OUR DUSTY MILKY WAY: CONSTRAINING THE DUST DISTRIBUTION IN THE DISK OF OUR GALAXY

Gail Zasowski[1]
Advisor: Steven R. Majewski[1]
[1]Department of Astronomy, University of Virginia, Charlottesville, VA, 22904
gz2n@virginia.edu

ABSTRACT

The interstellar dust permeating our home galaxy, the Milky Way, strongly affects astronomical observations and creates difficulties for studies of the Galaxy on both large and small scales. Our ability to accurately characterize both the large-scale structure of the Galaxy, and the smaller regions embedded within it, relies on our knowledge of the intrinsic nature and distribution of the intervening dust. We have developed a technique to obtain simultaneous distance and extinction information towards individual stars, using the fact that the majority of stars in the Galactic disk share a common intrinstic spectral energy distribution (SED) in the infrared. Deviations of the observed SEDs are then attributed to wavelength-dependent extinction along the line of sight. We apply this technique to stars contained in several large infrared catalogs; the enormous quantity of data points produces two- and three- dimensional Galactic extinction maps with high angular and spatial resolution and good signal-to-noise ratio. These maps will facilitate large-scale Galactic structure studies as well as provide better corrections of observational studies of stellar clusters, star-forming regions, and other elements crucial to a full understanding of the composition and history of our Galaxy and astronomical neighborhood.

Introduction

Our home galaxy of the Milky Way is, in some ways, one of the least-understood galaxies. This seemingly ironic truth stems from the fact that our sun is embedded in one of the denser regions of the galaxy—the disk—and so in all directions, our view of the Milky Way is blocked by the Milky Way itself (specifically, by the dust that permeates all of space between the stars). There are many scientifically interesting and relevant features that can be studied with less obscuration from dust above and below our “horizon” of the Galactic disk, but the disk itself contains a large fraction of the mass in the Galaxy and a large number of essential features–star formation regions, stellar clusters, giant molecular clouds, and spiral arms, to name a few. So knowledge of the disk components and structure is essential to an understanding of full Galactic structure, kinematics, and history.

The dust in the Galactic disk affects astronomical observations in two main ways. The first is simply a reduction in the amount of light reaching Earth from some distant object, caused by absorption or scattering of photons by the dust grains. This dimming due to dust is called *extinction* (as opposed to the dimming due to distance). This light-reduction by dust is wavelength-dependent, with blue light being preferentially scattered from the line of sight, so the second effect of dust is termed *reddening*. Astronomical objects viewed through dust thus appear both dimmer and redder than they intrinsically are, and these effects must be corrected for when analyzing data.

The difficulty with these corrections is that the relative effects of distance and dust towards an object are often difficult to disentangle, and the situation becomes even more complex when the object in question is, e.g., a star formation region with unknown physical effects of its own. Large-scale interstellar extinction maps have been made in a variety of ways (e.g. cold dust emission, statistical star counts, and HI emission; Schlegel et al. 1998; López-Corredoira et al. 2002; Lockman 2002) and are intended to provide a measure of the interstellar extinction towards any location on the sky. To date, these maps suffer from a number of problems, including low resolution and unreliability in high-extinction regions (like the Galactic disk), but the issue most relevant to this study is that these maps, by and large, record only the total line-of-sight extinction. This means that astronomers using the maps do not have any information on what fraction of the dust is actually affecting their observations, and using the recorded *total* amount can lead to over-correction. In order for reliable studies of inter-Galactic objects to be performed, the true three-dimensional dust distribution must be established, which is the eventual goal of this project.

This short paper is organized as follows—in the next section, we will provide a description and justification of our method for calculating extinction. Then we will briefly describe the large stellar surveys to which we apply our technique in order to produce maps and to study Galactic structure. Finally, we will show some examples of our results so far and discuss the future implications and applications of this study.

Description of Method

Qualitative Description

At the heart of our method is the assumption that the majority of stars in the Galactic disk (giant stars, stellar type K) share a common intrinsic spectral energy distribution (SED) in the infrared. In the limit that stars can be considered blackbodies, this statement is a result of the fact that infrared observation bands probe the Rayleigh-Jeans tail of the stellar SEDs. Thus the slope of stellar infrared SEDs is constant, and the infrared colors (the differences between brightnesses in two bands, measured in magnitudes) should be consistent from star to star. Of course, stars are not perfect blackbodies, especially the cooler stars like K giants, so we quantify our assumption using detailed theoretical stellar isochrones[1] (Girardi et al. 2002). We confirm the intrinsically small spread in infrared colors (typically $\lesssim 0.1$ mag) and hence the validity of this method. It is worth noting that this "color excess" technique has been employed by previous studies (e.g. Lombardi & Alves 2001; Lucas et al. 2007), but these have not utilized the large number of infrared bands and the long wavelength baseline of this study (see next section).

Color is a distance-independent measure, so any observed color difference, or reddening, can be attributed to reddening by dust as described above. This reddening is converted into an extinction (in magnitudes) using the extinction law of Indebetouw et al. (2005), who find the relationship between absolute extinction and selective extinction (reddening) to be nearly constant in the infrared across a wide variety of astrophysical environments.

In order to establish the full three-dimensional dust distribution, we use "red clump" (RC) stars, hydrogen-shell burning stars with a well-constrained absolute magnitude (intrinsic brightness). RC stars are easily identified in color-magnitude diagrams (Figure 1) and are extremely useful as standard candles. Knowing the absolute magnitude as well as the amount of dust individually to these stars allows us to determine a distance range for the intervening dust; a large sample of RC stars filling a three-dimensional volume probes dust at a variety of distances and builds a picture of the true distribution of the interstellar dust.

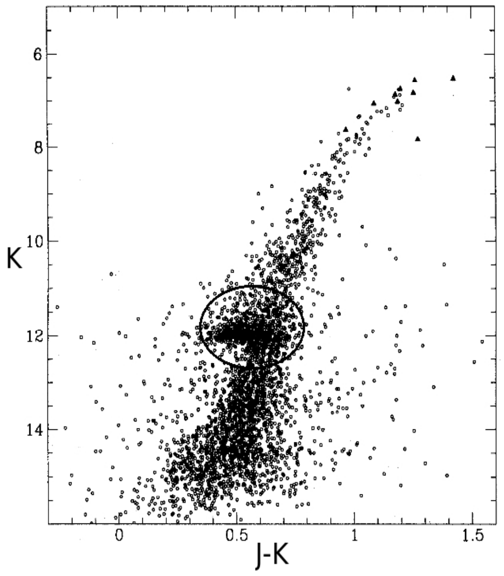


Fig. 1.— Example of an infrared color-magnitude diagram (CMD). This CMD is of the low-reddening globular cluster 47 Tucanae (Montegriffo et al. 1995), so there is very little dust extinction and no "smearing" due to distance variations. The ellipse indicates the red clump (RC) stars.

Quantitative Description

Our calculation of the extinction A_{Ks} (i.e. extinction in the Ks band) utilizes all available data of a given star in the infrared bands J, H, Ks, [3.6], [4.5], [5.8], and [8.0], where the final four re-

---

[1] http://stev.oapd.inaf.it/cgi-bin/cmd

fer to the wavelengths (in μm) of the Spitzer Space Telescope bands (see next section). The advantages of using multiple bands include an increased robustness to random fluke data and the ability to uniformly analyze a larger number of stars, some of which are not detected in all bands.

We begin by defining the infrared colors as $c_i \equiv$H-J,H-Ks,...,H-[8.0]. A subscript of "obs" indicates the actual observed measurement, "mod" refers to the theoretical isochrone color, "the(ory)" is the expected color after some (unknown) reddening A_{Ks}, and the σ's represent the associated uncertainties. We also define k_i ($\pm\sigma_{k_i}$)$\equiv \frac{E_i}{A_{Ks}}$, where E_i is the observed reddening.

The expression for the standard χ^2 measure-of-agreement (between c_j^{obs} and c_j^{the}) is

$$\chi^2 = \sum_j \frac{[c_j^{obs} - c_j^{the}]^2}{\sigma_j^2}. \quad (1)$$

Taking the derivative to find the minimizing value of A_{Ks}, we find

$$A_{Ks} = \frac{\sum_j \frac{k_j}{\sigma_j^2}(c_j^{obs} - c_j^{mod})}{\sum_j \frac{k_j^2}{\sigma_j^2}}, \quad (2)$$

where A_{Ks} is the measure of extinction towards any individual star. This is in contrast to other extinction-mapping methods, which use large-scale emission and have higher angular resolution limits.

To calculate distance, we use the simple distance-modulus relation

$$Ks - M_{Ks} = 5\ \log d - 5 + A, \quad (3)$$

where Ks is the observed magnitude in the Ks band, M_{Ks} is the absolute magnitude, d is the distance in parsecs, and A is the extinction. Normally we do not know M_{Ks}, but in the case of RC stars, it is fairly well-constrained ($M_{Ks,RC} \sim$ -1.6 ± 0.1 mag; López-Corredoira et al. 2002), and we easily calculate a distance range for the dust observed towards each individual RC star.

Description of Data

To create extinction maps with high angular and spatial resolution, we take advantage of the enormous infrared sky surveys recently performed using both space- and ground-based facilities. When combined, these surveys provide multi-wavelength observations of hundreds of millions of stars, a significant fraction of which are RC stars which we use to probe the interstellar dust distribution to distances of several kiloparsecs from our sun.

2MASS

The 2 Micron All Sky Survey (Skrutskie et al. 2006), completed in 2001, used dedicated telescopes in Arizona (USA) and Chile to survey 99.998% of the sky in the J (1.25 μm), H (1.65 μm), and Ks (2.17 μm) near-infrared bandpasses. The data products of this survey have proved invaluable, particularly to studies of regions previously (optically) obscured by dust. For this work, the 2MASS photometry provides the shorter-wavelength measurements, more sensitive to stellar temperature but also more susceptible to detectable reddening.

GLIMPSE

GLIMPSE (Galactic Legacy Infrared Mid-Plane Survey Extraordinaire; e.g. Benjamin et al. 2003) is a near- to mid-infrared survey of the Galactic disk, undertaken using the Infrared Array Camera (IRAC) on board the Spitzer Space Telescope. This camera has sensitivity at four wavelengths—3.6, 4.5, 5.8, and 8.0 μm—which cover a variety of interesting interstellar spectral features, including emission from warm dust and polycyclic aromatic hydrocarbons (PAHs). GLIMPSE, along with its successor and companion surveys GLIMPSE-II and GLIMPSE-3D, covers the inner two-thirds of the Galactic disk within 1° of the midplane (up to 4° in the central bulge regions). For our purposes, these data give us a much longer baseline in wavelength with which to detect reddening and allow us to include stars too cool to be detected with all of the shorter-wavelength 2MASS bands.

UKIDSS GPS

The UKIRT Infrared Deep Sky Survey is an currently-running infrared sky survey project, similar to 2MASS in band wavelengths but with two differences—it detects sources ~ 3 magnitudes fainter but covers less area. The UK Infrared Telescope (UKIRT) in Hawaii provides the data. Of particular interest to us is its Galactic Plane Survey project (GPS; Lucas et al. 2007), which overlaps much of GLIMPSE's coverage. As the data products become available to the non-ESO science community, we will replace our 2MASS photometry with the GPS data, increasing both the total number of usable sources and the average data-quality of all our sources.

Examples

Color-Magnitude Dereddening

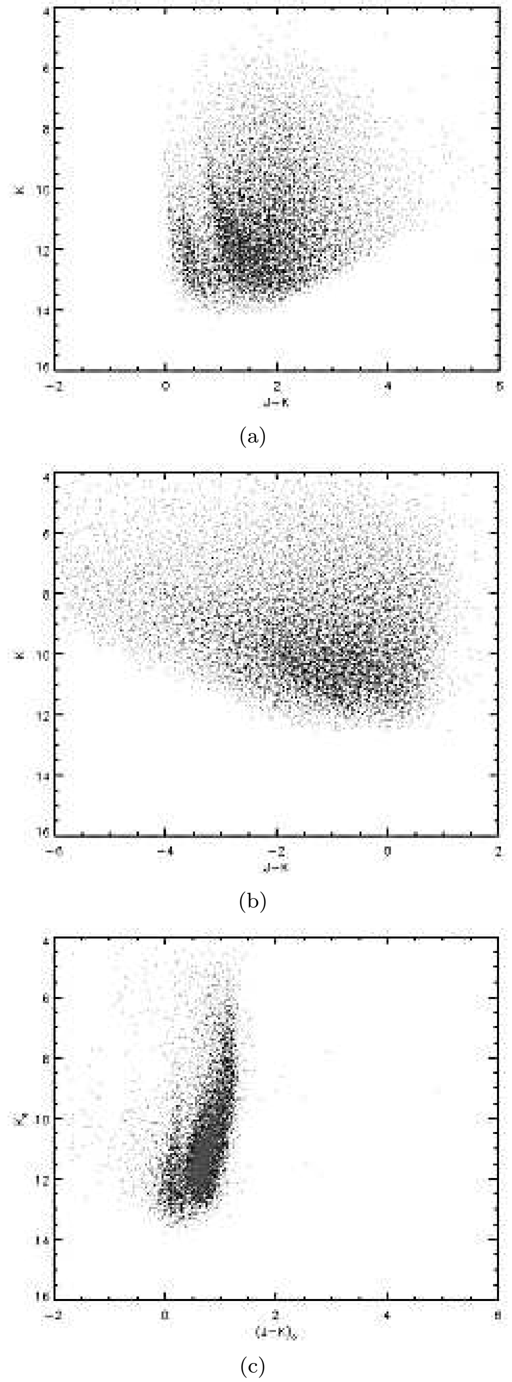
While Figure 1 shows a CMD with very low intrinsic reddening, Figure 2 contains a highly-reddened CMD and the result of our dereddening technique.

Panel 2(a) contains the most reliable unprocessed 2MASS data for a 2 deg^2 field centered at galactic coordinates (l,b)=(307.5,0)°. Notice the clear presence of the red clump ($Ks \sim$ 9-13.5, $(J-Ks) \sim$ 0.75-1.5), smeared vertically due to distance and both vertically and horizontally due to dust. We calculate extinction to each star shown, but the RC stars are the ones most useful for three-dimensional mapping. Panel 2(b) shows the same dataset "corrected" using the Schlegel et al. (1998) extinction maps. As these maps record the *total* extinction along the line of sight, our relatively nearby stars are over-corrected to unphysically blue colors. Finally, Panel 2(c) contains the data dereddened using our individual-star method. The RC has been returned to its proper color ($(J-Ks)$ $\sim$ 0.75) but still has a vertical extension—this is due to the spread in distances among the RC stars. The red giant branch and main-sequence turn-off features are also clearly visible.

Mapping

Figure 3 contains an example and comparison of extinction mapping. The middle panel (Figure 3(b)) is our map, calculated from RC and red giant branch stars, in linear grayscale showing A_{Ks} from 0 to 3 mag (corresponding to $\gtrsim$ 40 mag in V band). The top panel is the map derived from cool dust emission by Schlegel et al. (1998), and the bottom panel is the ^{13}CO (J=1→0) emission intensity map produced by the Galactic Ring Survey (Jackson et al. 2006). ^{13}CO is generally considered a good tracer of interstellar dust and has the advantage that spectral detections also contain velocity information.

Though our middle panel is generally similar to the commonly used Schlegel map (top), our use of an enormous number of stellar sightlines allows for much higher angular resolution and for the detection of weaker nearby clouds. As an example, notice the filaments clustered around (l,b) $\sim$ (26,0.8)° in our map. The same feature appears in the lower ^{13}CO map but not in the Schlegel one. This absence suggests that these filaments are relatively nearby (and so are "drowned out" by the increased extinction recorded in the Schlegel map at greater distances), and the velocity information



(a)

(b)

(c)

Fig. 2.— 2MASS data of a 2 deg^2 field centered at (l,b)=(307.5,0)°. (a) The raw $J-Ks, Ks$ data, (b) the same data "corrected" using the extinction maps of Schlegel et al. (1998), (c) the same data dereddened using our method (same axes as (a)), showing the main-sequence turn-off, the red clump, and the giant branch. See text for details.

contained in the ^{13}CO map allows us to calculate the radial velocity of the interstellar medium (ISM) at that spatial location. This type of kinematic information is essential for studies of Galactic structure and dynamics.

Even gaps in our data are informative when combined with e.g. the ^{13}CO map. For instance, the dark patch at (l,b) $\sim$ (23.5,-0.2)° is due to a lack of stars at that position, not genuine low extinction. This indicates that stars are obscured by a nearby, very dense cloud, which appears as a bright knot in both the Schlegel and ^{13}CO maps. Neither contain distance information on the cloud, but the distribution of our stars surrounding the area will constrain its location.

Future Studies

This project has potential for applications in many diverse areas. The following are a few of our plans and goals for the future.

Large-Scale Galactic Structure

As alluded to in the Introduction, some of the most important large-scale features of the Galaxy—e.g. spiral arms, a central bar, the disk warp—are not very well-understood because they are features of the dense disk itself, in which we are embedded. Three-dimensional extinction maps, and extinction-corrected starcount maps, have the ability to directly show the variations in stellar and ISM density corresponding to these features. At least two spiral arms (Scutum, Sagittarius) are theorized to have tangent points within the volume covered by our data, and the poorly-constrained near endpoint of the central bar lies near the edge of the coverage (but should be visible once the 2MASS data are supplanted by those of UKIDSS GPS).

Stellar Clusters

Globular and open stellar clusters are among the most convenient places to study details of stellar formation and evolution, as the stars have the same distance, reddening, age, and metallicity, so establishing good distances and reddenings is crucial. Application of our method to well-studied clusters will provide a means of fine calibration, and application to clusters with poorer data will improve current distance estimates. An additional advantage of our method is the ability to study differential reddening throughout a single cluster, which has been proposed as an explanation for some observed cluster oddities (Raimondo et al. 2002).

Extinction Law

Throughout this study we have assumed a constant infrared extinction law, using the values tabulated by Indebetouw et al. (2005). In general this is considered safe, but there are indications of deviations from this law in the Galactic bulge or in dense cores (e.g Nishiyama et al. 2008; Huard et al. 2006). So ideally we would like to calculate the extinction law of a given region before calculating the extinction. Because our dataset is so similar to the recent work of Indebetouw et al. (2005), we plan to recreate their method for each ~ 0.5 deg^2 field to estimate the relative extinction $A_{[\lambda]}/A_{Ks}$ and the color excess ratio $E_{[\lambda]-Ks}/E_{J-Ks}$ for our six wavelengths (λ) besides Ks.

Not only will this approach make our dereddening and dust measurements more accurate, but the spatial variation of the extinction law is itself a very interesting phenomenon. It is directly related to the physical characteristics, including chemical compositional and density, of the individual dust grains comprising the ISM.

We have developed a technique to calculate reddening towards individual stars in a robust and consistent way; applied to certain useful stellar populations with well-constrained absolute magnitudes, this technique allows for full three-dimensional mapping of the interstellar dust and stellar densities. The wide variety of potential applications—from large-scale Galactic structures to μm-sized dust grain composition—offer the opportunity to vastly improve our understanding of our home galaxy and astronomical neighborhood.

REFERENCES

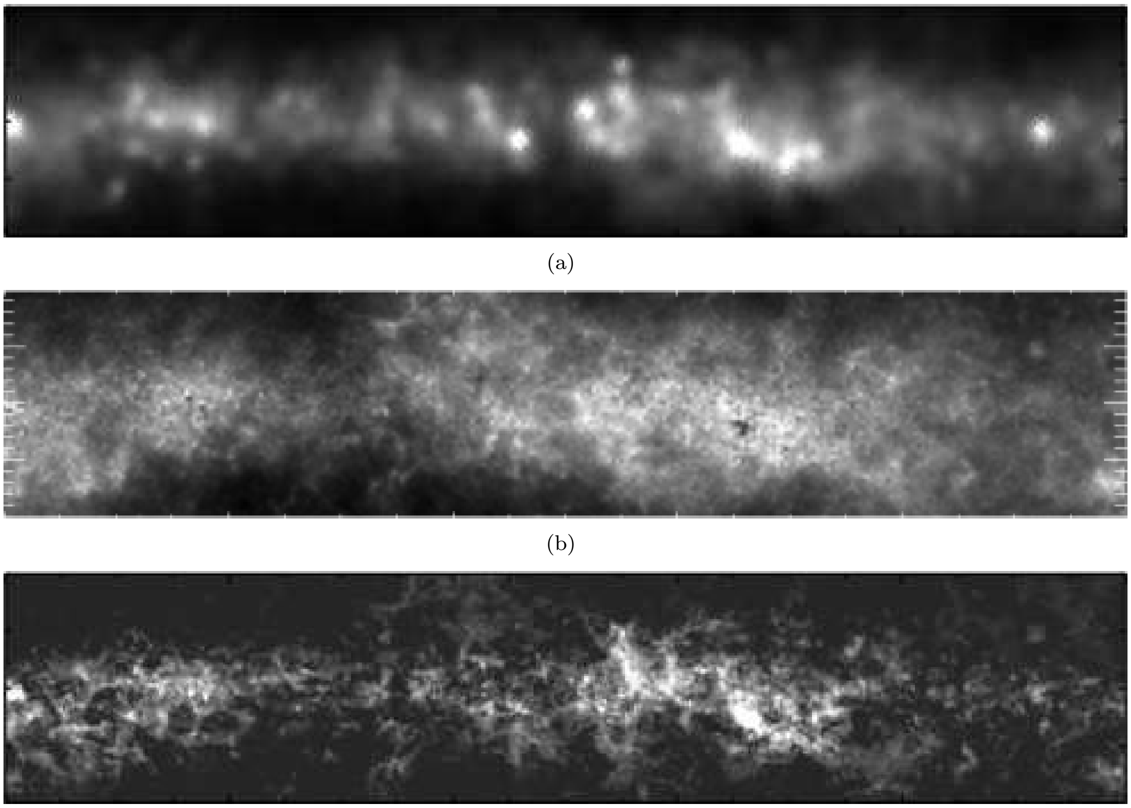
Benjamin, R. A., Churchwell, E., Babler, B. L., et al. 2003, PASP, 115, 953

Girardi, L., Bertelli, G., Bressan, A., et al. 2002, A&A, 391, 195

Huard, T. L., Pontoppidan, K. M., Boogert, A., Knez, C., & Shirley, Y. L. 2006, in Bulletin of the American Astronomical Society, Vol. 38, Bulletin of the American Astronomical Society, 1055–+

Indebetouw, R., Mathis, J. S., Babler, B. L., et al. 2005, ApJ, 619, 931

Jackson, J. M., Rathborne, J. M., Shah, R. Y., et al. 2006, ApJS, 163, 145



(a)

(b)

(c)

Fig. 3.— Section of galactic disk extending from *l*=30° (left) to *l*=20° (right), and *b* ranging from -1 to 1°. (a) Extinction map of Schlegel et al. (1998), (b) extinction map using our method, (c) ^{13}CO (J=1→0) emission map (Jackson et al. 2006). See text for details.

Lockman, F. J. 2002, in Astronomical Society of the Pacific Conference Series, Vol. 276, Seeing Through the Dust: The Detection of HI and the Exploration of the ISM in Galaxies, ed. A. R. Taylor, T. L. Landecker, & A. G. Willis, 107–+

Lombardi, M. & Alves, J. 2001, A&A, 377, 1023

López-Corredoira, M., Cabrera-Lavers, A., Garzón, F., & Hammersley, P. L. 2002, A&A, 394, 883

Lucas, P. W., Hoare, M. G., Longmore, A., et al. 2007, ArXiv e-prints, 712

Montegriffo, P., Ferraro, F. R., Fusi Pecci, F., & Origlia, L. 1995, MNRAS, 276, 739

Nishiyama, S., Nagata, T., Tamura, M., et al. 2008, ArXiv e-prints, 802

Raimondo, G., Castellani, V., Cassisi, S., Brocato, E., & Piotto, G. 2002, ApJ, 569, 975

Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525

Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163

This 2-column preprint was prepared with the AAS LaTeX macros v5.2.