpredict $R(W2)$ by 20–30 per cent. There are also large differences between

Figure 5. Reddening coefficients of the $z - J$, $J - H$ and $H - Ks$ colours deduced using the samples for the 2MASS passbands. (Left) Reddening of $z - J$, $J - H$ and $H - Ks$ colours versus that of $g - r$. (Right) Reddening of $z - J$, $J - H$ and $H - Ks$ colours versus $E(B - V)$ from SFD. The symbols and lines are similar to those in Fig. 3.
Figure 6. Reddening coefficients of the $Ks - W_1$ and $W_1 - W_2$ colours deduced using the samples for the WISE passbands. (Left) Reddening of $Ks - W_1$ and $W_1 - W_2$ colours versus that of $g - r$. (Right) Reddening of $Ks - W_1$ and $W_1 - W_2$ colours versus $E(B - V)$ from SFD. The symbols and lines are similar to those in Fig. 3.

Table 2. $R(a)$ for the GALEX, SDSS, 2MASS and WISE passbands.

| Band   | This work$^a$ | This work$^b$ | Fitzpatrick$^{c,d}$ | CCM$^{d,e}$ | O’Donnell$^{d,f}$ | SFD$^g$ | Seibert$^h$ | Majewski$^i$ |
|--------|---------------|---------------|---------------------|-------------|------------------|--------|-------------|-------------|
| FUV    | 4.89 ± 0.60   | 4.37 ± 0.54   | 6.783               | 6.892       | 8.29             |
| NUV    | 7.24 ± 0.08   | 7.06 ± 0.22   | 6.620               | 6.738       | 8.18             |
| u      | 4.39 ± 0.04   | 4.35 ± 0.04   | 4.214               | 4.278       | 4.259            | 5.155  |
| g      | 3.30 ± 0.03   | 3.31 ± 0.03   | 3.269               | 3.294       | 3.309            | 3.793  |
| r      | 2.31 ± 0.03   | 2.32 ± 0.03   | 2.270               | 2.393       | 2.373            | 2.751  |
| i      | 1.71 ± 0.02   | 1.72 ± 0.02   | 1.689               | 1.836       | 1.859            | 2.086  |
| z      | 1.29 ± 0.02   | 1.28 ± 0.02   | 1.261               | 1.340       | 1.346            | 1.479  |
| J      | 0.72 ± 0.01   | 0.72 ± 0.01   | 0.717               | 0.786       | 0.82             |
| H      | 0.46 ± 0.01   | 0.46 ± 0.01   | 0.464               | 0.508       | 0.53             |
| Ks     | 0.306         | 0.306         | 0.306               | 0.320       | 0.34             |
| W1     | 0.18 ± 0.01   | 0.19 ± 0.01   | 0.186               | 0.171       |                  |
| W2     | 0.16 ± 0.01   | 0.15 ± 0.01   | 0.123               | 0.096       |                  |

$^a$ Calculated using $R(Ks) = 0.306$ and reddening coefficients from the 2nd column of Table 1.

$^b$ Calculated using $R(Ks) = 0.306$ and reddening coefficients from the 3rd column of Table 1.

$^c$ Predictions of an $R(V) = 3.1$ Fitzpatrick extinction law at $E(B - V) = 0.4$ for a 7000-K source spectrum, assuming that SFD overpredict the true values of $E(B - V)$ by 14 per cent.

$^d$ The filter curves for GALEX, SDSS, 2MASS and WISE passbands are from Morrissey et al. (2005), the SDSS DR7 website, Cohen et al. (2003) and Wright et al. (2010), respectively.

$^e$ Predictions of an $R(V) = 3.1$ CCM extinction law at $E(B - V) = 0.4$ for a 7000-K source spectrum, assuming that SFD overpredict the true values of $E(B - V)$ by 14 per cent.

$^f$ Predictions of an $R(V) = 3.1$ O’Donnell extinction law at $E(B - V) = 0.4$ for a 7000-K source spectrum, assuming that SFD overpredict the true values of $E(B - V)$ by 14 per cent.

$^g$ Original SFD prescription.

$^h$ From Seibert et al. (2005).

$^i$ From Majewski et al. (2003).
panels of Figs 3–6 agree well with each other. More importantly, the newly deduced reddening coefficients for the $g - r$, $r - i$, $i - z$, $z - J$, $J - H$, $H - Ks$ and $Ks - W1$ colours agree well with the $R(V) = 3.1$ Fitzpatrick reddening law but do not favour the $R(V) = 3.1$ CCM and O’Donnell laws. This result suggests that the $R(V) = 3.1$ Fitzpatrick reddening law is to be preferred over the $R(V) = 3.1$ CCM and O’Donnell reddening laws. However, the $R(V) = 3.1$ Fitzpatrick law seems to underpredict $R(NUV - u)$ and $R(u - g)$ values by about 12 per cent, indicating that an update of the Fitzpatrick law in the UV is necessary. Note that the observed $R(NUV - u)/R(g - r)$ and $R(u - g)/R(g - r)$ ratios agree better with the CCM law than with the Fitzpatrick law.

Both the $R(V) = 3.1$ Fitzpatrick and CCM laws fail to explain the observed $R(FUV - NUV)$ values. The predicted $R(FUV - NUV)$ values are sensitive to the temperature of the source spectrum used. In this work, a 7000-K source spectrum is adopted to calculate the predicted reddening coefficients, while the temperatures of most targets for the GALEX passbands are below 7000 K. However, the predicted values increase as the temperature decreases, and therefore a more representative source spectrum will increase the differences between the observed and predicted $R(FUV - NUV)$ values. The large differences could also be caused by uncertainties of the source spectrum in the FUV band. To further investigate the differences, a much hotter and larger sample is needed. The Fitzpatrick and CCM reddening laws cannot explain the observed $R(W1 - W2)$ values either. This is probably because neither the Fitzpatrick nor the CCM law is valid for the WISE bands, and thus extrapolations have to be carried out to calculate the predicted $R(W1 - W2)$ values. Note that the observed small values of $R(W1 - W2)$ are consistent with previous studies of mid-IR extinction laws (e.g. Gao et al. 2009).

We have assumed $R(V) = 3.1$ in this work when calculating the predicted extinction coefficients by the Fitzpatrick, CCM and O’Donnell reddening laws. Given that $R(V)$ is sensitive to the IR colour excesses (Fitzpatrick 1999), we performed a consistent check using the data for the 2MASS passbands. By minimizing the differences between the observed reddening of $g - z$, $g - J$, $g - H$ and $g - Ks$ relative to $g - r$ and those predicted by Fitzpatrick reddening laws of different $R(V)$, we find the optimal value of $R(V)$ for each star in the target sample for the 2MASS passbands. A histogram of $R(V)$ values thus obtained is plotted in Fig. 9. The median and mean values of $R(V)$ are 3.09 and 3.12, respectively, consistent with the value adopted in the current work as well as with

![Figure 7](image-url)  
**Figure 7.** Comparison between the measured and predicted reddening coefficients using data from Table 1. The purple solid and dashed lines represent the ratios of the measured reddening coefficients in the 2nd and 3rd columns to those predicted by the $R(V) = 3.1$ Fitzpatrick law in the 4th column, respectively. The blue solid and dashed lines represent the ratios of the measured reddening coefficients in the 2nd and 3rd columns to those predicted by the $R(V) = 3.1$ CCM law in the 5th column, respectively. The cyan solid and dashed lines represent the ratios of the measured coefficients in the 2nd and 3rd columns to those predicted by the $R(V) = 3.1$ O’Donnell law in the 6th column, respectively.

![Figure 8](image-url)  
**Figure 8.** Comparison between the measured and predicted extinction coefficients using data from Table 2. The lines are similar to those in Fig. 7.

the $R(u)$ values deduced in this work and those of SFD, Seibert et al. (2005) and Majewski et al. (2003).

4 DISCUSSION

Fig. 7 shows a comparison between the measured and predicted reddening coefficients, using data from Table 1. Fig. 8 shows a comparison between the measured and predicted extinction coefficients, using data from Table 2. The purple solid and dashed lines represent the ratios of the measured coefficients in the 2nd and 3rd columns to those predicted by the $R(V) = 3.1$ Fitzpatrick reddening law in the 4th column, respectively. The blue solid and dashed lines represent the ratios of the measured coefficients in the 2nd and 3rd columns to those predicted by the $R(V) = 3.1$ CCM reddening law in the 5th column, respectively. The cyan solid and dashed lines represent the ratios of the measured coefficients in the 2nd and 3rd columns to those predicted by the $R(V) = 3.1$ O’Donnell reddening law in the 6th column, respectively. It is clearly seen that the two sets of coefficients derived from the data plotted in the left and right

![Figure 9](image-url)  
**Figure 9.** Histogram of $R(V)$ deduced using the sample for the 2MASS passbands. The median and mean $R(V)$ values of the sample are 3.09 and 3.12, respectively.
the average value for the Galactic diffuse interstellar medium. If the mean value of $R(V)$ is adopted, the differences between observations and the predictions of extinction laws will be slightly smaller, by less than 1.0 per cent. However, the main results of this work are not affected.

The SFD dust reddening map delivers the total amount of reddening along a sightline, and thus may overestimate the real value for a local disc star. The tight correlation between $E(g - r)$ and $E(B - V)$, as shown in the bottom-right panel of Fig. 3, however, suggests that most local disc stars have been excluded from our samples and that therefore this effect is unlikely to be important. To quantify this potential effect, we select a subsample of stars of $|b| \geq 15\degr$ from the target sample for the SDSS passbands and re-fit the data. We find a new value of 1.007 for $R(g - r)$, which is only 1.6 per cent larger than that from the original target sample. The differences between the new and original values of $R(u - g)$ and $R(i - z)$ are even smaller, confirming that this effect has not affected the main results of this work.

In our analysis, we have not included the effects of possible variations of $R(g - r)$, which is sensitive to the normalization of the reddening law, as a function of sky position and extinction. Such variations do exist at the level of a few to 10 per cent (S10; SF11). We have not considered the variations of the extinction law as a function of sky position and extinction either. However, there is evidence indicating that the law is fairly universal over the SDSS footprint (SF11). The reddening and extinction coefficients presented in the current work have been derived largely based on targets within the SDSS DR7 footprint, and should be applied to this area. They may not be suitable for other regions, for example the Galactic bulge and star-forming regions in the disc.

As noted earlier (Section 2.1), values of $T_{eb}$, $\log g$ and [Fe/H] adopted in the current analysis are averaged values yielded by the NGS1, k13, ANNR and ANNSR methods of SSPP; that is, by methods that do not rely on photometric data. To investigate the possible systematic effects of inaccurate reddening corrections on the SSPP adopted parameters, we examined the differences between the values of $T_{eb}$ adopted in this work and those adopted by the SSPP as a function of extinction. We found that the systematic difference increases from below 30 K at $E(B - V) \leq 0.01$ to over 100 K at $E(B - V) \sim 1.0$. We suggest that the reddening and extinction coefficients presented in this work should be adopted in future versions of SSPP and other related studies.

The ‘standard pair’ technique used to measure extinction to individual stars with photometric and spectroscopic observations, to study extinction laws and to detect and study the DIBs in the SDSS spectra can be easily extended to ongoing and planned large-scale spectroscopic surveys. The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST; Wang et al. 1996; Su et al. 1998; Xing et al. 1998; Zhao 2000; Cui et al. 2004; Zhu et al. 2006; see http://www.lamost.org/website/en/) is a 4-m-class telescope that is capable of recording spectra of up to 4000 objects simultaneously in a field of view of 5° in diameter. Commencing in the autumn of 2012, the LAMOST Galactic surveys (Deng et al. 2012), including the LAMOST Digital Sky Survey of the Galactic Anticenter (DSS-GAC; Liu et al., in preparation), started collecting spectra for millions of stars down to $r \sim 18$–19. The forthcoming next-generation astrometric satellite Gaia (Perryman et al. 2001; Katz et al. 2004) will yield distances for one billion Galactic stars to $V \sim 20$. By combining data from large spectroscopic surveys such as LAMOST and SDSS with those from the astrometric survey of Gaia and from large photometric surveys from the UV to the IR including WISE, 2MASS, SDSS, GALEX, and the Xuyi Schmidt Telescope Photometric Survey of the Galactic Anticenter (XSTPS-GAC; Yuan et al. in preparation), Pan-STARRS (Kaiser et al. 2002) and LSST (Tyson 2002), we will be able to carry out detailed studies of extinction and extinction laws, dust properties and distributions as well as DIBs and their carriers in a 3D way.

5 SUMMARY

With ‘star pairs’ selected from the SDSS spectroscopic archive, combing the SDSS, GALEX, 2MASS and WISE photometry that ranges from the far UV to the mid-IR, we have measured dust reddening in the $FUV - NUV$, $NUV - u$, $u - g$, $g - r$, $r - i$, $i - z$, $z - J$, $J - H$, $H - Ks$, $Ks - W1$ and $W1 - W2$ colours for thousands of stars. The measurements, together with $E(B - V)$ values from SFD, are used to deduce the observed, model-free reddening coefficients for these colours. The new coefficients are compared with previous measurements in the literature and with the predictions of various dust reddening laws. The results are as follows.

(i) The dust reddening map of SFD overestimates $E(B - V)$ by about 14 per cent, consistent with the earlier studies of S10 and SF11.

(ii) After taking into account the differences in reddening normalization, our newly deduced reddening coefficients for the $FUV - NUV$, $NUV - u$, $u - g$, $g - r$, $r - i$, $i - z$, $z - J$, $J - H$, $H - Ks$, $Ks - W1$ and $W1 - W2$ colours differ by respectively $-1640$, $15.5$, $12.6$, $-0.8$, $3.4$, $-0.7$, $3.5$, $2.5$, $1.4$, $2.2$ and $-50.7$ per cent from the predictions of the $R(V) = 3.1$ Fitzpatrick reddening law, and by respectively $-1730$, $13.0$, $8.1$, $10.0$, $8.0$, $-13.5$, $-1.7$, $-6.7$, $-17.1$, $-17.7$ and $-58.6$ per cent from the predictions of the $R(V) = 3.1$ CCM reddening law.

(iii) The new reddening coefficients for colours from $g - r$ to $W1 - W2$ favour the $R(V) = 3.1$ Fitzpatrick reddening law over the $R(V) = 3.1$ CCM and O’Donnell reddening laws. However, the Fitzpatrick law seems to underpredict $R(NUV - u)$ and $R(u - g)$ by about 12 per cent, indicating that an update of the Fitzpatrick law in the UV is needed.

Using the extinction coefficient of the $Ks$ band given by the $R(V) = 3.1$ Fitzpatrick law and the observed reddening coefficients presented in this work, we have obtained new extinction coefficients for the $FUV$, $NUV$, $u$, $g$, $r$, $i$, $z$, $J$, $H$, $W1$ and $W2$ passbands. We recommend that the new reddening and extinction coefficients should be generally used when performing reddening correction of Galactic stars with the SFD dust map in future. We stress, however, that the $FUV$- and $NUV$-band coefficients should be used with caution, given their relatively large measurement uncertainties.

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