A Test for Large-Scale Systematic Errors in Maps of Galactic Reddening

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ABSTRACT. Accurate maps of Galactic reddening are important for a number of applications, such as mapping the peculiar velocity field in the nearby universe. Of particular concern are systematic errors which vary slowly as a function of position on the sky, as these would induce spurious bulk flow. We have compared the redenning maps of Burstein & Heiles (BH) and those of Schlegel, Finkbeiner, & Davis (SFD) to independent estimates of the reddening, for Galactic latitudes \(|b| > 10^\circ\). Our primary source of Galactic reddening estimates comes from comparing the difference between the observed \(B - V\) colors of early-type galaxies, and the predicted \(B - V\) color determined from the \(B - V-M_g\) relation. We have fitted a dipole to the residuals in order to look for large-scale systematic deviations. There is marginal evidence for a dipolar residual in the comparison between the SFD maps and the observed early-type galaxy redenning. If this is due to an error in the SFD maps, then it can be corrected with a small (13%) multiplicative dipole term. We argue, however, that this difference is more likely to be due to a small (0.01 mag) systematic error in the measured \(B - V\) colors of the early-type galaxies. This interpretation is supported by a smaller, independent data set (globular cluster and RR Lyrae stars), which yields a result inconsistent with the early-type galaxy residual dipole. BH redenning are found to have no significant systematic residuals, apart from the known problem in the region \(230^\circ < l < 310^\circ\), \(-20^\circ < b < 20^\circ\).

1. INTRODUCTION

Accurate values of Galactic extinction are essential for a number of applications, such as measuring distances and peculiar velocities of galaxies. A small error of only 0.015 mag in the \(R\)-band Galactic extinction corresponds to a systematic distance error of 1% for the fundamental plane distance indicator. When measuring the large-scale bulk motion of galaxies, the small-scale accuracy of reddening maps is not critical, since random errors add to the scatter but do not introduce a systematic bias in the bulk flow. On the other hand, large-scale coherent systematic errors in the redenning would introduce corresponding systematic errors in the bulk flow.

In this paper, we test two redenning maps for such large-scale systematic errors: the redenning maps of Burstein & Heiles (1982, hereafter BH), which are based on neutral hydrogen (for decl. > \(-23^\circ\), Shane-Wirtanen galaxy counts are used to determine dust-to-gas ratios); and the maps of Schlegel, Finkbeiner, & Davis (1998, hereafter SFD), which are based on dust emission measured by \(IRAS\) with dust temperatures determined from DIRBE data. Note that the two maps are completely independent.

There is some evidence that the BH redenning are systematically in error in at least one large coherent region of the sky. Burstein et al. (1987, hereafter B87) found that the BH redenning were overestimates (by a factor of 2) in the region \(230^\circ < l < 310^\circ\), \(-20^\circ < b < 20^\circ\) (hereafter the Vela region). Note that this region lacks a dust-to-gas ratio estimate.

SFD calibrated their redenning maps using the colors of brightest cluster galaxies from Postman & Lauer (1995) and tested their maps with the \(B - V-M_g\) relation and the data of Faber et al. (1989). However, SFD did not test for coherent residuals as a function of longitude. Such residuals are the bane of peculiar velocity work; they are the focus of this paper.

To test the BH and SFD maps, we require a sample of distant objects with standard colors. Our primary sample is the early-type galaxy data set of Faber et al. (1989). We will make use of the tight correlation between \(M_g\) index and \(B - V\) color. Lynden-Bell et al. (1988) used the \(B - V-M_g\) relation to show that putative systematic errors in the BH redenning could not be large enough to explain the bulk flow of 570 km s\(^{-1}\) toward \(l = 307^\circ\), \(b = 9^\circ\). However, Lynden-Bell et al. did not attempt to push this farther and obtain constraints on the accuracy of the BH redenning. This was perhaps due to systematic uncertainties in the \(M_g\) index, which are at the level of \(-0.01\) in \(M_g\) (Davies et al. 1987), equivalent to 0.008 in \(E(B - V)\) or 0.03 in \(B\)-band extinction.

We have recently determined the corrections required to bring \(M_g\) indices from 23 different spectroscopic systems onto a standard system by comparing 1784 repeat \(M_g\) measurements for 418 galaxies (Smith et al. 1997; Hudson et al. 1999). As a result the uncertainties in the corrections to the \(7S\) \(M_g\) systems have been reduced by a factor of 5. This allows us to reexamine the redenning maps with increased accuracy.

There has been much discussion in the literature of the value of redenning at the poles, i.e., the zero point of the redenning.
maps. This zero point is impossible to calibrate using only extragalactic color standards. Fortunately, global zero point errors have no effect on peculiar velocity work since they are absorbed into the zero point of the distance indicator. We make no attempt in this paper to determine the correct zero point of the reddening maps.

The outline of this paper is as follows. In § 2, we use early-type galaxies as reddening estimators, and present our data and method (§ 2.1), results (§ 2.2) and discuss the effect of photometric errors in the $B - V$ data (§ 2.3). In § 3, we constrain the systematic errors in the SFD maps using independent reddening estimates obtained from globular clusters and RR Lyrae stars, and we summarize our results in § 4.

## 2. REDDENING FROM EARLY-TYPE GALAXIES

### 2.1. Data and Method

Our primary data are the early-type galaxies of the “Seven Samurai” (7S) survey (Faber et al. 1989), with $B - V$ colors measured within 67' from B87. However, we use revised $Mg_2$ data for these galaxies, which are corrected for offsets between $Mg_2$ measurements obtained from different telescopes (Hudson et al. 1999). Our corrected $Mg_2$ values agree well with the subset of the 7S data recently published by Trager et al. (1998).

We use only the $B - V$ data with $D_n$ photometric quality of 1, corresponding to random and systematic errors less than 0.02 dex (B87). The data are given in Table 1. Only the first and last four lines of the data are reproduced in the printed version. The full table is accessible electronically. Finally, we limit our analyses to Galactic latitudes $|b| > 10^\circ$. The $B - V - Mg_2$ relation has a scatter of only 0.028 mag. This relation is shown in Figure 1.

If we compare the $B - V - Mg_2$ relations of the subsample of cluster galaxies to the subsample of galaxies in groups (with velocity dispersions [Hudson 1993] less than ~400 km s$^{-1}$) or in the field, we find that the cluster galaxies are redder than group/field galaxies by 0.01 ± 0.004 mag at a given $Mg_2$.

Hudson (1999) shows that Malmquist bias effects can cause offsets between field and cluster samples at this level, even when distance-independent measures ($B - V$ and $Mg_2$) are compared. For the purposes of this paper, however, we are not concerned with the interpretation of this offset. We simply correct the $B - V$ colors of field galaxies by adding 0.01. The conclusions of this paper, however, are not affected if we neglect this correction.

The residuals from the $B - V - Mg_2$ relation for both SFD and BH reddenings are plotted on the sky in an Aitoff projection.
relation to predict the true $B - V$ and compare this with the observed $B - V_{\text{inst}}$ to obtain a reddening estimate

$$E(B - V)_{\text{Ellip}} = (B - V)_{\text{obs}} - [A + B \text{Mg}_2].$$  \hspace{1cm} (1)

where $A$ and $B$ are free parameters. Since our goal is to look for coherent residuals from the SFD and BH maps, we fit the map reddening to these reddening estimates allowing for a correction term. For the form of this correction, we adopt the lowest order spherical harmonic, i.e., a dipole. We have considered both additive and multiplicative dipole corrections to the redenings. We adopt a multiplicative correction, which is perhaps more realistic (e.g., a coherent error in the dust temperature). The reddening estimates are then fitted by

$$E(B - V)_{\text{Ellip}} = (1 + F \cdot \hat{r}) E(B - V)_{\text{map}},$$  \hspace{1cm} (2)

where $E(B - V)_{\text{map}}$ is the predicted reddening given by BH or SFD. $F$ is a dipole vector and $\hat{r}$ is the unit vector toward the galaxy. In practice, these two steps are performed simultaneously.

The residuals around these relations are slightly non-Gaussian, with a tail of blue objects. In order that our fit be robust, we minimize the sum of absolute deviations of the residuals. This is equivalent to fitting the median (Press et al. 1992). We estimate the significance of the dipole coefficients by performing Monte Carlo simulations in which the positions of early-type galaxies are randomized, while their $B - V$ and Mg$_2$ values are kept fixed.

### 2.2. Results

The result of the dipole fits to both SFD and BH are given in Table 2. For the SFD Mg$_2$ fit, we detect a marginally significant dipole (at the 92% CL) of toward $l = 80^\circ$, $b = 23^\circ$ (errors correspond to 66% confidence range). Note that the antipex of this dipole is $l = 240^\circ$, $b = -23^\circ$, which is in the Vela region.

We detect no significant residual dipole in the BH redenings, if the Vela region is excluded from the analysis. (If we

| Sample  | $N_{\text{obj}}$ | Scatter | Map  | Corr$^a$ | $|F|\ $ | $l\ $ | $b\ $ | Prob$^b$ |
|---------|-----------------|---------|------|----------|---------|-------|-------|--------|
| Ellip   | 311             | 0.028   | SFD  | 0.000    | 0.13    | 80    | 23    | 8.4    |
| Ellip$^*$| 296             | 0.031   | BH   | 0.000    | 0.17    | 64    | 17    | 44.7   |
| Ellip$^*$| 296             | 0.028   | SFD  | 0.000    | 0.13    | 94    | 15    | 13.1   |
| Ellip   | 311             | 0.028   | SFD  | 0.010    | 0.07    | 328   | -69   | 57.2   |
| Ellip$^*$| 396             | 0.031   | BH   | 0.010    | 0.11    | 47    | -27   | 87.7   |
| GC + RR | 137             | 0.028   | SFD  | 0.000    | 0.08    | 312   | -47   | 95.0   |
| Ellip + GC + RR | 448 | 0.028 | SFD | 0.000 | 0.05 | 98 | -35 | 38.6 |

$^a$ Correction applied to Northern $E(B - V)$ data.

$^b$ Probability that measured dipole could arise by chance.

$^c$ Excluding the Vela region.
exclude this region from the SFD analysis, the significance of the SFD dipole term drops to 87% CL). The lower significance of the BH dipole compared to SFD should not be misinterpreted as evidence that its residual dipole is lower—it is not—rather the reduced significance is due to the larger scatter in the residuals when BH reddenings are used, which leads to a larger error in the dipole: $|F_{\text{BH}}| = 0.17^{+0.13}_{-0.17}$.

Figure 3 shows the residuals from the $B - V - \text{Mg}_2$ relation as a function of the cosine of the angle from the apex ($l = 80^\circ$, $b = 23^\circ$ for SFD and $l = 64^\circ$, $b = 17^\circ$ for BH).

### TABLE 3

| $l$ | $b$ | $E(B-V)$ | $E(B-V)_{\text{corr}}$ |
|-----|-----|----------|-----------------------|
| 115.70 | −33.10 | 0.058 | 0.044 |
| 128.40 | −23.60 | 0.035 | 0.047 |
| 57.90 | −34.00 | 0.006 | 0.052 |
| 53.20 | −44.30 | 0.074 | 0.048 |
| ... | ... | ... | ... |
| 304.60 | 57.40 | −0.022 | 0.030 |
| 323.40 | 67.50 | −0.020 | 0.035 |
| 123.90 | 18.60 | 0.249 | 0.247 |
| 122.00 | 22.10 | 0.112 | 0.138 |

**Note.**—Table 3 is published in its entirety in the electronic edition of PASP. A portion is shown here for guidance regarding its form and content.

### 2.3. Discussion

We have modeled the residuals with a dipole term. However, it is also possible that the residuals are clustered in a few, smaller scale ($30^\circ$–$60^\circ$) patches on the sky. We have already discussed the Vela region, in which both the BH reddenings as well as those of SFD overestimate the reddening. The region $120^\circ < l < 180^\circ$, $0^\circ < b < 40^\circ$ (hereafter the Camaleopardis region), also stands out in Figure 2 due to its excess of red galaxies. The Camaleopardis region is opposite on the sky to the Vela region, so it is possible that these two regions together are the source of the dipole signal. The sparseness of the data do not allow us to determine whether the residuals are confined to smaller areas, or whether they vary more slowly (like a dipole).

At low Galactic latitudes, systematic errors are expected to be largest, both in the predictions and in the observed colors, due to the problems of contamination by foreground stars in the Milky Way. If we limit the analysis to Galactic latitudes $|b| > 20^\circ$, however, we still find an identical dipole for SFD and a somewhat larger dipole for BH, compared to the results found above for $|b| > 10^\circ$.

So far we have interpreted these residuals as errors in the reddenings. It is possible that systematic errors in the Mg$_2$ data or $B - V$ data are responsible for these residuals. The Mg$_2$ data for the seven spectroscopic systems tabulated by BS were corrected for systematic offsets, but the uncertainty in these corrections was 0.01 mag (Davies et al. 1987). By intercomparison of common data, these Mg$_2$ data have been recorrected and brought onto a common system (Hudson et al. 1999). While the corrections are large (as much as 0.02), the uncertainties in these corrections are now considerably smaller (typically 0.0025 mag). This translates to only 0.002 mag in $E(B-V)$, which is a factor of 5 smaller than the residual dipole. Therefore, systematic errors in Mg$_2$ cannot account for the residuals.

It is also possible that there are systematic errors in the $B - V$ colors. We have performed fits in which we allow for a systematic error in color between galaxies in the northern and southern celestial hemispheres. In Table 2 we also show fits for BH and SFD after a 0.01 mag correction applied to the Northern $B - V$ values. When this correction is applied, the residual dipole terms are small and consistent with zero. Thus, an offset in photometry can account for the residuals in the SFD comparison. In fact, the significance of this photometric correction is somewhat higher than the dipole term fitted above.

As discussed above, we cannot really distinguish between photometric errors in small patches of the sky and large-scale (north-south) photometric offsets. The $B - V$ colors tabulated in BS arise from 10 different photometric systems. Table 4B of BS indicates that, while most of their photometric systems are of high accuracy (better than 0.01 mag in $B - V$), there are several exceptions. Most notable of these is the K3 system...
The K3 system shows a systematic offset of 0.02 mag in $B-V$ and possibly a weak (uncorrected) color term (B87). Note that about half of the galaxies in the Cameleopardis region have $B-V$ colors from the K3 system, so this may account for some of the deviant galaxies in this region. It is beyond the scope of this paper to extract the K3 observations from the merged photometry of B87. We simply note that although one can interpret the residuals as a north-south photometric offset, it is also possible that errors from one or more subsystems could mimic the same effect.

Note that in Figure 2 both BH and SFD have residuals in the same locations (e.g., in the Vela and Cameleopardis regions). Since the two reddening maps are independent, this argues that the primary source of these residuals is due to photometric errors.

Therefore, while the residual dipole in the SFD comparison may be real, we conclude that it is more likely due to photometric errors. An independent sample is required to test this residual dipole more thoroughly.

3. REDDENING ESTIMATES FROM GLOBULAR CLUSTERS AND RR LYRAE STARS

We can perform an independent test of the reddenings using the estimated $E(B-V)$ toward distant globular clusters (GCs) and RR Lyrae stars.

We take GC $E(B-V)$ estimates from the compilation of Harris (1996), but exclude clusters with $|b| < 10$ and distance perpendicular to the Galactic plane, $|Z| < 3$ kpc. This leaves 50 GCs. We find that, in the mean, the estimated reddenings of the GCs are lower than those of SFD by $-0.008 \pm 0.004$ mag. This paper is not concerned with zero-point errors (the monopole term) because errors of this type drop out of many applications such as peculiar velocity studies. We have therefore simply increased all globular cluster $E(B-V)$ by 0.01 mag. The scatter of $E(B-V)$ is 0.027 mag.

We have also used the 86 RR Lyrae stars from the sample of Burstein & Heiles (1978). The data are reproduced in Table 3. Only the first and last four lines of the data are given in the printed version. The full table is accessible electronically. We find, in the mean, that the RR Lyrae sample has $E(B-V)$ lower than the SFD predictions by $-0.016 \pm 0.003$ mag. We have consequently increased all RR Lyrae $E(B-V)$ by 0.01 mag. The scatter around the SFD values is 0.027 mag, the same as found for the GCs and for the residuals from the early-type galaxy $B-V-Mg_2$ relation. The residuals for these two samples are shown in Figure 4.

Both the GC and RR Lyrae samples are sufficiently small that they do not place strong constraints on the residual dipole. Taken together, the best fit dipole is $F = 0.08 \pm 0.07$ toward $l = 312^\circ$, $b = -47^\circ$, although this result is not statistically significant; the GC/RR Lyrae sample is consistent with no residual dipole. Note, however, that this GC/RR F is in the opposite sense to the SFD $F$ found above. We can thus use the combined GC and RR Lyrae sample as an independent test of the early-type $B-V-Mg_2$ dipole. We generate 1000 bootstrap samples of the globular cluster and RR Lyrae solution and project these along $l = 80^\circ$, $b = 23^\circ$, the $B-V-Mg_2$ dipole direction. We obtain a residual as large as the $B-V-Mg_2$ case only 2% of the time. This argues that the $B-V-Mg_2$ dipole found above is more likely to be due to a systematic photometric offset between north and south. In any case, it establishes the $B-V-Mg_2$ dipole result as the upper limit to the large-scale errors in the SFD maps.

4. SUMMARY

We have compared the SFD and BH reddenings to an independent reddening estimate, namely the difference between the observed $B-V$ colors of early-type galaxies, and the predicted $B-V$ color determined from the $B-V-Mg_2$ relation. Specifically, we fitted a dipole to the residuals in order to look for large-scale systematic deviations.

For BH, we find no significant evidence for a dipole once the Vela region is excluded. For SFD, we find marginal (92\% CL) evidence of a dipole in the $E(B-V)$ residuals. We are unable to distinguish between two possibilities: (1) a small multiplicative dipolar correction term to the SFD reddenings (a 13\% increase toward $l = 80^\circ$, $b = 23^\circ$, and a corresponding decrease on the other side of the sky), or (2) a small photometric error of 0.01 mag in $E(B-V)$ between northern and southern hemispheres. We argue that the latter option is more likely, for the following reasons: (1) 0.01 mag is well within the expected photometric errors, and (2) the dipole for the BH reddenings is very similar to that of SFD in both amplitude and direction, even though the BH and SFD maps are independent. The sparseness of the data do not allow us to determine whether the residuals are actually due to smoothly varying large-scale photometric errors.
(dipolar) errors in SFD reddenings or in the photometry, or whether the problem lies in specific regions, e.g., the Vela region and/or the Cameleopardis region.

The sparser globular cluster and RR Lyrae reddening data are consistent with no dipole residual. Nevertheless, from this data set, we can exclude the dipole obtained from the early-type galaxies at the 98% confidence level.

Taken together, these results suggest that there are no large-scale errors in the SFD maps or in the BH maps (outside the Vela region). The 13% dipole correction to SFD should be taken as a reasonable upper limit on any large-scale error in those maps.

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