The Ultraviolet Extinction Map and Dust Properties at High Galactic Latitude

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Abstract

Extinction in ultraviolet is much more significant than in optical or infrared, which can be very informative to precisely measure the extinction and understand the dust properties in the low-extinction areas. The high Galactic latitude sky is such an area, important for studying the extragalactic sky and the universe. Based on the stellar parameters measured by the LAMOST and GALAH spectroscopy and the ultraviolet photometry by the Galaxy Evolution Explorer (GALEX) space telescope, the extinction of 1,244,504 stars in the GALEX/near-UV band and 56,123 stars in the GALEX/far-UV band is calculated precisely. The error of color excess is 0.009, 0.128, and 0.454 mag for $E_{G_{195},G_{694}}$, $E_{N_{175},G_{694}}$, and $E_{F_{175},G_{519}}$, respectively. They delineate the GALEX/near-UV extinction map of about a third of the sky mainly at the high Galactic latitude area with an angular resolution of $\sim0.7^\prime$. The mean color excess ratio in the entire sky area is derived to be 3.25, 2.95, and $-0.37$ for $E_{N_{175},G_{694}}/E_{G_{195},G_{694}}$, $E_{G_{195},G_{694}}/E_{G_{153},G_{694}}$, and $E_{F_{175},G_{519}}/E_{G_{195},G_{694}}$, respectively, which is in general agreement with the previous works, and their changes with the Galactic latitude and the interstellar extinction are discussed.

Unified Astronomy Thesaurus concepts: Ultraviolet extinction (1738); Interstellar dust (836)

1. Introduction

The interstellar medium (ISM) is full of dust and gas, where the dust, though about 1% in mass, is the dominant factor in extinction. The interstellar extinction changes from sight line to sight line and from distance to distance; even the extinction law itself changes with environment (see, e.g., Draine 2003). Because interstellar dust absorbs and scatters light that reforms the appearance of objects, a precise determination of the interstellar extinction map is crucial to recover the true brightness and spectrum of the objects. Thus, there have been many hard efforts to construct the extinction map.

The general two-dimensional (2D) extinction map usually yields the integral extinction along a given sight line, which can help make a rough correction without the distance information. Schlegel et al. (1998, SFD98) constructed a 2D reddening map based on the far-infrared emission of dust. Assuming a modified blackbody emission law in far-infrared, as well as a linear relationship between the dust optical depth at 100 $\mu$m and the reddening, they calibrate the optical depth map according to the measured color excess value of $E(B-V)$. Later, Peek & Graves (2010) provide a correction to the SFD98 extinction map by using passively evolving galaxies as color standards to measure deviations. The maps have an angular resolution of 4$^\prime$.5 and a 1$\sigma$ uncertainty of 1.5 mmag in $E(B-V)$, which are largely accurate for most of the areas with the $E(B-V)$ deviation below 3 mmag, but some regions deviate from SFD98 by as much as 50%. Spatial structure of the deviation is strongly correlated with the observed dust temperature in that SFD98 underpredict reddening in the regions of low dust temperature. With the newly available Planck all-sky observation, Planck Collaboration et al. (2014) also constructed a 2D map of dust reddening across the entire sky. They fit a modified blackbody dust emission model to the Planck and IRAS far-infrared emission maps and convert the dust emission into interstellar reddening from three parameters: dust optical depth at 353 GHz, thermal dust radiance, and a recommended extragalactic reddening estimate with point sources removed. Afterward, Planck Collaboration et al. (2016) present an all-sky modeling of Planck, IRAS, and Wide-field Infrared Survey Explorer (WISE) observations using the physical dust model by Draine & Li (2007, DL07). They employ the DL07 dust model to generate maps of the dust mass surface density, the dust optical extinction, etc. While these 2D maps are all based on the dust emission in far-infrared, recently some 3D extinction maps are obtained with the distance measured by the Gaia mission. With the availability of Gaia/DR2 (Gaia Collaboration et al. 2018), Andrae et al. (2018), Chen et al. (2019), and Green et al. (2019) established the 3D interstellar reddening map, which is derived from the multiband photometries of hundreds of millions of stars.

However, all these extinction maps are based on the infrared and optical observation, which may convert to the UV extinction from the given visual/infrared extinction. Cardelli et al. (1989, CCM89), O’Donnell (1994, O’D94), and Fitzpatrick (1999, F99) all report reddening laws with a single parameter, $R_V \equiv A_V/E(B-V)$, which implies some conversion factor from the visual to the UV extinction. Nevertheless, these laws are derived by the relatively high extinction stars. The vast areas of the sky of much lower extinction have not been adequately examined, and extrapolating these extinction laws to yield the UV extinction at high latitudes may not be that convincing. According to the variation in the UV colors and number density of galaxies, Peek & Schiminovich (2013) present an analysis of 373,303 galaxies selected from the Galaxy Evolution Explorer (GALEX) and WISE catalogs. They find that dust at high latitude is neither quantitatively nor qualitatively consistent with standard reddening laws. Extinction in the far-UV (FUV) and near-UV (NUV) is about 10% and 35% higher than expected, respectively, with significant variation across the sky. They find that no single $R_V$ parameter fits both the optical and UV extinction at high latitude, and that while both show detectable variation across the sky, these
variations are not related. The UV extinction map needs to be constructed separately considering the aforementioned variations. In comparison with optical and infrared wavelengths, the UV bands are more sensitive to interstellar extinction. For an average $R_V = 3.1$ law, the extinction at 2000 Å is about three times that at the visual 5000 Å (Mathis 1990). Thus, the UV extinction becomes evident at the low-extinction regions, where the visual/infrared extinction may be very small or undetectable. One such region is at the high Galactic latitude important for the study of the extragalactic sky and cosmology, where the UV extinction is of great significance to correct the extinction precisely. In addition, the UV extinction is important to understand the physical properties of dust.

GALEX is the largest UV survey; its NUV channel covers the 2175 Å bump, possibly a probe in polycyclic aromatic hydrocarbons (PAHs; Steglich et al. 2010), and its FUV channel probes the steep FUV rise of the extinction curve, associated with very small silicate grains (Weingartner & Draine 2001, WD01). Small grains dominate the heating of the diffuse ISM (Wolfire et al. 2003) and may act as tracers of variation in grain size distribution as a whole. The GALEX data set provides us a chance to study the UV extinction in detail.

Previously, we (Sun et al. 2018) calculated the intrinsic colors and color excesses related to the GALEX bands for about 25,000 A- and F-type dwarf stars. In this work, we will extend to many more stars, i.e., about 1 million, most of which are at high Galactic latitudes, and consequently build the large-area UV extinction map. Taking the Gaia blue ($G_{BP}$) and red ($G_{RP}$) band as reference, the UV extinction is used to retrieve the properties of dust at high Galactic latitude. In comparison with the previous studies of extinction map by multiband photometry such as Andrae et al. (2018), Chen et al. (2019), and Green et al. (2019), this size of the sample is moderate. The advantage of this work lies in the special band—UV. In addition, this work derives the intrinsic colors from spectroscopy rather than photometry, which is more accurate and reliable than statistical method. The paper is organized as follows. Section 2 describes the data to be used, followed by Section 3 on how the intrinsic colors and color excesses are calculated. Section 4 presents the results of the extinction map and discussions on the color excess ratios.

2. Data Preparation

The basic idea to calculate the color excess complies with that adopted in Sun et al. (2018). First, the relation of intrinsic colors with stellar effective temperature and metallicity is derived for the given luminosity class. Here only dwarf stars are taken because giants are red and rarely detected in the GALEX UV bands. In addition to the UV bands, the optical bands are needed in order to investigate the extinction law in the way of color excess ratio, and optical bands also provide an indicator to compare with other works. For its high accuracy and complete coverage of the sky, the selected optical survey is the Gaia photometry. The stellar parameters are taken from the spectroscopic surveys—LAMOST and Galactic Archaeology with HERMES (GALAH).

2.1. Photometric Data from the GALEX and Gaia Surveys

Unlike the spectroscopic surveys such as IUE, FUSE, and SWIFT, the GALEX GR/6+7 (Bianchi 2014) provides the largest high-quality photometric database in the UV. The two filters of GALEX are FUV ($\lambda_{eff} = 1528$ Å, 1344–1786 Å) and NUV ($\lambda_{eff} = 2310$ Å, 1771–2831 Å). The catalog we use is GUVcat_AIS_fov055, with the total number of unique AIS sources (eliminating duplicate measurements) being 82,992,086, and a typical depth of FUV = 19.9 and NUV = 20.8 AB mag (Bianchi et al. 2017).

In addition to astrometric information of proper motion and parallax, Gaia/EDR3 (Gaia Collaboration et al. 2021) provides photometry in three optical bands: the white-light $G$ band (330–1050 nm), and the blue ($G_{BP}$) and red ($G_{RP}$) bands by the prism photometers that collect low-resolution spectro-photometric measurements of source spectral energy distributions (SEDs) over the wavelength ranges 330–680 nm and 630–1050 nm, respectively (Gaia Collaboration et al. 2021). There are 1.8 billion sources in the catalog, where the nominal survey limit is $G = 20.7$ mag (Gaia Collaboration et al. 2016).

2.2. Spectroscopic Data from the LAMOST and GALAH Surveys

The primary spectroscopic database we use comes from the LAMOST survey (Luo et al. 2015), which is dedicated to the objects over the entire available northern sky. The observable areas are mainly from $-10^\circ$ to $+90^\circ$ in decl. Taking 4000 spectra in a single exposure, the limiting magnitude in the $r$ band is as faint as 19 mag at a resolution $R = 1800$ (Zhao et al. 2012). We use the LAMOST/DR7 catalog, which contains a total of 6,199,917 stars with the derived effective temperature $T_{eff}$, surface gravity log $g$, metal abundance $Z$, and their uncertainties.

In order to extend the sky coverage, we include the GALAH (Buder et al. 2021) survey as a supplement in the Southern Hemisphere. Using the HERMES spectrograph at the Anglo-Australian Telescope, they collect high-resolution ($R \approx 28,000$) spectra for 360 stars simultaneously. These stars are selected simply in magnitude ($12 < V < 14$), Galactic latitude ($|b| > 10^\circ$), and decl. (decl. $< +10^\circ$). There are 588,571 unique stars in DR3. Observed between 2013 November and 2019 February, they have derived radial velocities, stellar parameters, and abundances.

2.3. Combination of Photometric and Spectroscopic Data

The LAMOST/DR6 or GALAH/DR3 catalog is cross-matched separately with the Gaia/EDR3 by a radius of $1^\circ$ first, which results in the LAMOST–Gaia (“LG” hereafter, 6,142,479 stars) and the GALAH–Gaia (“GG” hereafter, 588,553 stars) catalogs for a large sky coverage in optical.

The LG or GG catalog is further cross-identified with the GALEX GR6/7 catalog by a radius of 3°. Finally, there are two catalogs, LAMOST–Gaia–GALEX (“LGG” hereafter, 1,985,278 stars) and GALAH–Gaia–GALEX (“GGG” hereafter, 279,604 stars), that will be used to study the color excesses in the UV bands.

1. http://dolomiti.pha.jhu.edu/uvsky
2. http://cosmos.esa.int/web/gaia
3. http://dr7.lamost.org/v1.1/
4. http://galah-survey.org
The red asterisks and bars denote the median values and their standard deviations, respectively.

GALAH sources are covered. The metallicity is limited from 4500 to 6000 K for the NUV band, and 5500 K for the FUV band to reduce the influence of chromospheric activity at low $T_{\text{eff}}$. The metallicity complies with the rules in the optical for the NUV band, but changed to $-0.6$ to 0.4 for the FUV band, and its error is required to be smaller than 0.3 dex.

Consequently, there are 4,192,015 stars (3,980,392 stars in LG and 211,623 stars in GG) with the optical measurements and 1,271,780 stars with the NUV photometry (1,156,319 stars in LGG and 115,461 stars in GGG), as well as 59,247 with the FUV photometry in LGG.

3.2. Selection of the Zero-extinction Sources in the $C_{\text{G}_{\text{BP}},\text{G}_{\text{RP}}}$ versus $T_{\text{eff}}$ and $Z$ Diagram

The blue-edge method is a convenient and accurate way to obtain the relations of the intrinsic color index with the effective temperature. This method has been used by several works, e.g., Wang & Jiang (2014), Xue et al. (2016), Jian et al. (2017), and Zhao et al. (2018, 2020). The essential idea is that the observed bluest color stands for the intrinsic one for a given luminosity class and effective temperature (Ducati et al. 2001).

For the UV bands, the influence of metallicity ($Z$) on the intrinsic color index is much more significant than in the optical or infrared and should be taken into account. Previously, Sun et al. (2018) chose the relatively high temperature sources to study the color excess ratio relevant to the UV band, where the effect of $Z$ is not serious and the stars are roughly divided into three groups. However, the present work handles the stars with a much larger range of stellar parameters, the extinction at high latitudes is usually small, and the effect of $Z$ should be processed more delicately. For this purpose, we first divide the optical LG and GG sample into groups with a step of 0.08 dex and 100 K in $Z$ and $T_{\text{eff}}$ respectively. Then, the intrinsic color index for each group is obtained by the blue-edge method for $C_{\text{G}_{\text{BP}},\text{G}_{\text{RP}}}$, i.e., the median color index of the bluest 5% of stars in the group chosen by a cyclic 3σ elimination. In this way, there are many more (25 for NUV and 13 for FUV) groups in metallicity. On the other hand, some groups have a small number of sources and the blue-edge method becomes unreliable. Such outliers are removed by finding the point deviating more than 1σ from the mean of their neighbors and then replaced by the mean of the neighboring 3 × 3 block. The result is shown in the top panel of Figure 2, where the range of $T_{\text{eff}}$ and $Z$ is slightly expanded in order to suppress the edge effect.

3.3. Calculation of $C_{0_{\text{UV,G}_{\text{BP}}}}$ with $T_{\text{eff}}$ and $Z$

It should be noted that there is no clear cut at $T_{\text{eff}}$ for chromospheric activity. Even after limiting $T_{\text{eff}} \geq 5000$ K and $T_{\text{eff}} \geq 6500$ K for NUV and FUV, respectively, the chromospheric activity at low temperature still has a chance to bring about a bluer UV color. Therefore, the zero-extinction sources selected above from the $C_{\text{G}_{\text{BP}},\text{G}_{\text{RP}}}$ versus $T_{\text{eff}}$ and $Z$ diagram are used to calculate $C_{0_{\text{NUV,G}_{\text{BP}}}}$ and $C_{0_{\text{FUV,G}_{\text{RP}}}}$ in each bin of $T_{\text{eff}}$ and $Z$, and the results of $C_{\text{NUV,G}_{\text{BP}}}$ and $C_{\text{FUV,G}_{\text{RP}}}$ are shown, respectively, in the middle and bottom panels of Figure 2.

It should be noted that the GALAH sample is one order of magnitude smaller than the LAMOST; thus, $C_{0_{\text{FUV,G}_{\text{RP}}}}$ is not calculated for them, and subsequently, the FUV-related extinction is not obtained for the GALAH sample.

We find that the relation between the intrinsic color index and the stellar parameters is so complex that it is difficult to describe all the characteristics of the numerical solutions with

Figure 1. Comparison of $T_{\text{eff}}$ and $Z$ of the GALAH sample with the LAMOST. The red asterisks and bars denote the median values and their standard deviations, respectively.
of $T_{\text{eff}}$ and $Z$, is taken as the uncertainty of the intrinsic color. The dispersion is mainly caused by the error of stellar parameters and observed color index, as well as the small change of intrinsic color index in a bin. Actually, the intrinsic color index obtained by linear interpolation should have smaller uncertainty than this dispersion. The median value of this dispersion is determined to be 0.007, 0.092, and 0.344 mag for $C_{\text{GBP-Grp}}$, $C_{\text{NUV-Grp}}$, and $C_{\text{FUV-Grp}}$ respectively. This error originates mainly from stellar parameters and photometry. The error of observed colors comes from photometry whose median is 0.005, 0.071, and 0.270 mag for $C_{\text{GBP-Grp}}$, $C_{\text{NUV-Grp}}$, and $C_{\text{FUV-Grp}}$ respectively. The combined error median becomes 0.009, 0.128, and 0.454 mag, respectively. The error is calculated for each source individually in this way.

Another practical way to estimate the error of the color excess is to compare the identical sources of the LAMOST and GALAH sample, which contains 17,472 common stars in $E_{\text{GBP-Grp}}$ and 9870 stars in $E_{\text{NUV-Grp}}$. The result is displayed in Figure 2, where the systematic difference should be small and is neglected. The dispersion is 0.04 mag in $E_{\text{GBP-Grp}}$ and 0.19 mag in $C_{\text{NUV-Grp}}$, which is comparable to the error derived above from the uncertainty of intrinsic and observed colors. For $E_{\text{FUV-Grp}}$, we specifically calculated the color excess of GALAH in the $T_{\text{eff}}$ range of 6500–7000 K and compared it with that of LAMOST. From 333 common sources, the dispersion is about 0.40, which is also consistent with the estimated uncertainty.

### 3.5. Comparison of the Optical Color Excess with the Green +2019 Work

As a by-product, the $E_{\text{GBP-Grp}}$ value is obtained for 4,169,769 sources composed of 3,959,547 stars in LG and 210,222 stars in GG. For the given coordinate and distance$^5$ from Gaia of a star, the $E_{B,V}^{\text{Green}}$ value by Green et al. (2019) can be retrieved by the Python code dustmap.$^6$ The linear fitting (see Section 4.2.1) between these two values in the top panel of Figure 5 yields $E_{B,V}^{\text{Green}} = 0.66 \pm 0.01 * E_{\text{GBP-Grp}} + 0.008$, with the residual of a median of $-0.005$ and a width of about 0.06 mag, whose distribution is displayed in the bottom panel of Figure 5, which is comparable to the 0.04 mag internal precision. Basically, there is no systematic difference with the Green+2019 work, and the standard deviation is small as well. Nevertheless, there are some stars for which $E_{B,V}^{\text{Green}} = 0$, while our derived $E_{\text{GBP-Grp}}$ span a range up to 2.0 mag. There are 21 sources with $E_{B,V}^{\text{Green}} < 0.05$ mag while $E_{\text{GBP-Grp}} \geq 2$ mag, which are $>3\sigma$ outliers in the linear fitting. Examination of their spectroscopic and photometric parameters finds no apparent problem. These sources are checked in the SIMBAD$^7$ database, two of which are found to have high proper motion, and we calculated the distance to be zero with the method of Smith & Eichhorn (1996) and Luri et al. (2018). Meanwhile, no distance is available in the Gaia/DR2 or EDR3 catalog (Bailey-Jones et al. 2018, 2021). For sure, the zero distance is incorrect, possibly caused by not considering the high proper motion so that the color excess from Green et al. (2019) can be not corresponding. But this is not the case for the other sources, which may be

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$^5$ The distance here is calculated from Gaia-measured parallax and its error by the Smith–Eichhorn correction method (Smith & Eichhorn 1996; Luri et al. 2018).

$^6$ https://dustmaps.readthedocs.io/

$^7$ http://simbad.u-strasbg.fr/simbad/
dense but small dust clouds (e.g., Bok globules) that cannot be resolved at the low-resolution map of interstellar extinction or dust emission by Planck. The details of these objects are listed in Table 1 with the position, distance, and extinction. As a whole, the residual (defined as $E_{G_{BP}, G_{RP}} - (0.66 \times E_{G_{BP}, G_{RP}} + 0.008)$) in the bottom panel of Figure 5 shows no obvious trend with $E_{G_{BP}, G_{RP}}$, and it is generally very close to 0. The other result is that $E_{G_{BP}, G_{RP}}/E_{G_{BP}, G_{RP}} = 0.66 \pm 0.01$, which is smaller than $E_{B,V}/E_{G_{BP}, G_{RP}} = 0.71 \pm 0.01$ (see Section 4.2.1) and $E_{B,V}/E_{G_{BP}, G_{RP}} = 0.76$ by Wang & Chen (2019).

Figure 3. The change of the color index $C_{G_{BP}, G_{RP}}$ (top), $C_{G_{UV}, G_{RP}}$ (middle), and $C_{G_{UV}, G_{RP}}$ (bottom) with $T_{\text{eff}}$ for the dwarf stars in the LAMOST/DR7 catalog with $-0.04 \leq Z < 0.04$. The black dots denote all the stars, the blue dots denote the selected zero-extinction sources, and the red dots denote the determined intrinsic color index in the corresponding bin.

Figure 4. Comparison of $E_{G_{BP}, G_{RP}}$ and $E_{G_{UV}, G_{RP}}$ of the LAMOST sample with the GALAH. The inset shows the median and standard deviation of the difference.

Figure 5. Comparison of $E_{G_{BP}, G_{RP}}$ derived in this work with $E_{G_{BP}, G_{RP}}$ from Green et al. (2019). The top panel displays the linear relation between them, with the median and the standard deviation of the residuals displayed in the inset, while the bottom panel shows the residual change with $E_{G_{BP}, G_{RP}}$. 

$E_{G_{BP}, G_{RP}} = 0.66 \pm 0.01 \times E_{G_{BP}, G_{RP}} + 0.008$

$E_{B,V} = 0.06 \pm 0.01$
4. Result and Discussion

4.1. The Ultraviolet Color Excess \(E_{\text{NUV},G}\) and \(E_{\text{FUV},G}\)

With the determined intrinsic color index, the NUV color excess \(E_{\text{NUV},G}\) is calculated for 1,244,504 sources (1,130,412 sources from LGG and 114,092 sources from GGG), and the FUV color excess \(E_{\text{FUV},G}\) is calculated for 56,123 sources from LGG. In comparison, Sun et al. (2018) calculated \(E_{\text{NUV},G}\) and \(E_{\text{FUV},G}\) for 25,496 and 4255 A- and F-type stars, respectively. The huge increase to a million stars is brought by a couple of improvements: (1) the extension to much lower effective temperature, from the previous 6500 K for NUV (7000 K for FUV) to the present 5000 K (6500 K), which is the major factor; (2) the updated LAMOST data release adding one million stars in their entire catalog; (3) less strict constraints on the photometric uncertainty in the UV bands; and (4) the inclusion of the GALAH database.

For the distribution of color excess, there are 207,942 and 16,822, i.e., 17% sources with \(E_{\text{NUV},G} < 0\) and 30% sources with \(E_{\text{FUV},G} < 0\), which is much higher than the proportion (4%) with \(E_{\text{gr},G} < 0\). In addition to the relatively large photometric error in the UV bands, the chromospheric activity can also lead to the negative color excess. Nevertheless, most stars show a positive \(E_{\text{NUV},G}\) and \(E_{\text{FUV},G}\) with the peak for both around 0.07 mag, much more significant than the optical excess, whose peak is around 0.03 mag. The change with Galactic longitude and latitude is displayed in Figure 6, where the median value denoted by the magenta line is obtained by an iterative 3σ clipping. Because the GALEX observation is far from complete toward the Galactic plane, the variation along the longitude lacks a large-scale trend except that the Galactic center and anticenter directions have relatively large background color excess, otherwise dominated by some small-scale local structures from star-forming regions. On the other hand, the change with latitude is very evident that the color excess starts to increase rapidly with the decreasing Galactic latitude at \(|b| < 20^\circ\) and the maximum value reaches to 2.25 and 2.12 mag in \(E_{\text{NUV},G}\) and \(E_{\text{FUV},G}\) respectively, toward the Galactic plane.

4.2. The Color Excess Ratio

4.2.1. \(E_{\text{NUV},G}/E_{\text{G}G,\text{G}}\) and \(E_{\text{FUV},G}/E_{\text{G}G,\text{G}}\)

In order to suppress the influence of numerous low-extinction stars, the median values in a bin of 0.005 mag of \(E_{\text{gr},G}\) are calculated by iteratively clipping stars beyond 3σ of the median. In addition, a bin with less than 10 sources is not used in linear fitting. As shown in the top panel of Figure 7, the Markov Chain Monte Carlo procedure is performed (Foreman-Mackey et al. 2013) for the linear fitting. The best estimates are the median values (50th percentile) of the posterior distribution, and the uncertainties are derived from the 16th and 84th percentile values, which result in a relation of \(E_{\text{NUV},G}\) and \(E_{\text{G}G,\text{G}}\). As \(E_{\text{NUV},G} = 3.25 \pm 0.04 \times E_{\text{G}G,\text{G}} - 0.0003\).

The number of sources in the FUV band is much lower than in the NUV. The same method is used for linear fitting, which yields \(E_{\text{FUV},G} = 2.95 \pm 0.16 \times E_{\text{G}G,\text{G}} + 0.015\) shown in the bottom panel of Figure 7.

As mentioned above, the linear fitting yields a color excess ratio of \(E_{\text{NUV},G}/E_{\text{G}G,\text{G}} = 3.25 \pm 0.04\) and \(E_{\text{FUV},G}/E_{\text{G}G,\text{G}} = 2.95 \pm 0.16\), which involving both the Gaia and GALEX filters has not been determined before. In order to check the consistency with previously determined \(E_{\text{NUV,B}}/E_{\text{B},\text{V}}\) and \(E_{\text{FUV,B}}/E_{\text{B},\text{V}}\), we further cross-identify the LG catalog with the APASS photometric survey in the B and V bands. The same linear fitting method is used as in the previous subsection, yielding \(E_{\text{B},\text{G}}/E_{\text{G}G,\text{G}} = 0.58 \pm 0.01\) and \(E_{\text{B},\text{V}}/E_{\text{G}G,\text{G}} = 0.71 \pm 0.01\). With \(E_{\text{NUV},G}/E_{\text{G}G,\text{G}} = 3.25\) and \(E_{\text{FUV},G}/E_{\text{G}G,\text{G}} = 2.95\), the values of \(E_{\text{NUV,B}}/E_{\text{B},\text{V}}\) and \(E_{\text{FUV,B}}/E_{\text{B},\text{V}}\) are 3.76 ± 0.08 and 3.34 ± 0.23, which is very close to the values of 3.77 ± 0.08 and 3.39 ± 0.17 by Sun et al. (2018). In addition, the optical color excess ratio can be compared to the results of Wang & Chen (2019), who used red clump stars to determine \(E_{\text{B},\text{G}}/E_{\text{G}G,\text{G}} = 0.72\) and
This agrees with ours at $E_{G_{V,BP}}$, but has a higher $E_{G_{G,BP}}$. This may be explained by using different tracers. This work takes dwarfs as tracers, while Wang & Chen (2019) use red clump stars. Definitely, the $FUV,GBP$ (left), $NUV,GBP$ (middle), and $G,BP$ (right) with Galactic longitude (top) and latitude (bottom). The magenta points and lines are the median values of background.

Figure 7. Linear fitting of the color excesses $E_{NUV,GBP}$ to $E_{GBP,GBP}$ (top) and $E_{FUV,GBP}$ to $E_{GBP,GBP}$ (bottom). The gray scale encodes the source densities, while the red plus signs and bars denote the median value and its standard deviation of each bin (see Section 4.2.1 for details). The inset shows the distribution of the residuals with its median and standard deviation.

Figure 8. The same as Figure 7, but for the relations of the color excesses $E_{FUV,NUV}$ and $E_{GBP,GBP}$ of all the LGG sample stars (top), as well as $E_{FUV,NUV}$ and $E_{SD,B,V}$ of the LGG sample stars at $|b|>20^\circ$ (bottom), where the results of Peek & Schiminovich (2013) are shown for reference.
dwarfs here bring about a shorter effective wavelength of the wide filter $G$ than the red clump stars.

4.2.2. The Color Excess Ratio $E_{FUV,NUV}/E_{GG,BP,RP}$

The linear fitting in the top panel of Figure 8 yields the relation between $E_{FUV,NUV}$ and $E_{GG,BP,RP}$, i.e., $E_{FUV,NUV} = (-0.37 \pm 0.15) \times E_{GG,BP,RP} - 0.031$, which agrees with $-0.30 \pm 0.16$ calculated in Section 4.2.1 from $E_{FUV,NUV}/E_{GG,BP,RP} = E_{NUV,GBP}/E_{GG,BP,RP}$. Again, a negative value of $E_{FUV,NUV}$ is found on average that confirms the result of Sun et al. (2018). This is particularly true for the relatively large and thus more reliable color excesses. This result can be understood because the effective wavelength of the NUV filter is around the peak of the 2175 Å bump for the sample stars, while that of the FUV filter is on the wing of the hump of the extinction curve.

Using the galaxies at high latitudes as tracers, Peek & Schiminovich (2013) studied the color excess $E_{FUV,NUV}$ of GALEX and found it to be positive, i.e., the extinction in the NUV band is smaller than in the FUV band. On the contrary, Sun et al. (2018) found $E_{FUV,NUV}$ to be negative for about 4000 stars that distribute in the whole GALEX area. Though this work uses a very similar method to Sun et al. (2018), the catalogs are updated and a much larger sample is useful, which makes it feasible to study the FUV extinction at high latitude alone.

The stars with $|b| > 20^\circ$ are further picked up to see if the color excess $E_{FUV,NUV}$ becomes positive at high latitude as found by Peek & Schiminovich (2013). The linear fitting yields $E_{FUV,NUV} = (-0.48 \pm 0.31) \times E_{GG,BP,RP} - 0.031$ shown in the bottom panel of Figure 8. Basically, the UV-to-optical color excess ratio at high latitude shows no difference with the entire sample. Nevertheless, at both high and low latitude, some fraction of stars show positive $E_{FUV,NUV}$ at $E_{GG,BP,RP} < 0.1$, which is the main range of Peek & Schiminovich (2013). This may lead them to conclude a positive $E_{FUV,NUV}$. In our sample, this range of color excess seems to be greatly affected by the errors, and a positive $E_{FUV,NUV}$ is inconsistent with the general trend.

4.3. Variation of the Color Excess Ratios

4.3.1. Variation with the Galactic Latitude and $E_{GG,BP,RP}$

The color excess is an indicator of the interstellar extinction law, so its variation may reflect the change of the dust properties.

The variation of the color excess ratios is investigated by using only the LGG sources in order to avoid the systematic difference in the stellar parameters between the LAMOST and GALAH survey. The change of $E_{NUV,GBP}/E_{GG,BP,RP}$ (top panel) and $E_{FUV,GBP}/E_{GG,BP,RP}$ (bottom panel) with the Galactic latitude is displayed in the left panels of Figure 9, where the color excess ratio of each star is denoted by black dots. The change of the median color excesses of the stars in a bin of 5° in the Galactic latitude is denoted by black dots, while the red asterisks and bars denote the ratio of the median value and its standard deviation of the color excesses in a bin of 5° in the Galactic latitude (left panel) or in a bin of 0.02 mag in $E_{GG,BP,RP}$ (right).
4.3.2. Effects of Stellar Effective Temperature and Interstellar Extinction on the Color Excess Ratios

Before discussing the implication of the variation of the color excess ratios on the dust properties, the influence of stellar effective temperature and interstellar extinction should be clarified because they both would shift the effective wavelengths ($\lambda_{\text{eff}}$) of the photometric filters and change the ratio, which is significant when the extinction is small like in this work. For this purpose, we choose four stars typical of the sample sources, i.e., the dwarf stars with log g = 4, Z = 0, and $T_{\text{eff}}$ = 5000, 6000, 7000, and 8000 K respectively, whose SED is calculated by the ATLAS9 model. The range of $E_{\text{G16-Grp}}$ is from 0.0 to 1.0. The SED is convolved with the F99 extinction law at $R_V = 3.1$ and the filter’s response curve to calculate the effective wavelengths, the corresponding color excess, and the color excess ratio. The results are illustrated in Figure 10. It can be seen that $E_{\text{NUV,Grp}}/E_{\text{G16-Grp}}$ is systematically larger for high $T_{\text{eff}}$, which is caused mainly by their larger shift to the shorter $\lambda_{\text{eff}}$ of the NUV band, and the difference between low $T_{\text{eff}}$ and high $T_{\text{eff}}$ diminishes with increasing color excess. On the contrary, $E_{\text{FUV,Grp}}/E_{\text{G16-Grp}}$ is larger for low $T_{\text{eff}}$ and the difference with high $T_{\text{eff}}$ is not reduced by increasing the color excess in the given range. This is because $\lambda_{\text{eff}}^{\text{FUV}}$ is almost constant in this $T_{\text{eff}}$ range, and the change of the ratio originates mainly from the shift of $\lambda_{\text{eff}}^{\text{G16}}$.

4.3.3. Change of $T_{\text{eff}}$ with the Galactic Latitude and $E_{\text{G16-Grp}}$

The change of $T_{\text{eff}}$ with the Galactic latitude and $E_{\text{G16-Grp}}$ is examined in order to peel off the influence of $T_{\text{eff}}$. Figure 11 shows that $T_{\text{eff}}$ changes with the Galactic latitude and $E_{\text{G16-Grp}}$, where the top panel takes into account the sources in the NUV catalog and the bottom panel the sources in the FUV catalog. The average $T_{\text{eff}}$ in a bin of $5^\circ$ in the Galactic latitude (red asterisks with the red bar for the standard deviation) increases from about 5700 K in the high Galactic latitude region to about 6500 K in the low Galactic latitude region. Meanwhile, the average $T_{\text{eff}}$ in a bin of 0.02 mag in $E_{\text{G16-Grp}}$ (red asterisks with the red bar for the standard deviation) increases from about 5800 K at low extinction to about 7500 K at high extinction. For the FUV catalog, the average $T_{\text{eff}}$ increases from about 6650 K in the high Galactic latitude region to 7600 K in the low Galactic latitude region, and the average $T_{\text{eff}}$ increases from about 6700 K at low extinction to about 8200 K at high extinction. In a word, $T_{\text{eff}}$ increases with the decreasing Galactic latitude and with the increasing extinction, and the steepness is stronger in the FUV than in the NUV band.

Considering the effects of $T_{\text{eff}}$ and $E_{\text{G16-Grp}}$ on the color excess ratios in combination with the change of $T_{\text{eff}}$ with the Galactic latitude and $E_{\text{G16-Grp}}$, the following would be expected: (1) at high latitude, $T_{\text{eff}}$ is low and $E_{\text{G16-Grp}}$ is small, and thus $E_{\text{NUV,Grp}}/E_{\text{G16-Grp}}$ should be smaller than the average and $E_{\text{FUV,Grp}}/E_{\text{G16-Grp}}$ should be approximate to the average; (2) at low latitude, $T_{\text{eff}}$ is high and $E_{\text{G16-Grp}}$ is big, and thus $E_{\text{NUV,Grp}}/E_{\text{G16-Grp}}$ should be bigger than the average and $E_{\text{FUV,Grp}}/E_{\text{G16-Grp}}$ should also be approximate to the average; (3) at small $E_{\text{G16-Grp}}$, $T_{\text{eff}}$ is low, which is the same as Case (1); (4) at large $E_{\text{G16-Grp}}$, $T_{\text{eff}}$ is high, which is the same as Case (2). Consequently, $E_{\text{NUV,Grp}}/E_{\text{G16-Grp}}$ is expected to increase with increasing $E_{\text{G16-Grp}}$ or decreasing latitude, while $E_{\text{FUV,Grp}}/E_{\text{G16-Grp}}$ is expected to be more or less constant independent of the latitude and color excess.

Comparing these expectations with what is found in Figure 11, it can be argued that the tendency of the change of $E_{\text{NUV,Grp}}/E_{\text{G16-Grp}}$ cannot be accounted for by stellar $T_{\text{eff}}$ and the color excess. The measured ratio $E_{\text{NUV,Grp}}/E_{\text{G16-Grp}}$ shows no increasing tendency with $E_{\text{G16-Grp}}$; moreover, a small rise appears at small $E_{\text{G16-Grp}}$, which disagrees with the increasing trend from $\sim 3.1$ at low extinction to $\sim 3.2$ at high extinction expected from Figures 10 and 11. For $E_{\text{FUV,Grp}}/E_{\text{G16-Grp}}$, which

![Figure 10](image-url)

Figure 10. The change of the color excess ratio due to the shifts of the effective wavelength of the filters by the extinction and stellar $T_{\text{eff}}$ (see text for details) for $E_{\text{NUV,Grp}}/E_{\text{G16-Grp}}$ (top panel) and $E_{\text{FUV,Grp}}/E_{\text{G16-Grp}}$ (bottom panel).
Figure 11. The change of $T_{\text{eff}}$ with Galactic latitude (left panel) and $E_{G_{\text{BP}}-G_{\text{RP}}}$ (right panel). The top panel is the result of the NUV catalog. The bottom panel is the result of the FUV catalog. The gray scale encodes the source density. The red asterisks denote the median value for every 5° in the Galactic latitude (left panel) and every 0.02 mag in $E_{G_{\text{BP}}-G_{\text{RP}}}$ (right panel). The red error bar shows the standard deviation.

Figure 12. Gridding map by the HEALPix method of $E_{\text{NUV}-G_{\text{BP}}}$ (top left), $E_{G_{\text{BP}}-G_{\text{RP}}}$ (top right), and their errors (bottom panels).
is basically constant, there is no evident contradiction with the expectation brought by the difference of $T_{\text{eff}}$ and $E_{\text{G}_\text{Bp},G_{\text{Bp}}}$. Nevertheless, the small decrease at the very low $E_{\text{G}_\text{Bp},G_{\text{Bp}}}$ is inconsistent with the expectation from Figures 10 and 11, i.e., from $\sim3.0$ at low extinction to $\sim3.2$ at high extinction. We may conclude that the change of $E_{\text{NUV},G_{\text{Bp}}}/E_{\text{G}_\text{Bp},G_{\text{Bp}}}$ and $E_{\text{FUV},G_{\text{Bp}}}/E_{\text{G}_\text{Bp},G_{\text{Bp}}}$ needs some variation of the dust properties to account for, such as the dust size distribution, but we will not go further on this point.

4.4. The Near-ultraviolet Extinction Map

With the color excess $E_{\text{NUV},G_{\text{Bp}}}$ for more than one million stars, the NUV extinction map can be constructed. But for the FUV band, only about 50,000 measurements are available, which is not enough to delineate the FUV extinction sky, so the FUV band will not be studied further. In order to make the NUV extinction map, the HEALPix algorithm (Hierarchical Equal Area isoLatitude Pixelization) for pixelizing a sphere (Górski et al. 2005) is used with the Python code “healpy” to grid our data. We select $N_{\text{side}}=128$ and divide the whole sky into 196,608 pixels ($N_{\text{pix}}$), which means about 0.2 deg$^2$ per pixel. The median value by an iterative $3\sigma$ clipping is taken as the representative value of each bin. The map of median values and standard deviations is shown in the left column of Figure 12. This map has 76,934 pixels covering a third of the sky, 83% of which has more than five sources (see Figure 13). In comparison, the map of $E_{\text{G}_\text{Bp},G_{\text{Bp}}}$ has 107,388 pixels covering half of the sky, 90% of which has more than five sources (see the right column of Figures 12 and 13). It should be noticed that there are 3987 pixels in $E_{\text{NUV},G_{\text{Bp}}}$ and 3098 pixels in $E_{\text{G}_\text{Bp},G_{\text{Bp}}}$ with only one source, which correspondingly yields a zero standard deviation and is not taken into account in the bottom panels of Figure 12.

The large-scale structures of the NUV extinction map agree very well with the optical one, as shown in Figure 12. The most prominent features include the Orion and the Tau-Per-Aur complexes at the antecenter direction, the Ophiuchus cloud at the Galactic center direction, Aquila South, and the Chamaeleon clouds along $b \sim -20^\circ$. The general increase toward the Galactic plane is apparent, with some small-scale structures at high latitudes.

5. Summary

Using the stellar parameters from the updated spectroscopic database from the LAMOST survey in the northern hemisphere and the GALAH survey in the south, the accurate interstellar extinctions in the GALEX UV bands are obtained for a significantly increased number of stars. This large sample forms the solid basis to construct the extinction map and to study the extinction law in the UV. The main results of this work are as follows:

1. In combining the stellar parameters from the LAMOST and GALAH spectroscopic survey with the color indexes from the GALEX and Gaia photometric survey, the color excesses $E_{\text{NUV},G_{\text{Bp}}}$ and $E_{\text{FUV},G_{\text{Bp}}}$ are obtained for 1,244,504 stars and 56,123 stars by using the blue-edge method to calculate the intrinsic color indexes. For reference, the color excess $E_{\text{G}_\text{Bp},G_{\text{Bp}}}$ is obtained for 4,169,769 stars.

2. The color excess ratios, $E_{\text{NUV},G_{\text{Bp}}}/E_{\text{G}_\text{Bp},G_{\text{Bp}}}$ and $E_{\text{FUV},G_{\text{Bp}}}/E_{\text{G}_\text{Bp},G_{\text{Bp}}}$, are derived to be $3.25 \pm 0.04$ and $2.95 \pm 0.16$, respectively, for the entire sample, which highly agrees with the derived $E_{\text{NUV},\text{NUV}}/E_{\text{G}_\text{Bp},\text{G}_{\text{Bp}}}$ = $-0.37 \pm 0.15$, as well as with our previous result (Sun et al. 2018). The derived $E_{\text{FUV},\text{NUV}}/E_{\text{G}_\text{Bp},\text{G}_{\text{Bp}}}$ at $|b| > 20^\circ$ is also negative.

3. The UV extinction map is constructed by using the HEALPix method ($N_{\text{side}}=128$), which covers a third of the sky with an angular resolution of $\sim0^\circ.4$. Correspondingly, the optical extinction map covers about half of the sky.

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Software: Astropy (Astropy Collaboration et al. 2013), Dustmap (Green 2018), Healpy (Zonca et al. 2019), Topcat (Taylor 2005).

Facilities: GALEX, LAMOST, GALAH, Gaia.

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8 https://healpy.readthedocs.io/
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