SPATIAL VARIATIONS OF GALAXY NUMBER COUNTS IN THE SLOAN DIGITAL SKY SURVEY. II. TEST OF GALACTIC EXTINCTION IN HIGH-EXTINCTION REGIONS

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ABSTRACT

Galactic extinction is tested using galaxy number counts at low Galactic latitude obtained from five-band photometry of the Sloan Digital Sky Survey. The spatial variation of galaxy number counts for low-extinction regions of $E(B-V) < 0.15$ is consistent with the all-sky reddening map of Schlegel and coworkers and the standard extinction law. For higher extinction regions of $E(B-V) > 0.15$, however, the map of Schlegel and coworkers overestimates the reddening by a factor of up to 1.4, which can likely be ascribed to the departure from proportionality of reddening to infrared emissivity of dust. This result is consistent with the analysis of Arce & Goodman for the Taurus dark cloud complex.

Key words: dust, extinction — techniques: photometric

1. INTRODUCTION

The Sloan Digital Sky Survey (SDSS; York et al. 2000) provides an unprecedented wide-field imaging survey of the sky with homogeneous, few-percent-error photometry. It allows the study of spatial variations of the projected galaxy number density over the wide field. In our previous publication (Fukugita et al. 2004, hereafter Paper I), it was shown that the variation of the galaxy number counts is accounted for by the Galactic extinction and large-scale galaxy clustering.

Galaxy counts provide a clean test of the Galactic extinction integrated out to the edge of the Milky Way, provided that the galaxies are sampled to sufficiently faint magnitude and their numbers are sufficiently large (see, e.g., Hubble 1934; Burstein & Heiles 1982). The test does not need any models or external calibrations to derive extinction. Moreover, using SDSS photometric data, extinctions in five bands can be determined independently, and the extinction curve can be derived. The primary limitation of this technique is that one cannot explore the small scales where spatial variations of the galaxy distribution are strongly affected by galaxy clustering. The mean amount of Galactic extinction can be well documented, and the error for scales larger than 1° can be made smaller than the order that concerns us. The study in Paper I indeed verified the validity of the reddening map of Schlegel et al. (1998, hereafter SFD) on the scale of 1° and the extinction laws of Cardelli et al. (1989) and O’Donnell (1994) to within 5% for five optical colors. More recently, a similar but more detailed analysis revealed in very low extinction regions slight underestimates of extinction in the SFD map, which are likely due to the contamination of infrared emission from galaxies in the map of far-infrared dust emission (Yahata et al. 2006).

Our study of extinction in Paper I was limited to regions of low extinction [$E(B-V) < 0.15$] since the galaxies used are derived from the main survey area of SDSS (DR1; Abazajian et al. 2003), which intentionally avoids the region of large extinction to explore extragalactic science. A significant amount of SDSS imaging data, however, have been obtained at low Galactic latitudes for the purpose of photometric commissioning and calibrations. A part of such surveys that include the Orion region are published in Finkbeiner et al. (2004). The purpose of the present paper is to extend our study to high-extinction regions and examine the validity of the reddening map and the extinction law given by SFD.

We note that some indication has already been reported that the SFD reddening map may not be correct for high-extinction regions from a study of stars in the background of the Taurus dark cloud complex (Arce & Goodman 1999a; Arce & Goodman suggested that extinction derived from SFD is overestimated by a factor of 1.3–1.5 in regions with $A_V > 0.5$ mag, or $E(B-V) > 0.16$. Our study tests this result in the Orion region.

In §2 we describe the sample, data selection, and procedure to derive extinction from galaxy number counts. Section 3 presents the results together with some discussion. A summary is given in §4.

2. DATA AND ANALYSIS

The imaging by the SDSS telescope (Gunn et al. 1998, 2006) is carried out with the SDSS $ugriz$ filters (Fukugita et al. 1996). Our analysis is based on the data given by Finkbeiner et al. (2004). We use the data of stripe 82 (southern equatorial stripe), which are derived from photometric scans, runs 211(82S), 259(82N), and 273(82S). This is the only stripe in Finkbeiner et al. (2004) for which a north-south pair of stripes, which are needed to form a contiguous area, are observed. The region covers $11.55^\circ < \alpha < 91.55^\circ$ and $-1.25^\circ < \delta < +1.25^\circ$, corresponding to $125^\circ < l < 207^\circ$ and $-62^\circ < b < -10^\circ$. Figure 1 shows the region covered by the current data set overlaid on the reddening map of SFD for the Galactic southern hemisphere. The total area of our data set, 200 deg$^2$, is about 10% of that covered by Paper I derived from SDSS DR1. The mean selective reddening $E(B-V)$ increases from 0.03 at a high Galactic latitude to $\approx 1$ in the Orion region close to the Galactic plane, as seen in Figure 2, which shows the $E(B-V)$ of SFD averaged over the $2.5^\circ \times 2.5^\circ$ regions along the stripe. We note that extinction in dark cloud regions is patchy, and $E(B-V)$ occasionally reaches $>10$ mag for small regions, typically for $15'$.

An object catalog and five-color band images are given in Finkbeiner et al. (2004). The catalog is created by the photometric
pipeline photo, version 5.4.25, which is used to produce DR2 (Abazajian et al. 2004) and later data releases (Abazajian et al. 2005; Adelman-McCarthy et al. 2006, 2007). We select galaxies primarily using the objType parameter in the catalog, but drop objects that are flagged as EDGE, BRIGHT, SATURATED, or BLENDED. It sometimes happens that some objects are not detected in all five bands. We judge the detection using a logical OR of the BINNED1, BINNED2, and BINNED4 flags set per band, which mean that objects are detected in a $1 \times 1$, $2 \times 2$, and $4 \times 4$ binned image, respectively. The entries that are not detected in a given band are not included in our number counts in that band. There are some entries in the catalog whose corresponding objects appear to be much too faint for the quoted magnitudes; their surface brightness is indeed faint. The occurrence of this type of spurious detection is common in all color bands. When the surface brightness distribution is plotted for the galaxy sample, these objects produce a spike at nearly zero surface brightness. Since the reason for the inclusion of such entries in the catalog is not clear, we apply a surface brightness cut at the level of sky background to exclude those entries in the $r$ band. This procedure automatically removes the surface brightness spikes in the $g$, $i$, and $z$ bands. For the $u$ band, there are many true galaxies that have low surface brightness, so we cannot separate the fake spike from the tail of true galaxies; we simply assume that the removal of the spike in the $r$ band also removes spurious objects in the $u$ band. This procedure rejects about 2% of the $r$-band-selected galaxies in the reddened magnitude range of $17.5 < r < 19.5$. We find that most of these entries are flagged as noptetro, but if we used noptetro as the selection criterion we would miss an additional 3% of objects, which are mostly true galaxies.

To account for patchy extinction structure in a heavily reddened region, we divided the total area of 200 deg$^2$ into pixels of $2.3' \times 2.3'$. This pixel size was adopted to match that of the SFD reddening map (2.372'). There are 135,200 such pixels in our area. All pixels are sorted in order of increasing $E(B-V)$ values of the SFD map and grouped every 4225 pixels, so that the sum of the area of each group amounts to $2.5' \times 2.5'$, which is large enough to determine extinction from galaxy number counts. Figure 3 shows the mean $E(B-V)$ value of each group. Half of the groups have $E(B-V) < 0.1$. Since the group of the largest $E(B-V)$ spans too wide a range of reddening, we subdivide it into four; namely, the last four points have been grouped with 1056 pixels (one-quarter of 4225). The last data set includes
pixels with $E(B - V)$ from 1 to 33; it is dropped from our analysis. The present analysis differs from that in Paper I in that contiguous regions of $2.5' \times 2.5'$ are considered. Such an analysis is not appropriate to deal with a sample that includes high-extinction regions, since extinction is very patchy for dark cloud regions and the average of extinction over a large area does not necessarily match the magnitude offset calculated from galaxy counts.\footnote{For example, in an area where half of the region is clear and the other half is extincted by 20 mag, then the mean extinction would be 10 mag. However, galaxies can be observed in the clear area, and the number of galaxies will be half that expected for the case without extinction. This leads us to infer that the magnitude offset would be about 0.5 mag.} For this reason we divide the area into small regions and assemble the region according to extinction values in the present paper. For low-extinction regions, the details of the binning are not important.

We use Petrosian magnitudes (see Stoughton et al. 2002; Strauss et al. 2002) in our study. Petrosian magnitudes are suitable for the analysis given in this paper, since the Petrosian radii are unaffected by the foreground extinction and Petrosian magnitudes measure the same fraction of the flux of galaxies regardless of their foreground extinction. This means that we can correct for the extinction properly just by subtracting the extinction value in each band. This does not hold for other galaxy magnitudes such as isophotal or aperture magnitudes. We have to note that Petrosian magnitudes are not corrected for seeing variations, unlike model magnitudes, which are point-spread function--convolved model fits. The fraction of total magnitude measured by the Petrosian magnitude will change as galaxies become smaller as a result of worse seeing (Blanton et al. 2001). This effect is only a few percent for the galaxies used in this study ($17.5 < r < 22.0$ or $1.0'' < r_50 < 3.0''$) and does not affect our results. We refer readers interested in astrometric calibrations to Pier et al. (2003) and in photometric calibrations of the main survey to Smith et al. (2002); see also Hogg et al. 2001; Tucker et al. 2006) and Ivezić et al. (2004). Since the secondary standard-star “patches” are sparse or nonexistent for much of the Orion region, photometric calibrations for the current data use the calibration algorithm. (See Finkbeiner et al. [2004] and Gunn et al. [2006] for details.)

We derive the mean extinction-free galaxy number count (differential count) $\bar{N}(m)$ from the entire sample in low-extinction regions of $E(B - V) < 0.1$ by employing the SFD reddening map and the default standard extinction law, $k(r) = A_r/E(B - V) = 2.751$ (Table 6 of SFD). We take this mean relation as the reference. We then count the number of galaxies for each group without applying the extinction correction and fit to the reference count by shifting the amount of magnitude $\Delta m$, i.e., as $\bar{N}(m + \Delta m)$; this $\Delta m$ represents the extinction in the specific region.

We first work with the $r$-band counts but extend the study later to other color bands. It is desirable to work with number counts at a level as faint as possible, so that the galaxy number density is sufficiently large to minimize the Poisson noise and the spatial distribution of galaxies is sufficiently smooth to minimize the large-scale clustering effects. Paper I uses the data in the magnitude range of $r = 18.5 - 20.5$. In the current study, this approach is not appropriate; the reddening expected in the SDF map varies from $E(B - V) = 0.03$ to 0.9 (regions of the largest extinction are discarded). This range corresponds to $A_r = 0.08 - 2.5$, and the count in highly reddened regions falls out of the range set as the reference magnitude band. To avoid this problem we set the range in a way that the dereddened magnitude range is the same for all regions. We use the counts whose number density per square degree per 0.5 mag is

$$1.8 < \log N(m) < 2.6,$$  \hspace{1cm} (1) 

and fit $N(m)$ to the reference count to derive $\Delta m$. This range corresponds to $r = 17.5 - 19.5$ on the reference galaxy number count, which is 1 mag brighter than that in Paper I. This is still reasonably faint, yet photometric measurements are made at a high signal-to-noise ratio, and star-galaxy separation is sufficiently reliable even with extinction. This ability to classify objects is particularly important for our study, because the contamination of stars becomes more serious at low Galactic latitude where the star density is high, and high extinction pushes the objects to fainter magnitudes. The number of galaxies contained in a $2.5' \times 2.5'$ area integrated over $1.8 < \log N(m) < 2.6$ is approximately 4100. The expected Poisson noise of 1.6% is negligible for the present work. It occasionally happens that the faint end of equation (1) goes beyond the magnitude at which incompleteness starts ($r = 22.0$); in this case we drop the data in the bins that go beyond the incompleteness limit. Figure 4 shows examples of $r$-band galaxy counts in low- and high-extinction regions. We see in this figure how magnitude offsets are evaluated.

The normalization of the reference number count in the current sample is lower by 5% than that derived in Paper I [$\Delta \log N(m) = 0.02$].\footnote{Half of this difference is explained by the zero-point offset of photometry between DRI and Finkbeiner et al. (2004), the latter being fainter by $\approx 0.02$ mag. The other half is due to the present omission of objects that produce the spike at zero surface brightness explained above; we did not apply this cut in Paper I.} Half of this difference is explained by the zero-point offset of photometry between DRI and Finkbeiner et al. (2004), the latter being fainter by $\approx 0.02$ mag. The other half is due to the present omission of objects that produce the spike at zero surface brightness explained above; we did not apply this cut in Paper I.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Example galaxy number counts in the $r$ band. Top: Low-extinction [$E(B - V) = 0.03$] region. Bottom: High-extinction [$E(B - V) = 0.26$] region. Solid lines represent the reference galaxy counts. Filled circles (and dashed lines) represent the observed galaxy counts, which are shifted to match the reference counts by the amount of $\Delta m$ (open circles). The bands indicated by dotted lines are the range that is used for matching.}
\end{figure}
We carry out a similar analysis for the four other color bands. The reference range of counts (as \( \log N \)), the corresponding de-reddened magnitude range, the approximate number of galaxies, and the limiting magnitude are given in Table 1. Note that we must choose a range of number of galaxies that is smaller in the bluer bands. In particular, the \( u \) counts go quickly out of the reference range in the presence of extinction. After deriving reference number counts in the extinction-free limit of the low-extinction galaxy samples, we compute \( \Delta m \) for the counts in each group. In deriving the reference counts we assume the standard extinction curve, \( k(\lambda) = A_\lambda / (E(B - V)) \), with \( k(\lambda) = 5.155, 3.793, 2.086, \) and 1.479 for \( u, g, i, \) and \( z \). Note that \( k(\lambda) \) varies by a factor of 3.5 across \( u \) to \( z \) and by a factor of 2.5 if we drop the \( u \) band. This makes use of the \( g, r, i, \) and \( z \) colors appropriate to study the extinction curve, even if we exclude \( u \) for its poorer photometry.

We find the offset in the normalizations of the reference count, \( \Delta \log N(m) = 0.3, 0.03, 0.03, \) and 0.05 for \( u, g, i, \) and \( z \) compared to those in Paper I. The offsets in the \( g, i, \) and \( z \) bands are explained in the same way as for the \( r \) band. The offset in the \( u \) band is large. The shape of the counts at the faint end also differs from that in Paper I. These differences originate from the fact that \( u \)-band surface brightness is faint for many galaxies, and the photon-collecting efficiency in the \( u \) band is low, both contributing to poor photometry in this color band. A comparison of the photometry between DR1 and Finkbeiner et al. (2004) for common galaxies shows that the two magnitudes differ typically by as much as 0.5 mag randomly.\(^3\) There are also some differences in the selection procedure. In the present analysis we required detection in the \( u \) band in a \( 1 \times 1, 2 \times 2, \) or \( 4 \times 4 \) binned image, which we did not do in Paper I. The surface brightness cut in \( r \) is exercised in the present analysis. The effect is small for the \( r \) band, but this drops 10\% of objects for 18.0 < \( u < 20.0 \) in the \( u \)-band count. These effects altogether might induce a large error for the \( u \)-band count. We expect, however, that a substantial part of the errors is likely to cancel when we deal with relative quantities, such as those in our analysis.

### 3. RESULTS

In Figure 5 we show \( \Delta m \) versus Galactic extinction, \( A_{\text{SFD}} \), calculated from the reddening map of SFD averaged over each group with the effective area of \( 2.5^\circ \times 2.5^\circ \), assuming the standard extinction curve. For each group, we applied a jackknife method with the data divided into 10 samples to estimate statistical errors. The horizontal bars stand for the range of \( A_\lambda \) in each group. The data points for which the faint end of the observed magnitude corresponding to equation (1) becomes fainter than the incompleteness limit are shown by open circles. We note that the scatter of the points is substantially reduced compared to those

\(^3\) For stars this large scatter is not seen. The difference between the two magnitudes is no more than twice those in the \( r \) or \( g \) bands; the mean scatter is 0.03 mag at \( u = 19 \).

| Band | Range of Counts | Magnitude | Number of Galaxies | Limiting Magnitude |
|------|----------------|-----------|--------------------|-------------------|
| \( u \) | 1.0–1.8 | 18.0–20.0 | 800 | 21.6 |
| \( g \) | 1.3–2.1 | 17.5–19.5 | 1600 | 22.4 |
| \( r \) | 1.8–2.6 | 17.5–19.5 | 4100 | 22.0 |
| \( i \) | 1.8–2.6 | 17.0–19.0 | 3800 | 21.2 |
| \( z \) | 1.7–2.6 | 16.5–18.5 | 3100 | 19.8 |

![Figure 5](image-url)
from the counts whose faint end extends beyond the incompleteness limit, in addition to the problem of photometry discussed above. We take the results with the $u$ band hereinafter only for the purpose of seeing the broad, rather than quantitative, consistency.

The departure from the identity regression is more clearly demonstrated in Figure 7, where the ratio of $C_{1}^{m}/A_{SFD}$ is plotted as a function of $A_{SFD}$ for each band. The mean values are presented as horizontal bars (for numerical values see Table 2) for the ranges of $E(B-V) = 0.05-0.15$, $0.15-0.45$, and $0.40-1.00$. For $0.05 < E(B-V) < 0.15$, these ratios are consistent with unity within 1 $\sigma$ errors. Apparent departure from unity, $C_{1}^{m} < A_{SFD}$, is visible for higher extinction ranges. The ratio $A_{SFD}/C_{1}^{m}$ is approximately 1.25 for $E(B-V) = 0.15-0.45$ and 1.4 for $E(B-V) = 0.45-1.00$ irrespective of the color bands (again, except for the $u$ band).

Two alternative interpretations for this observed departure are (1) the reddening function $k(\lambda)$ is nonlinear for large $A_{\lambda}$, or (2) the selective reddening $E(B-V)$ estimated by SFD is not correct for large extinction. To distinguish between the two possibilities, the regressions of $C_{1}^{m}$ among different color bands are plotted in Figure 8. The dotted lines show the relations expected for the standard extinction law, i.e., $C_{1}^{m}/C_{1}^{r} = k(\lambda_{1})/k(\lambda_{2})$. Note that the scales of the abscissa and ordinate are not identical.

The figure shows that the data points follow the expected relation; no nonlinearity is observed in the extinction curve across the regions of low to high extinction.

We can estimate $k(\lambda)$ relative to the reference band, which we take to be the $r$ band. Defining $k_{0}^{m} = k(\lambda)/k(r)$, we can calculate this quantity from the observed relation $C_{1}^{m}/C_{1}^{r} = k_{0}^{m}$. The results from this analysis are shown in Figure 9. The $k$-values in Table 3 are obtained by multiplying $k(r) = 2.751$ by $k_{0}^{m}$. The observed values of $k(\lambda)$ are consistent with those of the standard extinction curve.

This analysis suggests that $E(B-V)$ of SFD is overestimated for high-extinction regions. Using $C_{1}^{m}/A_{SFD}$ from the $g$ to $z$ bands, we suggest that the true selective reddening can be written as

$$E(B-V)^{\text{true}} = E(B-V)^{\text{SFD}} \times \left\{ 0.87 - 0.13 \text{erf} \left[ \frac{E(B-V)^{\text{SFD}} - 0.19}{0.11} \right] \right\},$$

in terms of $E(B-V)^{\text{SFD}}$. The prediction of this function is presented in Figure 7.
In agreement with the analysis of Arce & Goodman (1999a), we ascribe the overestimate of $E(B-V)$ by SFD to the inaccuracy of the conversion of 100 $\mu$m emission of dust ($D^T$) to selective reddening for high-extinction regions. SFD assumed a simple linear relation between reddening and 100 $\mu$m emission, $E(B-V) = pD^T$, where $p$ is a parameter. To determine $p$, SFD used the relation between the intrinsic $B-V$ color and the Mg2 line index of elliptical galaxies. Of the 389 elliptical galaxies used, only ~20 reside in regions with $E(B-V) > 0.15$, and there are no elliptical galaxies in the region of $E(B-V) > 0.4$. We notice that the fitting of the 100 $\mu$m versus $E(B-V)$ relation of SFD (see their Fig. 6) starts deviating from linear for $E(B-V) \geq 0.15$. From their Figure 6, the value of $\delta(B-V)$ is about $-0.08$ mag for elliptical galaxies whose $E(B-V)$ values are between 0.2 and 0.4; this corresponds to an overestimation of the reddening by 1.2–1.4 when a linear relation is assumed. This is quantitatively consistent with our result. The relation between the reddening and 100 $\mu$m emission should be modified to incorporate the nonlinearity.

We briefly discuss the possible reasons for the difference between 100 $\mu$m emission and reddening from a linear relation. Overestimation of reddening can be caused by the overestimation of 100 $\mu$m emission. According to the procedure of SFD, 100 $\mu$m emission will be overestimated when the color temperature estimated from the ratio of intensities at 100 and 240 $\mu$m is underestimated. If dense clouds have larger dust grains, their equilibrium temperature will be lower even in the same radiation field. This will cause overestimation of the 100 $\mu$m emission. Could the composition be different? SFD assumed an emissivity model with $\epsilon_\nu = \nu^\alpha$ with $\alpha = 2.0$. If there are materials with $\alpha = 1.5$, their temperature will be underestimated. This is the

| BAND | $0.05-0.15$ | $0.15-0.45$ | $0.45-1.00$ |
|------|-------------|-------------|-------------|
| $u$  | 1.130 ± 0.063 | 0.950 ± 0.019 | ...         |
| $g$  | 1.095 ± 0.085 | 0.829 ± 0.015 | 0.718 ± 0.031 |
| $r$  | 1.017 ± 0.055 | 0.818 ± 0.022 | 0.734 ± 0.019 |
| $i$  | 1.028 ± 0.075 | 0.791 ± 0.038 | 0.694 ± 0.023 |
| $z$  | 1.079 ± 0.103 | 0.800 ± 0.057 | 0.681 ± 0.031 |

Table 2: Mean Values of $\Delta m_i/A_{SFD}$

Fig. 7.—Ratio of $\Delta m_i/A_{SFD}$ as a function of $A_{SFD}$ for the five color bands. The meaning of the open circles is the same as in Fig. 5. The mean values for different ranges of $E(B-V)$ (0.05–0.15, 0.15–0.45, and 0.45–1.00) are indicated as horizontal bars, and the empirical fitting function of eq. (2) is shown with dotted curves.
Fig. 8.—Regression of $\Delta m_j$ between different combinations of $u, g, r, i,$ and $z$. The meaning of the open circles is the same as in Fig. 5. The dotted lines are relations expected for the standard extinction law.
same as we have seen. How about mixed temperature along the line of sight? From Figure 2 of SFD the column density will be underestimated when there are two regions at different equilibrium temperatures. This is the opposite from what we have seen. From this brief discussion, the difference of grain size and equilibrium temperatures. This is the opposite from what we have underestimated when there are two regions at different equi-

teration. This is the opposite from what we have underestimated when there are two regions at different equi-

4. SUMMARY

We have tested Galactic extinction using galaxy number counts at low Galactic latitude using the SDSS galaxy sample of Finkbeiner et al. (2004) that covers 200 deg$^2$ from low $E(B - V) = 0.03$ to high $E(B - V) = 1$ extinction regions. The variation

TABLE 3

| Color Band | Standard Extinction Curve | Derived from $\Delta N(m)$ |
|------------|----------------------------|-----------------------------|
| $u$ | 5.155 | 5.611 ± 0.165 |
| $g$ | 3.793 | 3.779 ± 0.045 |
| $r$ | 2.751 | 2.751 (normalization) |
| $i$ | 2.086 | 1.9748 ± 0.015 |
| $z$ | 1.479 | 1.397 ± 0.019 |

of galaxy number counts is consistent with Galactic extinction described by the prediction of SFD for low-extinction regions of $E(B - V) < 0.15$. For high-extinction regions of $E(B - V) > 0.15$, the SFD extinction prescription overestimates the reddening by a factor of up to 1.4, which we interpret as a result of the departure of the linear relation between 100 $\mu$m infrared emission and selective extinction.

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