UNIVERSALITY OF THE NEAR-INFRARED EXTINCTION LAW BASED ON THE APOGEE SURVEY

SHU WANG AND B. W. JIANG

Department of Astronomy, Beijing Normal University, Beijing 100875, China; shuwang@mail.bnu.edu.cn, bjiang@bnu.edu.cn

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ABSTRACT

Whether the near-infrared (NIR) extinction law is universal has long been a debated topic. Based on the APOGEE H-band spectroscopic survey, a key project of SDSS-III, the intrinsic colors of a large number of giant stars are accurately determined from the stellar effective temperature. Taking advantage of this and using a sample of 5942 K-type giants, the NIR extinction law is carefully revisited. The color excess ratio \( E(J - H)/E(J - K_S) \) being representative of the NIR extinction law, shows no dependence on the color excess when \( E(J - K_S) \) changes from \( \sim 0.3 \) to \( \sim 4.0 \), which implies a universal NIR extinction law from diffuse to dense regions. The constant value of \( E(J - H)/E(J - K_S) \), 0.64, corresponds to a power law index of 1.95. The other two ratios, \( E(H - K_S)/E(J - K_S) \) and \( E(J - H)/E(H - K_S) \), are 0.36 and 1.78, respectively. The results are consistent with the MRN dust size distribution.

Key words: dust, extinction – infrared: ISM

Online-only material: color figures

1. INTRODUCTION

Early studies found that near-infrared (NIR; \( 0.9 \mu \text{m} < \lambda < 3 \mu \text{m} \)) extinction follows a power law, \( A_{\lambda} \propto \lambda^{-\alpha} \). Furthermore, the index has been claimed to be constant as reviewed by Draine (1989), since its value is concentrated in a small range, such as \( \alpha \approx 1.61 \) (Rieke & Lebofsky 1985), 1.70 (Whittet 1988), 1.75 (Draine 1989), 1.8 (Martin & Whittet 1990; Whittet et al. 1993). This constancy points to a universal law in NIR even if the extinction law in the UV and visual wavebands changes significantly with the environment as indicated by the varying selective ratio \( R_{\lambda} \) from \( \sim 2.0 \) to \( \sim 6.0 \) (Cardelli et al. 1989).

We currently have a new view of the NIR extinction law. The power law index \( \alpha \) clearly takes different values and becomes systematically large, mostly \( \alpha > 2.0 \), in comparison with previous values of 1.6–1.8. For example, Messineo et al. (2005) obtained a value of 1.9, supported by the following measurements: Nishiyama et al. (2006), 1.99; Stražys & Laugalys (2008), 2.07; Gosling et al. (2009), 2.64; Nishiyama et al. (2009), 2.23; Stead & Hoare (2009), 2.14; Zasowski et al. (2009), 2.26; Schödel et al. (2010), 2.21; and Fritz et al. (2011), 2.11. One exception is 1.65 obtained by Indebetouw et al. (2005). When we investigated the infrared extinction toward five regions of the Coalsack nebula, the values of \( \alpha \) were also larger than 2.1 in the translucent and dense clouds, while \( \alpha = 1.73 \) in a diffuse region (Wang et al. 2013).

There are a couple of uncertainties in determining the NIR extinction law. Using individual stars that are usually very luminous in the infrared, the determination suffers from the uncertainty of the intrinsic infrared colors partly due to the spectral type and light variation of red giants. On the other hand, a statistical method that uses a group of stars of presumably the same spectral type relies completely on the photometric colors, which brings about impurities because the photometric criteria unavoidably mix some objects with similar colors. To make things more complicated, Stead & Hoare (2009) argued that the power law index, very often taken as the measure of the NIR extinction law, changes with the spectral energy distribution of the tracer, which affects the effective wavelength \( (\lambda_{\text{eff}}) \) of the filters.

With the data release DR10 of Sloan Digital Sky Survey (SDSS) in 2013, the Apache Point Observatory Galaxy Evo-

lution Experiment (APOGEE) survey opens the possibility of accurately determining the stellar intrinsic color index (CI) of numerous giant stars suitable for investigating the NIR extinction law. This work tries to take advantage of both individual determination of intrinsic CIs and statistical method to study the NIR extinction law.

2. DETERMINATION OF THE INTRINSIC COLORS OF K-TYPE GIANTS

Our study is based on the APOGEE project. APOGEE is a large-scale, high-resolution NIR spectroscopic survey of the Galactic stars, one of the four experiments in SDSS-III (Eisenstein et al. 2011). APOGEE targeted about 100,000 giant stars with Two Micron All Sky Survey (2MASS) \( H \) magnitude down to 13 mag with \( S/N > 100 \) (Allende Prieto et al. 2008; Zasowski et al. 2013). APOGEE measures the stellar parameters, including effective temperature \( T_{\text{eff}} \), surface gravity \( \log g \), and metal abundance \( Z \), to an accuracy of 150 K in \( T_{\text{eff}} \), 0.2 dex in \( \log g \), and 0.1 dex in \( Z \) (Mészáros et al. 2013).

2.2. The \( T_{\text{eff}} \)–Color Relation of the APOGEE K-type Giants

The NIR intrinsic colors of normal stars were defined by Johnson (1966) by adopting the average observed colors of stars within a distance of 100 pc from the Sun. No interstellar extinction was corrected so that the derived intrinsic colors surpassed the real values. Ducati et al. (2001) revised the Johnson result by expanding the sample to the Catalog of Infrared Observation, a database of over 396,000 infrared observations of >=64,000 sources in the wavelength range from 1 to 1000 \( \mu \text{m} \) (Gezari et al. 1999), and taking the bluest color as the intrinsic CI for a given spectral type. They naturally obtained systematically bluer colors than Johnson (1966). However, the uncertainty of the CIs increases for cold stars with the shrinking size of the corresponding sample and increase in scattering.

We independently determine the intrinsic CIs of the APOGEE K-type giants which will be used to study the NIR extinction law. The APOGEE objects are originally from the 2MASS all-sky survey (Skrutskie et al. 2006), which measures the brightness in the \( JHK_S \) bands and the observed CIs. By combining
the stellar parameters from APOGEE and the observed CIs from 2MASS, the intrinsic CIs are derived through a method similar to Ducati et al. (2001), i.e., taking the blue envelope from 2MASS, the intrinsic CIs are derived through a method applied to all the stars in the APOGEE sample, this work only deals with the APOGEE-nominated K-type giants to be used as tracers of the NIR extinction law. Concentrating only on K-type giants improves the reliability of the derived CIs thanks to a relatively narrow range of \( T_{\text{eff}} \). To study the extinction, the K-type giants already penetrate to deep extinction sightlines with the color excess (CE) \( E_{JKS} \equiv E(J - K_S) \sim 4.0 \) (about 24 mag in \( A_V \)). In comparison, G-type giants trace shallower extinction (cf. blue dots in Figure 1 with \( E_{JKS} \) mostly < 1.5), and the stellar parameters of late M-type giants have not been accurately determined for the APOGEE survey partly due to difficulty in modeling.

As we can see in Figure 1, the \( T_{\text{eff}} \)-color diagram for the stars classified as giants by the APOGEE project, the ranges of \( T_{\text{eff}} \) of K-type and G-type giants overlap in 4800 K \( \lesssim T_{\text{eff}} \lesssim 5000 \) K. We set the upper limit of the K-type giants to be \( T_{\text{eff}} \lesssim 4800 \) K, which coincides with the upper limit of Bessell & Brett (1988) for a K-type giant. At the lower end, \( T_{\text{eff}} \) agrees with the APOGEE catalog value, 3500 K, though in practice this occurs at 3600 K, which is actually lower than the classical boundary of K-type giants. Bessell & Brett (1988) defined the lower boundary of K-type giants to be \( \sim 3800 \) K, and \( T_{\text{eff}} = 3600 \) K corresponds to a spectral type of M4. These possible early M-type giants are included because they still follow a well-defined \( T_{\text{eff}} \)-color relation and more importantly they trace high extinction. The surface gravity satisfies \( \log g \leq 3.0 \) in accordance with the criterion for giants in the APOGEE catalog. In addition, the stars used for tracing are required to have a photometric error \( \leq 0.05 \) mag in all the 2MASS bands. To get obvious NIR extinction, we constrain the stars to within the Galactic plane, \( |b| \leq 5^\circ \). As the metallicity may affect the intrinsic color, \( Z \) is limited to \( > -1.0 \). The following summarizes the characteristics of the sample: (1) \( 3500 \) K \( \leq T_{\text{eff}} \leq 4800 \) K, (2) \( \log g \leq 3.0 \), (3) \( \sigma_{HK_S} \leq 0.05 \) mag, (4) \( |b| \leq 5^\circ \), and (5) \( Z > -1.0 \). The final sample consists of 6074 APOGEE-nominated K-type giants.

Figure 1 shows the variation of the observed CIs with the \( T_{\text{eff}} \) of the sample giants (black dots) together with the G-type giants. The bluest stars in these \( T_{\text{eff}} \) versus observed color diagrams, \( J - H, H - K_S \), and \( J - K_S \) (hereafter \( C_{JH}, C_{HK_S} \), and \( C_{JK_S} \)), are considered to have negligible extinction, and their observed colors are taken to be the intrinsic ones. This idea is in principle the same as Ducati et al. (2001), but we have determined the bluest edge slightly differently. As Figure 1 shows, we first chose the bluest stars within a bin of \( \delta T_{\text{eff}} = 50 \) K and then make a quadratic fitting to the bluest stars as follows:

\[
C_{JH}^0 = 4.37 - 1.27 \times \left( \frac{T_{\text{eff}}}{10^3 \text{ K}} \right) + 0.098 \times \left( \frac{T_{\text{eff}}}{10^3 \text{ K}} \right)^2, \tag{1}
\]

\[
C_{HK_S}^0 = 3.35 - 1.29 \times \left( \frac{T_{\text{eff}}}{10^3 \text{ K}} \right) + 0.128 \times \left( \frac{T_{\text{eff}}}{10^3 \text{ K}} \right)^2, \tag{2}
\]

\[
C_{JK_S}^0 = 9.19 - 3.26 \times \left( \frac{T_{\text{eff}}}{10^3 \text{ K}} \right) + 0.309 \times \left( \frac{T_{\text{eff}}}{10^3 \text{ K}} \right)^2, \tag{3}
\]

where \( C_{JH}^0, C_{HK_S}^0 \), and \( C_{JK_S}^0 \) denote the intrinsic CIs \( (J - H)_0, (H - K_S)_0 \), and \( (J - K_S)_0 \). The red lines in Figure 1 show the fitting results.

Two factors are considered for the final adoption of the intrinsic CI at a given \( T_{\text{eff}} \). One is the measurement error of the CI. The selection of the photometric accuracy of 0.05 mag at most brings about 0.1 mag error in the CI, which not only causes the non-sharp edge but also makes the bluest stellar CI actually bluer than the true intrinsic CI. To compensate for this underestimation, a redward shift of 0.02 and 0.03 mag is added to \( C_{JH}^0 \) and \( C_{HK_S}^0 \), respectively, as judged from visual inspection. The other factor is the consistency between the three CIs as only two are independent at a given \( T_{\text{eff}} \). The intrinsic CIs at typical \( T_{\text{eff}} \) are shown in Table 1. The internal error of the intrinsic colors |\( \Delta | = |C_{JH}^0 + C_{HK_S}^0 - C_{JK_S}^0| \) are

| Table 1

| \( T_{\text{eff}} \) (K) | 3600 | 3800 | 4000 | 4200 | 4400 | 4600 | 4800 |
|-----------------|------|------|------|------|------|------|------|
| \( C_{JH}^0 \)   | 1.06 | 0.95 | 0.85 | 0.76 | 0.67 | 0.59 | 0.52 |
| \( C_{HK_S}^0 \) | 0.37 | 0.30 | 0.24 | 0.20 | 0.16 | 0.13 | 0.11 |
| \( C_{JK_S}^0 \) | 1.45 | 1.26 | 1.09 | 0.94 | 0.82 | 0.72 | 0.65 |
In principle, the three CEs, of their negative CEs, 5942 stars are left in subsequent analysis. The derived CIs at 3600 K however are about 0.1 mag redder than, e.g., Bessell & Brett (1988). Nonetheless, no modification is done. This could be caused by the uncertainty in $T_{\text{eff}}$ that could have happened in either the APOGEE project or in previous work, and there is no sign that the red line in Figure 1 overestimates the CI. Moreover, the CE will be calculated within this system so that internal consistency should be retained.

2.3. The Red Clump Stars

The red clump (RC; K2III) stars own the reputation of having constant luminosity and small color scattering. Their absolute magnitude is around $M_K = -1.61$ mag (Alves 2000). The intrinsic CI $C_{\text{HK}}^0$ of RC stars is centered around 0.75 (Wainscoat et al. 1992), or 0.65 (González-Fernández et al. 2014). Thus, RC stars are frequently used as tracers of IR interstellar extinction. The RC stars chosen by their clumping in the contour map of the $T_{\text{eff}}$–log $g$ diagram have 4550 K $\leq T_{\text{eff}}$ $\leq$ 4800 K and 2.2 $\leq$ log $g$ $\leq$ 2.9, consistent with $T_{\text{eff}} = 4750 \pm 160$ K and log $g = 2.41 \pm 0.26$ (Puzeras et al. 2010). Based on the $T_{\text{eff}}$–color relation derived above, the NIR intrinsic CIs of the RC stars are 0.52 $\leq C_{\text{HK}}^0$ $\leq$ 0.61, 0.11 $\leq C_{\text{HK}}^0$ $\leq$ 0.14, and 0.65 $\leq C_{\text{HK}}^0$ $\leq$ 0.75. It turns out that Wainscoat et al. (1992) and González-Fernández et al. (2014) gave the upper and lower limits, respectively. The consistency with previous results (e.g., Bessell & Brett 1988; Wainscoat et al. 1992), or 0.65 (González-Fernández et al. 2014) gave the upper and lower limits, respectively. The consistency with previous results (e.g., Bessell & Brett 1988; Wainscoat et al. 1992). The derived CIs at 3600 K however are about 0.1 mag redder than, e.g., Bessell & Brett (1988). Nonetheless, no modification is done. This could be caused by the uncertainty in $T_{\text{eff}}$ that could have happened in either the APOGEE project or in previous work, and there is no sign that the red line in Figure 1 overestimates the CI. Moreover, the CE will be calculated within this system so that internal consistency should be retained.

3. THE NIR EXTINCTION LAW

To avoid the uncertainty in the choice of the filter wavelength (effective or isophotal) when converting from a color excess ratio (CER) to a power law index, we take the CER as the measure of the NIR extinction law. The CER depends much less on the filter wavelength than the power law index because the photometry is performed in wide bands.

3.1. Color Excess Ratio

The calculation of CEs is very straightforward from the difference between the intrinsic CI (derived from its dependence on $T_{\text{eff}}$) and the observed CI. After dropping 132 sources because of their negative CEs, 5942 stars are left in subsequent analysis. In principle, the three CEs, $E_{\text{JH}}$, $E_{\text{HK}}$, and $E_{\text{JK}}$, are derived for every sample star and can be regarded as the indicator of the NIR extinction law individually. However, a statistical linear fitting between the CEs is adopted to alleviate significantly the uncertainty of individual measurements.

The intercept of the linear fitting should be considered carefully although it is usually ignored. Physically, the CE, proportional to the total interstellar extinction, becomes zero when either of the other two CEs is zero. That means the intercept of the linear fitting between any two CEs should be zero ideally, or very close to zero with the uncertainty in the colors. In previous statistical studies of interstellar extinction, this constraint is rarely taken into account, very often because only the slope of the linear fitting of the observed CIs, rather than the CER itself, is calculated.

The linear fitting results are displayed in Figure 2 as follows: $E_{\text{JH}}/E_{\text{JK}} = 0.641 \pm 0.001$, $E_{\text{HK}}/E_{\text{JK}} = 0.360 \pm 0.001$, and $E_{\text{JH}}/E_{\text{HK}} = 1.748 \pm 0.008$, where the lines are forced to pass through (0,0). The histogram of the residuals is displayed as an inset, with the standard deviation of 0.029, 0.030, and 0.082, respectively. The three ratios are independently calculated, with very good internal consistency, as $E_{\text{JH}}/E_{\text{JK}}$ and $E_{\text{HK}}/E_{\text{JK}}$, yield $E_{\text{JH}}/E_{\text{HK}} = 1.78$. Although any one of the three ratios can be taken to be the indicator of the NIR extinction law, the $E_{\text{JH}}/E_{\text{JK}}$ ratio is favored because of its large wavelength interval leading to stability against uncertainty. On the other hand, $E_{\text{JH}}/E_{\text{HK}}$ is very weak against the error, since $E_{\text{HK}}$ is only about a third of $E_{\text{JK}}$. This weakness stands out particularly at small $E_{\text{HK}}$. Nonetheless, this ratio was very often cited as the measure of the NIR extinction law, possibly for its sensitivity to
the variation of the NIR extinction power law index as shown in Table 2.

3.2. Dependence of $E_{JHK}$ on $E_{IK}$

This work takes the stars from all the fields surveyed by APOGEE with the Galactic longitude $0^\circ < l < 220^\circ$, and has no bias toward any specific environment. Nonetheless, the magnitude of the CE represents in general the environment because of its proportionality to the density of dust. Therefore, we investigate the variation of the CER $E_{JHK}/E_{IK}$ along the CE $E_{IK}$ to determine whether the NIR extinction law is universal.

Figure 3(a, upper) displays the values of $E_{JHK}/E_{IK}$ from all sample stars, with a red horizontal line highlighting the linear fitting result, i.e., $E_{JHK}/E_{IK} = 0.641$. It can be seen that all stars are apparently around the red line. There is no clear systematic tendency toward either an increase or decrease as $E_{IK}$ changes from very small values representative of diffuse interstellar medium (ISM) to $E_{IK} \sim 5$ mag, which is equivalent to a visual extinction of $\sim 50$ mag attainable only in dense regions. A correlation analysis results in a Pearson correlation coefficient of 0.03, indicative of no relation between $E_{JHK}/E_{IK}$ and $E_{IK}$.

On the other hand, the dispersion in $E_{JHK}/E_{IK}$ is apparent and presents a tendency to increase when $E_{IK}$ gets small. Whether this dispersion is genuine needs to take into account the error. The error of the $E_{JHK}/E_{IK}$ values comes from a few contributors. The primordial errors originate from that of $T\text{eff}$ and photometry. The average error of the APOGEE stellar parameter $T\text{eff}$ is $\sim 100$ K. Using it to derive the NIR intrinsic colors from Equation (1) brings about an average error of 0.05, 0.02, 0.07 mag, respectively, for $E_{IK}$, $E_{HK}$, and $E_{JK}$.

Constraining the photometric quality of selected stars $E_{IK} \leq 0.05$ mag, the average photometric error is $\sim 0.02$; consequently, the average error of the observed CI is $\sim 0.04$ (<1% of stars have the observed color error $\sim 0.1$). Combining the photometric error in the $JHK$ bands and the error in the intrinsic colors, the uncertainties of the CEs are $E_{JHK} \sim 0.09$, $E_{HK} \sim 0.06$, and $E_{JK} \sim 0.11$. Given these errors in the CEs, the error of the CER $(E_{JHK}/E_{JK})_{\text{err}}$, which depends on both $E_{JHK}$ and $E_{JK}$, can be calculated under the error propagation theory. The error calculated by this method is displayed in Figure 3(a, lower) for all sources. The error rises rapidly as $E_{IK}$ decreases.

For a given $E_{JHK}/E_{IK} = 0.641$, the error $(E_{JHK}/E_{IK})_{\text{err}}$ at $E_{IK} = 0.3$ is 10 times larger than at $E_{IK} = 3$, specifically, from 0.38 to 0.038. At $E_{IK} = 0.1$, the error reaches 1.14. The error amplitude and its tendency both agree very well with the dispersion of $E_{JHK}/E_{IK}$ in Figure 3(a, upper). Therefore, the dispersion can be fully explained by the error.

The case for $E_{JHK}/E_{IK}$ is shown in Figure 3(b). The error is about three times that of $E_{JHK}/E_{IK}$; analogous to the dispersion. A correlation analysis yields a Pearson correlation coefficient of 0.05, indicative also of no relation between $E_{JHK}/E_{IK}$ and $E_{IK}$. This result confirms the non-variation of the NIR extinction law.

Because there is no apparent tendency with increasing reddening and with the dispersion accountable by the error of the CER, we conclude that there is no variation of the ratio $E_{JHK}/E_{IK}$ with $E_{IK}$, i.e., the extinction law in the NIR JHK bands is universal from diffuse to dense interstellar clouds.

4. DISCUSSION

Various parameters delineate the NIR extinction law. The ones most often used are the power law index $\alpha$, the three CERs, or the extinction normalized to the $K$ band. For a convenient comparison, we calculated the corresponding $\alpha$ and $A_J/A_K$ from the CERs. The values of $\alpha$ are $1.95^{+0.02}_{-0.01}$, $1.95^{+0.02}_{-0.02}$, and $1.88^{+0.02}_{-0.02}$ derived from $E_{JHK}$, $E_{HK}$, and $E_{HK}$, respectively, when adopting the $\lambda_{\text{eff}}$ of $JHK$ bands at 1.25, 1.65, and 2.15 $\mu$m, yielding $A_J/A_K = 2.88$ at $\alpha = 1.95$.

In addition, the unavailable parameters are calculated for previous works using the provided information on CER or the power law index $\alpha$, the three CERs, or the extinction normalized to the $K$ band. For a convenient comparison, we calculated the corresponding $\alpha$ and $A_J/A_K$ from the CERs. The values of $\alpha$ are $1.95^{+0.02}_{-0.01}$, $1.95^{+0.02}_{-0.02}$, and $1.88^{+0.02}_{-0.02}$ derived from $E_{JHK}$, $E_{HK}$, and $E_{HK}$, respectively, when adopting the $\lambda_{\text{eff}}$ of $JHK$ bands at 1.25, 1.65, and 2.15 $\mu$m, yielding $A_J/A_K = 2.88$ at $\alpha = 1.95$.

1 If the standard deviations of the residual of the linear fitting are taken to be the uncertainty of the CERs, the derived $\alpha$ with errors becomes $1.95^{+0.07}_{-0.04}$, $1.95^{+0.09}_{-0.07}$, and $1.88^{+0.06}_{-0.04}$ from $E_{JHK}$, $E_{HK}$, and $E_{HK}$, respectively.

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Table 2
Summary of the Results and Comparison with Previous Works

| Works                          | $E_{JHK}/E_{IK}$ | $E_{HK}/E_{IK}$ | $E_{HK}/E_{JK}$ | $A_J/A_K$ | $\alpha$ | Environment |
|-------------------------------|-----------------|----------------|----------------|-----------|---------|-------------|
| This work                     | 0.64            | 0.36           | 1.78           | 2.88      | 1.95    | Average     |
| Landini et al. (1984)          | 0.62 (0.62)     | 0.38           | 1.71           | 2.42      | 1.63 (1.85)| G333.6-0.2 (HI) |
| Martin & Whitsett 1990         | 0.63            | 0.37           | 1.71           | 2.65      | 1.8     | Diffuse ISM |
| Racca et al. (2002)            | 0.68            | 0.32           | 2.08           | 3.92      | 2.52    | Coalsack globule 2 |
| Indebetouw et al. (2005)       | 0.64            | 0.36 (0.36)    | 1.78           | 2.86 (2.50)| 1.94 (1.65)| l = 42° and 284° |
| Nasi et al. (2006)             | 0.62            | 0.38           | 1.66           | 2.50      | 1.69    | ρ Oph, Chamaeleon |
| Nishiyama et al. (2006)        | 0.64 (0.58)     | 0.36 (0.34)    | 1.80 (1.72)    | 2.94      | 1.99    | Galactic center |
| Stead & Hoare (2009)           | 0.65            | 0.35           | 1.88           | 3.19      | 2.14    | 27° < l < 100° |
| Wang et al. (2013)             | 0.65            | 0.35           | 1.86 (1.86)    | 3.14 (3.14)| 2.11 (2.10)| Coalsack |
| WD01 RV = 3.1                 | 0.62            | 0.38           | 1.63           | 2.40      | 1.62    | Diffuse     |
| WD01 RV = 5.5                 | 0.62            | 0.38           | 1.62           | 2.38      | 1.60    | Dense       |

Average of previous works 0.64 0.36 1.77 2.84 1.90 Diversified

Note. The $\alpha$ values derived from $E_{JHK}/E_{IK}$, $E_{HK}/E_{IK}$, and $E_{JK}/E_{IK}$ are 1.01, 2.26, and 1.82, respectively, when using the 2MASS $\lambda_{\text{eff}}$. 

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The Astrophysical Journal Letters, 788:L12 (6pp), 2014 June 10

Wang & Jiang
1.84 when the $\lambda_{\text{eff}}$ of the $K$ band shifts from 2.15 $\mu$m for 2MASS to 2.22 $\mu$m for the Johnson system. The other possible reason comes from the use of $\lambda_{\text{eff}}$ instead of the isophotal wavelength ($\lambda_{\text{iso}}$). As for the 2MASS system, adopting $\lambda_{\text{iso}}$, 1.24, 1.66, and 2.16 $\mu$m for the $JHK_s$ bands would yield $\omega = 1.65$ and $A_J/A_{K_s} = 2.51$ for the given $E_{J}/E_{K_s} = 0.64$, consistent with the smaller values of Indebetouw et al. (2005) who used $\lambda_{\text{iso}}$.

We investigate one more possible reason for the discrepancy, the effect of metallicity. Gao et al. (2013) obtained a value of $E_{J}/E_{K_s} = 1.25$ for the LMC NIR extinction which agrees well with previous studies but is significantly lower than the Galactic value. Meanwhile their $E_{J}/E_{K_s} = 0.64$ coincides very well with the present work. A metal-poor sample of 735 giants in the whole APOGEE sky is selected under the same criteria but with $Z < -1.0$. Most of them are located in the halo as expected and with low extinction ($E_{K_s} < 1$). Using the same method as for the non-metal-poor giants, we obtained the NIR CERs $E_{J}/E_{K_s} = 0.73$, $E_{HK}/E_{K_s} = 0.36$, and thus $E_{J}/E_{HK} = 2.03$, which exhibits some difference from the non-metal-poor sample. The trend, however, is opposite to the work of Gao et al. (2013). Due to mainly the low extinction and also the small number of stars, these results are quite uncertain. On the other hand, the LMC is not as poor as the sample stars. Whether and how the metallicity affects the NIR extinction law needs further investigation.

The Weingartner & Draine (2001, WD01) dust model produces an invariant NIR extinction law when $R_V$ changes from 3.1 to 5.5, corresponding to the power law index from 1.62 to 1.60 as shown in Table 2. This can explain the universality of the NIR extinction law even though the change of dust size distribution leads to apparent variation in the optical extinction law. Their results are consistent with ours when using the standard deviations as uncertainties for $\omega$. On the other hand, if we assume the dust size distribution conforms to classical power law with an index of 3.5 (Mathis et al. 1977), our model calculation (Wang et al. 2013) yields $E_{J}/E_{K_s} = 0.65$ when $\omega_{\text{max}}$, the maximum cutoff radius of the spherical dust grains, occurs at 0.25 $\mu$m. This means the dust size distribution of the MRN model better matches our result.

5. SUMMARY

Based on the NIR spectroscopic survey project APOGEE, a sample of giant stars consisting of mainly K-type and some early M-type stars is selected. The relations between the effective temperature and three NIR intrinsic colors are constructed by fitting the bluest colors with a quadratic line. When the extinction changes from small to very large values, the CERs, indicators of the NIR extinction law, show no apparent variation. The constant CERs are $E_{J}/E_{K_s} = 0.64$, $E_{HK}/E_{K_s} = 0.36$, and $E_{J}/E_{HK} = 1.78$. $E_{J}/E_{K_s} = 0.64$ is converted to a power law index of 1.95 given the $\lambda_{\text{eff}}$ of 2MASS. This result is consistent with the MRN dust size distribution.

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