Detections of Dust in the Outskirts of M31 and M33

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Abstract
M31 and M33 serve as ideal places to study distributions of dust in the outskirts of spiral galaxies. In this Letter, using about 0.2 million stars selected from the LAMOST data and combining precise photometry and parallaxes from the Gaia DR2, we have constructed a two-dimensional foreground dust reddening map toward the M31 and M33 region (111°2 ≤ gl ≤ 136°2, −36°5 ≤ gb ≤ −16°5). The map has a typical spatial resolution of about 12 and precision of 0.01 mag. The complex structure of dust clouds toward M31 is revealed. By carefully removing the foreground extinction from the dust reddening map of Schlegel et al., we thus have obtained a residual map to study dust distributions in the outskirts of M31 and M33. A large amount of dust is detected in the M31 halo out to a distance of over 100 kpc. Dust in the M31 disk is found to extend out to about 2.5 times its optical radius, with a distribution that is consistent with either an exponential disk with a scale length of 7.2 kpc or two disks with a scale length of 11.1 kpc within its optical radius and 18.3 kpc beyond its optical radius. Dust in the disk of M33 is also found to extend out to about 2.5 times its optical radius, its distribution beyond one optical radius is consistent with an exponential disk with a scale length of 5.6 kpc. Our results provide new clues to the distributions and cycling of dust in galaxies.

Unified Astronomy Thesaurus concepts: Andromeda Galaxy (39); Circumgalactic medium (1879); Interstellar dust (836)

1. Introduction
Dust is ubiquitous in the universe, from the interstellar medium (Draine 2003), to the circumgalactic medium (CGM; Tumlinson et al. 2017), to the intragalactic medium (Shchekinozov & Nath 2011). Studies of distributions and properties of dust from the Milky Way to extra-galaxies have wide implications, including formation, transportation, and destruction of dust, formation, and evolution of galaxies, and precise reddening correction to reveal the intrinsic properties of astronomical objects.

It has been known for decades that galactic dust/gas disks extend beyond the dimensions inferred from the stellar disks in both the Galaxy and extra-galaxies. By comparing scale lengths in different photometric bands, dust scale lengths are also found to be much larger than the stellar ones, up to a factor of 2 (e.g., Casasola et al. 2017). The presence of extended dust distributions in spiral galaxies is also supported by far-infrared observations of dust emission. By modeling the COBE observations at 140 μ and 240 μ, Davies et al. (1997) find a dust disk with a radial scale length 1.5 times the stellar for the Galaxy. The result is further confirmed by three-dimensional modeling of the Galactic dust distribution with the LAMOST data (Li et al. 2018). With similar techniques, evidence for an extended distribution of cold dust was also found for extra-galaxies (e.g., Hinz et al. 2006). By combining the signal of 110 spiral galaxies, Smith et al. (2016) report the direct detection of dust emission that extends out to at least twice the optical radius. And they find that the distribution of dust is consistent with an exponential at all radii with a gradient of about −1.7 dex per R25, corresponding to a dust scale length of 0.44 R25.

Using an occulting galaxy technique, Holwerda et al. (2009) find a dusty disk much more extended than the starlight, with spiral lanes seen in extinction out to 1.5 R25 radii.

Dust is also believed to exist in the CGM. Zaritsky (1994) reports a preliminary detection of a dusty halo, through the additional color excess of background objects in fields close to two galaxies, compared to that of field objects. Based on the angular correlation between the reddening of about 85,000 quasars at z > 1 and the positions of 24 million galaxies at z ∼ 0.3 detected in the SDSS (York et al. 2000), Ménard et al. (2010) have detected the presence of extended halos of dust from 20 kpc to several Mpc. Dust clouds in the Galactic halo have also been detected to a distance of about 30 kpc (H. B. Yuan et al. 2020, in preparation).

M31 and M33, as respectively the largest and third largest galaxies in the Local Group, serve as ideal places not only to study the dust in external spiral galaxies with an extremely high spatial resolution (e.g., Draine et al. 2014), but also to study distributions of dust in the very outskirts of galaxies. Tempel et al. (2010) have constructed a three-dimensional galaxy model with axisymmetric stellar populations and a dust disk to estimate extinction and the intrinsic luminosity and color distributions of M31, using the Spitzer far-IR maps to determine the dust distribution. The resulting scale length of the dust disk with a simple exponential law is 8.5 kpc, about 1.8 times the stellar scale length. However, this work is only limited to about one optical radius. Dust distributions in the outskirts of M31 and M33 have not been investigated yet, due to the difficulties in separating their weak signals from the foreground Galactic dust, either in far-IR emission or in absorption.

Thanks to the scientific significance of M31 and M33 and the good match between the size (and position) of M31 and the field of view (and site weather) of LAMOST (Cui et al. 2012), M31 and its vicinity region have been extensively targeted by LAMOST during its commissioning, pilot, and regular survey...
phases (Yuan et al. 2015). A large number of foreground stars have been well observed and their reddening values can be accurately estimated with the so-called star-pair technique (e.g., Yuan et al. 2013). In this work, we use accurate reddening estimates of 193,847 stars to construct a foreground dust reddening map toward the M31 and M33 region. Then by comparing with the dust reddening map of Schlegel et al. (1998), we aim to explore how dust is distributed in the outskirts of the two galaxies. The paper is organized as follows. In Section 2 we introduce our data and method used to construct the foreground reddening map. The resulting map and distributions of dust in the outskirts of M31 and M33 are presented in Sections 3 and 4. The results are discussed in Section 5. We summarize in Section 6.

The following general parameters of M31 and M33 are adopted in this work: for M31, the R.A. is 10°68458 and the decl. is 41°26875 (Jarrett et al. 2003), the optical radius is 1°58, the inclination angle is 77°8 (de Vaucouleurs et al. 1991), the major axis position angle is 38°0 (Chemin et al. 2009), and the distance is 785 kpc (McConnachie et al. 2005). For M33, the R.A. is 23°46208 and the decl. is 30°65994 (Jarrett et al. 2003), the optical radius is 0°59, the inclination angle is 53°9 (de Vaucouleurs et al. 1991), the major axis position angle is 50°5 (Jarrett et al. 2003), and the distance is 809 kpc (McConnachie et al. 2005).

2. Data and Method

2.1. Data

LAMOST spectroscopic data (Deng et al. 2012; Zhao et al. 2012; Liu et al. 2014) combined with Gaia DR2 (Gaia Collaboration et al. 2018) photometry and parallaxes are used to construct a foreground dust reddening map toward the M31 and M33 region in this work.

We first select spectroscopic data from the LAMOST DR5, which has delivered more than 8 million stellar spectra with spectral resolution of $R=1800$ and limiting magnitude of $r \sim 17.8$ mag (Deng et al. 2012; Liu et al. 2014). Stellar effective temperatures, surface gravities, and metallicities are derived by the LAMOST Stellar Parameter Pipeline (Wu et al. 2011), with the precision of about 110 K, 0.2 dex, and 0.15 dex, respectively (Luo et al. 2015). Additional targets in the second value-added catalog (Xiang et al. 2017) of the LAMOST Spectroscopic Survey of the Galactic Anti-center (LSS-GAC; Liu et al. 2014; Yuan et al. 2015) are also used. As the LSS-GAC DR2 value-added catalog contains targets that were observed during the commissioning and testing time and not included in the LAMOST official data releases. Basic stellar parameters in the LSS-GAC value-added catalogs are derived with the LAMOST Stellar Parameter Pipeline at Peking University (LSP3; Xiang et al. 2015, 2017).

The following criteria are used to select sample stars: (1) $11\rlap{.}1 \lesssim \text{decl.} \lesssim 13\rlap{.}2$ and $-36\rlap{.}5 \lesssim \text{lat.} \lesssim -16\rlap{.}5$; (2) SNR $\geq 10$; (3) positive Gaia DR2 parallaxes; and (4) $1.0 + 0.015(BP - RP)^2 < \text{phot}_{BP\_RP\_excess}\_factor < 1.3 + 0.06(BP - RP)^2$ to exclude stars whose BP/RP photometry is probably contaminated from nearby sources (Evans et al. 2018). In cases of duplicated targets, the one with the higher/highest SNR is used. In total, about 160,000 stars from the LAMOST DR5 and 40,000 stars from the LSS-GAC DR2 are selected.

2.2. Estimates of Reddening for Individual Stars

A straightforward star-pair method is adopted to obtain reddening values of the selected stars. The method assumes that stars of the same stellar atmospheric parameters have the same intrinsic colors. Thus, the intrinsic colors of a reddened star can be derived from its control pairs/counterparts of the same atmospheric parameters ($\Delta T_{\text{eff}} < T_{\text{eff}} + (0.00003 + T_{\text{eff}}^2)K$, $\Delta \log g < 0.5$ dex, $\Delta [\text{Fe/H}] < 0.3$ dex) that suffer from either nil or well-known extinction (Yuan et al. 2013). For the control stars, their reddening values are from the SFD98 map and required to be smaller than 0.02 mag, their distances to the Galactic plane are required to be larger than 1 kpc to ensure that they are far above the Galactic dust disk. Given the high precision of Gaia DR2 photometry, reddening values of $E(BP - RP)$ are computed in this work, using the same star-pair algorithm of Yuan et al. (2015; see their Section 5 for more details).

To make our Galactic foreground reddening map in the M31 and M33 region directly comparable to the SFD98 map, values of $E(BP - RP)$ are converted to $E(B - V)$ via the following temperature and reddening dependent reddening coefficient $R_{BP-RP}$ (Y. Sun et al. 2020, in preparation):

$$R_{BP-RP} = 1.060 - 0.253 \times E(B - V)_{\text{SFD}} + 0.264 \times E(B - V)_{\text{SFD}}^2 + 5.355 \times 10^{-6} \times T_{\text{eff}} - 4.050 \times 10^{-5} \times T_{\text{eff}} \times E(B - V)_{\text{SFD}} + 6.639 \times 10^{-9} \times T_{\text{eff}}^2.$$  (1)

The formula is empirically determined from a large sample of LAMOST DR5 stars, with their values of $E(BP - RP)$ estimated using the same star-pair algorithm and values of $E(B - V)$ from the SFD98 map. The hotter stars are, the smaller reddening stars suffer, and the larger $R_{BP-RP}$ values are. At $E(B - V) = 0.1$ mag, the values increase from 1.15 at $T_{\text{eff}} = 4000$ K to 1.47 at $T_{\text{eff}} = 8000$ K. At $T_{\text{eff}} = 6000$ K, the values decrease from 1.30 at $E(B - V) = 0.05$ mag to 1.28 at 0.10 mag. A very small number of stars whose estimated reddening values are larger than those of the SFD98 map by 0.05 mag are also excluded.

2.3. Estimates of Galactic Foreground Reddening for Different Sightlines

In previous subsections, we select 193,847 stars within a $25\rlap{.}^\circ \times 20\rlap{.}^\circ$ region covering both M31 and M33 and obtain their reddening values. A total of 500 $\times$ 400 sightlines, in intervals of $3^\circ$ in both the Galactic longitude and latitude directions, are used to construct the 2D Galactic foreground reddening map toward the M31 and M33 region in this work. Each sightline contains stars within a small “rectangular” region of $12\rlap{.}^\circ \times 12\rlap{.}^\circ$. Note that there are common stars between adjacent sightlines. If there are fewer than 10 stars for a given sightline, the size is doubled to 24' to obtain a reliable result. If the number of stars is still less than 10, the sightlines are masked and not used in the following analysis. The top left panel of Figure 1 shows the resulting spatial resolutions. The top right panel shows the histogram distributions of number of stars used for sightlines in the white and gray regions.

Then for each sightline, we use the following function to fit its distance-reddening relation:

$$y = a - b \cdot e^{-x^2},$$

Ruoyi & Haibo
where $x$ is the distance, $y$ is the reddening $E(B - V)$, and $a$, $b$, and $c$ are three parameters to be constrained. If we assume a single exponential distribution of dust, then $a$ and $b$ are equal and represent the total Galactic foreground reddening of a given sightline. If there is a dust cloud very close to the Galactic disk, then $a$ and $b$ are different, $a$ still represents the total Galactic foreground reddening, $b$ represents the contribution from the exponential dust disk, and $a - b$ represents the additional contribution from the dust cloud. Both scenarios ($a = b$, $a \neq b$) are considered. It is found that the resulting two $a$ values are very close. Therefore, both $a$ and $b$ parameters are set to be free in this work.

For the $c$ parameter, which is related to the scale height of the dust disk, we set lower and upper limits of 0.2 and 0.6 kpc, respectively. The limits correspond to a dust scale height of about 70 and 210 pc, within the range of literature values (e.g., Li et al. 2018). A fitting routine, MPFIT, is used to perform the least-square fit by utilizing the Levenberg–Markwardt technique (Markwardt 2009). The initial values for $a$, $b$, and $c$ are adopted to be 0.05, 0.05, and 0.4, respectively. The fitting results are very robust and insensitive to the adopted initial values. A $2\sigma$ clipping is also performed during the fitting.

The top panels of Figure 1 show selected examples of fitting results of different sightlines toward M31. In the central region, our fitted values of foreground Galactic extinction are significantly smaller than the corresponding values from the SFD map, as expected. The differences become smaller as sightlines get further away. The bottom panels of Figure 1 show examples of sightlines that are far away from M31 and display large discrepancies between the SFD98 and LAMOST maps. So far we have obtained a two-dimensional dust reddening map (LAMOST map hereafter) for the M31 and M33 region. The map has a typical spatial resolution of 12', as shown in the top right panel of Figure 2. The SFD98 map has a spatial resolution of 6"1, about 2 times higher than that of the LAMOST map. The LAMOST map is another example of sightlines that are far away from M31 and display large discrepancies between the SFD98 and LAMOST maps.

3. A Two-dimensional Foreground Dust Reddening Map

The SFD98 map is widely used to perform foreground reddening correction of extragalactic targets. Note that a negative offset of 0.003 mag is found for the SFD98 map by comparison with the Planck result (Planck Collaboration et al. 2014). Therefore, 0.003 mag has been added to the SFD98 map throughout this work. However, due to the difficulties in removing dust emission from very nearby galaxies, such as Magellanic Clouds and M31, the SFD98 map is not applicable to these galaxies. As expected and seen in Figure 2, reddening values of the LAMOST map are systematically lower than those of the SFD98 map in regions around M31, especially within its optical radius.

Typical values of reddening toward Magellanic Clouds and M31 from the SFD98 map are estimated from the median dust emission in surrounding annuli: $E(B - V) = 0.075, 0.037, 0.062$ mag for the Large Magellanic Cloud, Small Magellanic Cloud, and M31, respectively (Schlegel et al. 1998). Given the large field of view of these galaxies, Galactic foreground reddening corrections using the aforementioned values probably suffer large uncertainties. The LAMOST map shows that there are Galactic foreground “cirrus” clouds in front of the
M31 galaxy. Within the optical radius, the median value of reddening is 0.069 mag, the peak-to-peak value is 0.035–0.097 mag, the dispersion is 0.011 mag. The precise Galactic foreground reddening map obtained in this work is also very crucial in order to (1) measure precise extinction curves across different regions of M31 to study their variations with different environments (Bianchi et al. 1996; Dong et al. 2014; Clayton et al. 2015) and then (2) perform better reddening correction of M31 targets to reveal the stellar populations, the structure of M31 using photometry of large numbers of individual stars (e.g., Dalcanton et al. 2012). Note that dust emission in the central part of M110 is also detected in the bottom left panel of Figure 2, consistent with the fact that M110 contains a population of young blue stars at its center.

To check the precision of the LAMOST map, we first select stars that are far above the Galactic plane (|Z| > 1.2 kpc) and far away from M31 (gl > 124°2 or gl < 118°2 or gb > −18°5 or gb < −24°5). The left panels of Figure 3 plot comparisons of LAMOST reddening estimates with those from the SFD98 map for the selected stars. The two measurements...
agree well at a dispersion of 0.023 mag, suggesting that the reddening estimates have a typical precision of 0.023 mag for individual stars. The precision depends on SNRs of LAMOST stars. For stars of SNRs lower than 20, the precision decreases to 0.026 mag. There is a tail of stars that have systematically lower LAMOST reddening than SFD reddening. Those stars typically have lower SNRs. Note the LAMOST estimates are systematically lower by a very small number of 0.003 mag. The precision is systematically lower by about 0.001 mag at a projected distance of ~5 \( R_{25} \) radii. The numbers agree very well with those of Ménard et al. (2010), who find that a background source is typically reddened from a \( z \sim 0.3 \) galaxy by about 0.01 mag at a separation of 20 kpc, and by about 0.001 mag at 100 kpc. A simple spherically symmetric power-law distribution of dust in the M31 halo, with galactocentric distance \( r \) between 1.1 and 5 \( R_{25} \) radii, is adopted to fit the observed curve. The resulting curve is overplotted in orange and agrees well with the observed one. A power-law index of ~0.84 is obtained, suggesting higher dust densities in the inner halo but more dust in the outer halo. Without correction for the reddening dependent systematics of the SFD98 map, the resulting curve is systematically lower by about 2.5 mmag, varying slightly with \( r \). In such a case, the dust halo can still be detected up to a distance of ~4 \( R_{25} \) radii. Beyond 4 \( R_{25} \) radii, negative reddening values are detected, suggesting that the correction is necessary.

Elliptical annuli centered on M31 are also used to study dust distribution in the disk of M31. Possible contaminations from the M31 halo are subtracted according to the observed curve in the left panel of Figure 4. For regions within 1.1 \( R_{25} \) radii, 0.008 mag is adopted. The project effect has also been corrected by multiplying \( \cos(77.8°) = 0.21 \), where 77.8° is the inclination of the M31 disk. The middle panel of Figure 4 plots the reddening of the M31 dust disk as a function of galactocentric distance, seen as if it is edge-on. Dust in the M31 disk is found to extend out to about 2.5 times its optical radius, whose distribution is consistent with either an exponential with a scale length of 7.2 kpc or an exponential with a scale length of 11.1 kpc within its optical radius and another one of 18.3 kpc beyond its optical radius. Our result is consistent with Tempel et al. (2010), who find a dust disk scale length of 9.8 kpc within its optical radius, about 1.8 times the stellar scale length. In the latter case, we note a prominent reddening jump at its optical radius. If without correction for the reddening dependent systematics of the SFD98 map, the resulting curve for the M31 dust disk is hardly changed. Note that to make the plot in the logarithmic scale, a constant of 0.002 mag is added to make sure all the data points are positive. At \( R > 2.5 R_{25} \), negative reddening of the M31 dust disk is detected. This is probably caused by an oversubtraction of the halo component. As discussed in the coming section, there is a possible lack of dust in the halo of M31 along its major axis direction.

4. Dust Distribution in the Outskirts of M31 and M33

To study dust distribution in the outskirts of M31 and M33, we first correct for the reddening dependent systematics of the SFD98 map for regions outside the optical radius of M31 using the linear formula \( E(B - V)_{\text{corr}} = 1.070 * E(B - V) - 0.0017 \), as indicated in the top right panel of Figure 3. The updated residual map is shown in the bottom right panel of Figure 2. To avoid possible uncertainties in the correction, only regions of \( E(B - V)_{\text{SFD}} < 0.09 \) mag are used in the following analysis. Radial trends are then studied by averaging in annuli centered on the two galaxies. Their errors are also estimated by their standard deviations divided by the square root of the number of pixels.
disk with a scale length of 0.68 $R_{25}$, i.e., 24.1 and 5.7 kpc. This number is very close to the scale length of its extended outer stellar disk (25/4, 6.0 kpc, Grosset al. 2011), 1.5 times larger than its stellar scale length in optical (9/6, van den Bergh 1991). If without correction for the reddening dependent systematics of the SFD98 map, the resulting curve for the M33 dust disk is systematically lower by about 1.5 mmag, but the profile is unchanged. At $R > 2R_{25}$, negative reddening of the M33 dust disk is detected. This is probably caused by systematic errors in the correction of the SFD98 map, particularly for the blue region in the lower right of M33. The SFD98 map suffers systematics that depend on dust reddening, dust temperature, and positions, and we only make a simple reddening dependent linear correction in this work.

**5. Discussion**

We find that M31 has a large and dusty halo. This result is consistent with the work of Lehner et al. (2015, 2020) who show the presence of an extended and massive CGM around M31 via absorption line studies of dozens of quasars. The result also agrees well with Ménard et al. (2010), who find strong evidence for the existence of a diffuse component of dust in galactic halos, extending from 20 kpc to several megaparsecs. The projected reddening profiles from 20 to 100 kpc are also similar, as mentioned in the previous section. Using cosmological hydrodynamical simulations, Péroux et al. (2020) recently reported a strong dependence of gas mass flow rates and gas metallicity of CGM on azimuthal angle with respect to its central galaxy: outflows are more favored along the galaxy minor axis and tends to have higher metallicity than inflows. Therefore, one would expect less dust along the galaxy major axis direction. We note a possible lack of dust in the halo of M31 along its major axis direction, thus maybe providing direct observational evidence of the findings of Péroux et al.

Ménard et al. estimate that the dust mass in the halo of Milky Way–like galaxies ($\sim 5 \times 10^7 M_\odot$) is comparable to that commonly found in galactic disks (Draine et al. 2007). Assuming simply uniform dust properties across the disk and halo of M31, we have estimated the mass fractions of dust in its disk ($0 < 2.5 R_{25}$) and halo ($0 < 5 R_{25}$) according to their reddening profiles (Figure 4). We find that roughly 75% of dust is in the halo and only 25% is in the disk, and only 1.5% is in its outer disk ($1 < 2.5 R_{25}$). Based on a physical dust model, Draine et al. (2014) have estimated a total dust mass of $5.4 \times 10^7 M_\odot$ in the disk of M31 out to a distance of 25 kpc. Following the method of Ménard et al. (see their Section 5.1), we estimate a total dust mass in the halo of M31 to be $\sim 1.8 \times 10^8 M_\odot$, assuming an SMC-type dust and $R_V = 4.9$. The above estimates suggest that about three-quarters of dust is in the halo of M31. If without correction for the reddening dependent systematics of the SFD98 map, the total dust mass in the halo of M31 ($0 < 4 R_{25}$) decreases to $\sim 0.77 \times 10^8 M_\odot$, the dust mass in the disk is unchanged. In such a case, about 55% of dust is in the halo of M31.

In the above analysis, we have ignored the contributions of dust in the Galactic halo to the reddening of the M31 halo. If there are distant dust clouds in the Galactic halo that are not probed by our sampling stars, the resulting LAMOST reddening map will be underestimated, and reddening from the M31 halo will be overestimated. However, considering the rapidly decreasing reddening profile for the M31 halo, the effects of dust in the Galactic halo should be weak.

A number of radio observations have revealed an M31 neutral gaseous halo extending from its disk to at least halfway to M33 (Braun & Thilker 2004; Lockman et al. 2012; Kerp et al. 2016). About half of the gas in its gaseous halo is in an extended, diffuse component, with another half composed of clouds that are likely to be fuel for future star formation in M31 and M33 (Wolfe et al. 2013). Further explorations of properties of dust in the outskirts and CGM of M31 and M33 and associations with gas are very promising to constrain galactic outflows and recycling, one of the key ingredients for understanding galaxy evolution.

**6. Summary**

In this work, using 193,847 LAMOST stars with precise reddening estimates and parallaxes, we have constructed a large two-dimensional foreground dust reddening map toward the M31 and M33 region (111° < l < 136°, −36° < b < −16°), at a typical spatial resolution of about 12′. The map agrees well with the SFD98 map in most regions and has a typical precision of 0.01 mag. The map shows the complex structure of dust clouds toward the M31, suggesting that the map should be used for precise foreground reddening corrections in studies such as measuring variations of extinction curves across different regions of M31.
By carefully removing the foreground reddening from the SFD98 map, the distribution of dust in the outskirts of M31 and M33 are revealed in great detail to a very large distance. We find that a significant amount of dust in clumpy and filamentary structures exists in the halo of M31, out to a distance of over 100 kpc. Reddening caused by dust in the M31 halo decreases from about 0.01 mag at the center to 0.001 mag at a projected distance of \(~5 R_{25}\). Dust in the M31 disk extends out to about 2.5 times its optical radius, whose distribution can be described by either an exponential disk of scale length 7.2 kpc or two disks of scale length 11.1 kpc within its optical radius and 18.3 kpc beyond its optical radius. Dust in the disk of M33 is also found to extend out to about 2.5 times its optical radius, beyond one optical radius, its distribution is consistent with an exponential disk of scale length 5.6 kpc. Our results combined with future observations will provide new clues on the distributions, properties, and cycling of dust in spiral galaxies.

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