THE BOLOCAM GALACTIC PLANE SURVEY. VIII. A MID-INFRARED KINEMATIC DISTANCE DISCRIMINATION METHOD

Timothy P. Ellsworth-Bowers1, Jason Glenn1, Erik Rosolowsky2, Steven Mairs3, Neal J. Evans II4, Cara Batterby1, Adam Ginsburg1, Yancy L. Shirley5,6, and John Bally1

1 CASA, University of Colorado, UCB 389, University of Colorado, Boulder, CO 80309, USA; timothy.ellsworthbowers@colorado.edu
2 Department of Physics and Astronomy, University of British Columbia Okanagan, 3333 University Way, Kelowna, BC V1V 1V7, Canada
3 Department of Physics and Astronomy, University of Victoria, 5800 Finnerty Road, Victoria, BC V8P 1A1, Canada
4 Department of Astronomy, University of Texas, 1 University Station C1400, Austin, TX 78712, USA
5 Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA

Received 2013 February 8; accepted 2013 April 15; published 2013 May 22

ABSTRACT

We present a new distance estimation method for dust-continuum-identified molecular cloud clumps. Recent (sub-)millimeter Galactic plane surveys have cataloged tens of thousands of these objects, plausible precursors to stellar clusters, but detailed study of their physical properties requires robust distance determinations. We derive Bayesian distance probability density functions (DPDFs) for 770 objects from the Bolocam Galactic Plane Survey in the Galactic longitude range 7.5° ≤ ℓ ≤ 65°. The DPDF formalism is based on kinematic distances, and uses any number of external data sets to place prior distance probabilities to resolve the kinematic distance ambiguity (KDA) for objects in the inner Galaxy. We present here priors related to the mid-infrared absorption of dust in dense molecular regions and the distribution of molecular gas in the Galactic disk. By matching a numerical model of Galactic mid-infrared emission and simple radiative transfer, we match the morphology of (sub-)millimeter thermal dust emission with mid-infrared absorption to compute a prior DPDF for distance discrimination. Selecting objects first from (sub-)millimeter source catalogs avoids a bias towards the darkest infrared dark clouds (IRDCs) and extends the range of heliocentric distance probed by mid-infrared extinction and includes lower-contrast sources. We derive well-constrained KDA resolutions for 618 molecular cloud clumps, with approximately 15% placed at or beyond the tangent distance. Objects with mid-infrared contrast sufficient to be cataloged as IRDCs are generally placed at the near kinematic distance. Distance comparisons with Galactic Ring Survey KDA resolutions yield a 92% agreement. A face-on view of the Milky Way using resolved distances reveals sections of the Sagittarius and Scutum–Centaurus Arms. This KDA-resolution method for large catalogs of sources through the combination of (sub-)millimeter and mid-infrared observations of molecular cloud clumps is generally applicable to other dust-continuum Galactic plane surveys.

Key words: dust, extinction – Galaxy: kinematics and dynamics – Galaxy: structure – infrared: ISM – ISM: clouds – stars: formation

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Recent (sub-)millimeter surveys of the Galactic plane (ATLASGAL, Schuller et al. 2009; Hi-GAL, Molinari et al. 2010; BGPS, Aguirre et al. 2011) have detected tens of thousands of molecular cloud cores and clumps in thermal dust emission. As plausible precursors to stellar clusters, OB associations, or smaller stellar groups, molecular cloud clumps can yield clues about the formation of massive stars (McKee & Ostriker 2007). The masses and temperature profiles of these objects are key to unraveling this process. Recent work has sought to measure these quantities (Russell et al. 2011; Eden et al. 2012), but a robust and comprehensive tally does not yet exist.

Derivation of masses for molecular cloud clumps from dust continuum data requires an estimate of the heliocentric distance to each object and the temperature of the emitting dust. Analysis of Herschel Hi-GAL data is beginning to yield temperature maps of the Galactic plane (Peretto et al. 2010; Battersby et al. 2011). While a detailed understanding of the interplay between dust temperature and the environment and evolution of molecular cloud clumps is important, variations in the assumed dust temperature by a factor of two only produce a factor of a few difference in the mass derived from (sub-)millimeter observations. In contrast, the derived mass of a molecular cloud clump is proportional to the square of its heliocentric distance; accurate distance estimates play a far larger role in the mass calculation. Recent studies of isolated regions, with well-determined distances, such as Perseus and Ophiuchus (Ridge et al. 2006; Enoch et al. 2006; Rosolowsky et al. 2008), have unveiled many properties of molecular cloud cores in recent years (Enoch et al. 2007; Schnee et al. 2010). To gain similar insight into the larger molecular cloud clumps seen spread throughout the Galactic plane, a robust method for distance determinations for large data sets is required, because the distances to most clumps are subject to the kinematic distance ambiguity (KDA).

The most straightforward method for estimating the heliocentric distance (\(d_0\)) to a molecular cloud clump is to project its observed line-of-sight velocity (\(v_{LSR}\)), derived from molecular line Doppler shifts, onto a Galactic rotation curve. These kinematic distances are generally unique for the outer Galaxy, but inner Galaxy sources are subject to the KDA, a projection effect of the orbital motion for objects within the solar circle (\(R_0\)). A line of sight intersecting a circular orbit at Galactocentric radius \(R_{gal} < R_0\) crosses that orbit twice, each with different spatial velocities but both with the same \(v_{LSR}\). Various techniques have been suggested for resolving the KDA (21 cm H\textsc{i} absorption: Anderson & Bania 2009, Roman-Duval et al. 2009; the presence
of mid-infrared dark clouds: Rathborne et al. 2006, Peretto & Fuller 2009; H₂CO absorption: Sewilo et al. 2004; and near-infrared extinction: Marshall et al. 2009, Foster et al. 2012; this paper presents a method based on comparing mid-infrared extinction with (sub-)millimeter emission.

Appearing as dark absorption features against a bright mid-infrared background, infrared dark clouds (IRDCs) offer a practicable means for resolving the KDA. IRDCs are most striking against the broad, diffuse Galactic emission near infrared wavelengths (cf. Foster et al. 2012). Studies of IRDCs at (sub-)millimeter wavelengths reveal that they are dense molecular cloud clumps (Johnstone et al. 2003; Rathborne et al. 2006; Battersby et al. 2010, 2011). As extinction features, IRDCs must lie in front of enough mid-infrared emission to be visible. It is possible to a priori assign the near kinematic distance for the darkest clouds (e.g., Butler & Tan 2009; Peretto & Fuller 2009), but recent work by Battersby et al. (2011) has shown that molecular cloud clumps may be visible as slight intensity decrements in the mid-infrared at the far kinematic distance despite not being dark enough to be cataloged as IRDCs. To encompass this second set of objects, we classify all dust-continuum-identified molecular cloud clumps with mid-infrared intensity decrements of any amount as Eight-Micron Absorption Features (EMAFs), whether cataloged as either an IRDC or not. These constitute a generalized collection of cold molecular cloud clumps identified first by dust-continuum emission and then checked for infrared absorption. The EMAF definition excludes objects extensively undergoing the later stages of star formation or that are exposed to strong ultraviolet radiation, as both processes excite polycyclic aromatic hydrocarbon (PAH) emission near λ = 8 μm, rendering invisible any absorption. Investigating the mid-infrared properties of molecular cloud clumps based on this classification avoids a bias toward the darkest, nearby IRDCs.

This paper presents a quantitative distance estimation technique for molecular cloud clumps based on Bayes’ Theorem. A distance probability density function (DPDF) is computed using a distance likelihood derived from kinematic information (observed VLSR) and prior probabilities, based on ancillary data sets that are applied in an effort to resolve the KDA. We present here two such priors. The first involves the comparison between observed mid-infrared absorption and millimeter emission of individual molecular cloud clumps, and the second is based on the Galactic-scale distribution of molecular gas. In addition to those described here, any number of additional priors may be applied to constrain the distance estimate.

The apparent optical depth of an EMAF calculated naively from mid-infrared images is likely less than the true value due to diffuse 8 μm emission lying between the cloud and the observer. By parameterizing the amount of total mid-infrared emission along a line of sight lying in front of a molecular cloud clump as the “foreground fraction” (f_{foreground}), simple radiative transfer arguments may be used to derive the true optical depth. The recent numerical Galactic infrared emission model of Robitaille et al. (2012) offers an estimate of f_{foreground} as a function of d_{⊙} in the Galactic plane. The maximum likelihood distance to a molecular cloud clump may be derived by comparing the optical depth calculated from (sub-)millimeter thermal dust continuum data with the absorption optical depth derived from the mid-infrared images and f_{foreground}(d_{⊙}). This comparison generates a DPDF that takes into account Galactic-scale conditions along a given line of sight, including spiral structure. A DPDF derived in this manner contrasts the widely used “step-function” method whereby a molecular cloud clump is automatically assigned the near kinematic distance upon association with a cataloged IRDC.

The methodology presented here is valid only for molecular cloud clumps that exhibit mid-infrared absorption, and therefore is but one means for distance discrimination for large catalogs of dust-continuum-identified objects. We present an automated means for deriving Bayesian DPDFs for mid-infrared dark molecular cloud clumps detected by the Bolocam Galactic Plane Survey (BGPS), but this method is applicable to all (sub-)millimeter Galactic plane surveys.

This paper is organized as follows. Section 2 describes the data sets used. The DPDF formalism is described in Section 3. Section 4 outlines the generation of prior DPDFs for EMAFs. Results from the Bayesian DPDFs are presented in Section 5. Implications of this work are discussed in Section 6, and conclusions are presented in Section 7.

2. DATA SETS

2.1. The Bolocam Galactic Plane Survey

The BGPS (Aguirre et al. 2011; Ginsburg et al. 2013) is a λ = 1.1 mm continuum survey covering 170 deg² at 33′′ resolution. The BGPS was observed with the Bolocam instrument at the Caltech Submillimeter Observatory (CSO) on Mauna Kea. It is one of the first large-scale blind surveys of the Galactic plane in this region of the spectrum, covering −10° ≤ ℓ ≤ 90° with at least |b| ≤ 0.5, plus selected regions in the outer Galaxy. For a map of BGPS V1.0 coverage and details about observation methods and the data reduction pipeline, see Aguirre et al. (2011, hereafter A11).

From the BGPS V1.0 images, 8358 millimeter-wave dust-continuum sources were identified using a custom extraction pipeline. The BGPS catalog (Bolocat) contains source positions, sizes, and flux densities extracted in various apertures, among other quantities (see Rosolowsky et al. 2010 for complete details). BGPS V1.0 pipeline products, including image mosaics and the catalog, are publicly available. For this work, we utilized the flux densities measured in a 40′′ top-hat aperture, which has the same solid angle as the BGPS 33′′ FWHM Gaussian beam (Ω = 2.9 × 10⁻⁸ sr), in addition to the map data. A flux calibration multiplier of 1.5 ± 0.15 was applied to both Bolocat and the image mosaics to correct a V1.0 pipeline error (see A11 and Ginsburg et al. 2013 for a full discussion).

The BGPS data pipeline removes atmospheric signal using a principle component analysis technique that discards time-stream signals correlated spatially across the bolometer array. This effectively acts as an angular filter, attenuating angular scales comparable to or larger than the array field of view (FOV; see A11, their Figure 15). The implication is that the BGPS is not sensitive to scales larger than 6′. The effective angular size range of detected BGPS sources therefore corresponds to anything from molecular cloud cores up to entire clouds depending on the heliocentric distance (Dunham et al. 2011). In this work we refer to BGPS objects as “molecular cloud clumps” for simplicity, but recognize that distant sources are likely larger structures.

7 Available through IPAC at http://fsc.ipac.caltech.edu/data/BOLOCAM_GPS
Table 1

| Species | Transition | $\nu$ (GHz) | Resol.* | $n_{\text{eff}}$ (cm$^{-3}$) | $N_{\text{BGPS}}$ | Reference |
|---------|------------|-------------|---------|-----------------------------|----------------|-----------|
| HCO$^+$ | $J = 3\rightarrow 2$ | 267.6 | 28 | $10^4$ | 6194 | 1 |
| N$_2$H$^+$ | $J = 3\rightarrow 2$ | 279.5 | 27 | $10^3$ | 6194 | 1 |
| CS      | $J = 2\rightarrow 1$ | 97.98 | 64 | $5 \times 10^3$ | 553 | 2 |
| NH$_3$  | (1,1)      | 23.69 | 31 | $10^3$ | 631 | 3 |

Notes.

* Beam FWHM.

† Approximate effective density for line excitation at $T = 20$ K (Evans 1999).

‡ Number of unique BGPS sources observed in this line.

References. (1) Y. L. Shirley et al. 2013, in preparation; (2) Y. Shirley 2012, private communication; (3) Dunham et al. 2011.

2.2. Spectroscopic Follow-up of BGPS Sources

Several spectroscopic follow-up programs have been conducted to observe BGPS sources in a variety of molecular emission lines that trace the dense gas associated with molecular cloud clumps. These surveys provide both kinematic and chemical information, and are typically beam-matched to the BGPS to facilitate comparison to the dust-continuum data. From these observations, a line-of-sight velocity ($v_{\text{LSR}}$) was successfully fitted for each of more than 3,500 detected sources. A summary of spectroscopic programs is presented in Table 1.

In a pilot study (Schlingman et al. 2011) and complete survey (Y. L. Shirley et al. 2013, in preparation), all 6194 Bolocat objects at $\ell \gtrsim 7.5$ were observed using the Heinrich Hertz Submillimeter Telescope (HHT) on Mt. Graham, Arizona. These studies simultaneously observed the $J = 3\rightarrow 2$ rotational transitions of HCO$^+$ ($\nu = 267.6$ GHz) and N$_2$H$^+$ ($\nu = 279.5$ GHz). Because these molecular transitions trace fairly dense gas ($n_{\text{eff}} \approx 10^4$ cm$^{-3}$), the line-of-sight confusion seen in CO studies is largely absent. In fact, Shirley et al. find that only 2.5% of HCO$^+$ detections have multiple velocity components. These objects, likely an overlap of two or more molecular cloud clumps along the line of sight, are not used in this study. Detectability in HCO$^+$ is a strong function of millimeter flux clumps along the line of sight, are not used in this study. These objects, likely an overlap of two or more molecular cloud clumps. These surveys provide both kinematic and chemical information, and are typically beam-matched to the BGPS to facilitate comparison to the dust-continuum data. From these observations, a line-of-sight velocity ($v_{\text{LSR}}$) was successfully fitted for each of more than 3,500 detected sources. A summary of spectroscopic programs is presented in Table 1.

Seeking to characterize the physical properties of BGPS sources, Dunham et al. (2011) used the Robert F. Byrd Green Bank Telescope to observe the lowest inversion transition lines of NH$_3$ near 24 GHz. They observed 631 BGPS sources in the inner Galaxy. The NH$_3$ (1,1) inversion is the strongest ammonia transition at the cold temperatures of BGPS sources ($T \approx 20$ K), and we used this transition exclusively for the NH$_3$ velocity fits.

2.3. The Spitzer GLIMPSE Survey

The Spitzer GLIMPSE survey (Benjamin et al. 2003; Churchwell et al. 2009) was used to identify mid-infrared extinction features associated with BGPS-detected sources. The GLIMPSE survey area completely encompasses the BGPS for $|b| \leq 1.0$ and $\ell \leq 65^\circ$ (there are several sections of the BGPS that flare out to $|b| \leq 1.5$, see A11). We used the V3.5 IRAC Band 4 mosaics (25.7 $\mu$m) to identify absorption features. Point sources (stars) identified in the Band 1 mosaics ($\lambda_c = 3.6$ $\mu$m) were removed from the Band 4 images to accentuate diffuse emission (see Section 4.2). Stars were modeled as Gaussian peaks since the mosaicing process from individual IRAC frames produces a spatially variable point-spread function (PSF), hampering star-subtraction. The Band 4 mosaics have an angular resolution $\sim 2''$, and a pixel scale of 1''. GLIMPSE images have undergone zodiacal light subtraction based on a zodiacal emission model (see the data product manual), so signal remaining in the mosaics is Galactic in nature. There is, however, a significant effect due to scattering of light within the IRAC camera that causes the surface brightness of extended emission to appear brighter than it actually is (Reach et al. 2005). The method used in this study to correct for scattered light is described in Section 4.2, and a derivation of the correction factors required for quantities measured from the publicly available GLIMPSE mosaics is given in Appendix B.

3. DISTANCE PROBABILITY DENSITY FUNCTIONS

3.1. Approach and Utility

We introduce an automated distance determination technique for molecular cloud clumps that allows for the joint application of many individual distance estimation methods. Bayes’ Theorem provides a framework for creating DPDFs for dust-continuum-identified molecular cloud clumps that encode the confidence in source distances. Kinematic distances derived from $v_{\text{LSR}}$ and a Galactic rotation curve constitute the likelihood functions in the Bayesian context. Because these likelihoods are subject to the KDA, prior DPDFs based on ancillary data must be applied to constrain the distance estimates. The posterior DPDF is simply the product of the likelihood with the priors, suitably normalized. Relative amplitudes of the posterior DPDF at each distance along the line of sight ($d_o$) correspond to the probability of the source being at that distance.

Within this framework, any number of prior DPDFs may be applied to constrain the distances to molecular cloud clumps. This paper describes two such priors. The first, applicable to all molecular cloud clumps, is based on the Galactic distribution of molecular hydrogen. Because the scale height of the molecular disk is small, this prior favors the near kinematic distances for objects at high Galactic latitudes. The second prior involves the use of EMAFs. Not all molecular cloud clumps are visible as absorption features, however, so this prior (described in detail in Section 4) applies only to a subset of objects. To expand the collection of molecular cloud clumps with well-constrained...
DPDFs, additional techniques (e.g., HISRA, NIREX, etc.) would need to be applied.

Not only do DPDFs provide a structure for applying multiple techniques for distance discrimination, they also encode the distance uncertainty and level of confidence in the KDA resolution. When used to derive the mass or other property of a molecular cloud clump, DPDFs provide a means for determining the associated uncertainty. The DPDFs derived in this work are computed out to a heliocentric distance of 20 kpc in 20 pc intervals. To facilitate the use of integrated probabilities, DPDFs are normalized to unit total probability such that \( \int_0^\infty \text{DPDF} \, d(d_\odot) = 1 \).

3.2. Extracting a Distance from the DPDF

The proper use of DPDFs for calculating derived quantities is to build a distribution by randomly sampling distances from the DPDFs in a Monte Carlo fashion, preserving all information about distance placement and uncertainty. There are applications, however, that benefit from or require a single distance estimate with uncertainty (such as distance comparisons with other studies). There are two primary distance estimates that may be derived from a DPDF. The maximum-likelihood distance (\( d_{\text{ML}} \)) is the distance which maximizes the DPDF. This represents the single best-guess at the distance for cases where a large fraction of the total probability lies within a single peak. The associated uncertainty may be defined as the confidence region around \( d_{\text{ML}} \) that encloses at least 68.3\% of the integrated DPDF, and whose limits occur at equal relative probability. This so-called isoprobability confidence region is generally asymmetric, and may represent lopsided error bars several kiloparsecs in size if both kinematic distance peaks are required to enclose sufficient probability. The full width of this uncertainty (FW68) of the DPDF is typically derived from a DPDF. The maximum-likelihood distance (\( d_{\text{ML}} \)) is the first moment of the distribution, \( \bar{d} = \int_0^\infty d_\odot \text{DPDF} \, d(d_\odot) \). (1)

If the DPDF is well-constrained to a single peak, \( d_{\text{ML}} \) and \( \bar{d} \) will be nearly equivalent. In cases where the KDA resolution is not well-constrained, however, these distance estimates may be substantially different and \( \bar{d} \) is not a good estimator of the distance. The uncertainty associated with \( \bar{d} \) may be computed from the second moment of the DPDF as

\[
\sigma_\bar{d} = \left( \int_0^\infty \left( d_\odot - \bar{d} \right)^2 \text{DPDF} \, d(d_\odot) \right)^{1/2}.
\] (2)

The \( \sigma_\bar{d} \) represent the variance of the DPDF, and only approximate Gaussian confidence intervals for single-peaked DPDFs. Ultimately, the choice of a single-value distance estimate will depend on the specifics of the application; various cases are discussed in Section 6.1.2.

3.3. Using DPDFs to Estimate Physical Parameters

While distances to objects are often interesting in isolation, their primary use is to convert observational quantities into physical properties of the object. DPDFs offer a simple way to propagate the uncertainties in distance through these calculations. For example, the maximum-likelihood mass of a molecular cloud clump can be estimated as

\[
M_{\text{ML}} = \alpha S_{1,1} d_{\text{ML}}^2.
\] (3)

where \( S_{1,1} \) is the \( \lambda = 1.1 \) mm flux density, and \( \alpha \) contains the dust physics and temperature. Adoption of a DPDF representation allows marginalization over distance to obtain the expectation value of the mass:

\[
\langle M \rangle = \int_0^\infty \alpha S_{1,1} d_\odot^2 \text{DPDF} \, d(d_\odot).
\] (4)

Practically, this integration can be accomplished by Monte Carlo methods, drawing a large number of distance samples from the DPDF and evaluating the average mass. Uncertainties in the expectation value can be determined using methods paralleling those used for distance above.

Bimodal DPDFs again lead to complications, as the expectation value will commonly be found at a value with low probability. A maximum likelihood distance can be adopted to avoid this aesthetic feature, but marginalization over the distance remains the most rigorous approach. Ideally, additional prior DPDFs should be applied in order to minimize bimodality.

3.4. Kinematic Distance DPDFs

Kinematic distances form the foundation for the Bayesian approach to distance estimation, computed from the intersection of the Galactic rotation curve projected along the line of sight, \( v(d_\odot) \), with the observed molecular line \( v_{\text{LSR}} \). Transformation of velocity uncertainties onto the distance axis is facilitated by the use of two-dimensional probability density functions, \( p(v_{\text{LSR}}, d_\odot) \).

The rotation curve function, \( P_{\text{rot}}(v_{\text{LSR}}, d_\odot) \), is constructed as

\[
P_{\text{rot}}(v_{\text{LSR}}, d_\odot) = \exp \left( -\frac{(v_{\text{LSR}} - v(d_\odot))^2}{2\sigma_{\text{vir}}^2} \right),
\] (5)

where the uncertainty \( \sigma_{\text{vir}} \) is the magnitude of expected virial motions within regions of massive-star formation, accounting for peculiar motions of individual molecular cloud clumps (\( =7 \) km s\(^{-1}\); Reid et al. 2009).

The function is Gaussian in \( v_{\text{LSR}} \), and is centered along \( v(d_\odot) \); if integrated over \( v_{\text{LSR}} \), a uniform DPDF is obtained. The probability density function from spectral line information (\( P_{\text{spec}} \)) is a Gaussian centered at the measured \( v_{\text{line}} \), with observed line width \( \sigma_{\text{line}} \), independent of \( d_\odot \). As with \( P_{\text{rot}} \), this function yields a uniform DPDF when integrated over \( v_{\text{LSR}} \).

Since \( P_{\text{rot}} \) does vary as a function of \( d_\odot \), localized peaks in the \( (v_{\text{LSR}}, d_\odot) \) plane result when it is multiplied by \( P_{\text{spec}} \). The desired one-dimensional DPDF\(_{\text{kin}} \) is obtained by subsequent integration over \( v_{\text{LSR}} \).

DPDF\(_{\text{kin}} \) is double-peaked and symmetric about the tangent distance for objects with \( R_{\text{gal}} < R_0 \), and single-peaked otherwise. The \( v(d_\odot) \) were computed using the flat rotation curve of Reid et al. (2009). Schönrich et al. (2010) subsequently derived newer estimates of the solar peculiar motion, affecting rotation curve fits to the maser parallax data of Reid et al. The updated values used here are \( R_0 = 8.51 \) kpc, and \( \Theta_0 = 244 \) km s\(^{-1}\) (M. Reid 2011, private communication).

---

11 This is the expected virial velocity, per coordinate, for an individual object (i.e., molecular cloud clump) within a high-mass star-forming region of mass \( \sim 3 \times 10^4 \, M_\odot \) and radius \( \sim 1 \) pc (Reid et al. 2009).
new solar motion values also had the effect of decreasing the magnitude of the apparent Galactic counter-rotation of high-mass star forming regions, an effect likely arising from molecular gas interacting with the spiral potential, from 15 km s\(^{-1}\) to 6 km s\(^{-1}\).

Kinematic distances are sensitive to the slope of \(v(d_{\odot})\), itself a function of Galactic longitude. For lines of sight along \(b \approx 0^\circ\) within \(\sim 10^\circ\) of the Galactic longitude cardinal directions, \(v(d_{\odot})\) is either very flat or sharply peaked; small departures from circular motion therefore translate into large deviations in derived kinematic distances. Furthermore, since \(v(d_{\odot})\) is derived assuming circular orbits about the Galactic center, radial streaming motions of the gas are not accounted for, meaning that DPDF-derived distance estimates carry the basic limitations of any kinematic distance determination. To minimize the effects of non-circular motion, regions known to have significant streaming must be excluded from consideration. In particular, the presence of the long Galactic bar at \(R_{\text{gal}} \lesssim 3\) kpc (Fux 1999; Rodriguez-Fernandez & Combes 2008) and its associated radial streaming motions restrict the use of kinematic distance measurements to locations outside this radius. In the Galactic longitude–velocity (\(\ell–v\)) diagram, these restrictions amount to excluding much of \(|\ell| \lesssim 20^\circ\). Features at low longitude known to be outside the Galactic bar (such as the Scutum–Centaurus Arm, also labeled as the “Molecular Ring;” Dame et al. 2001, their Figure 3), may be considered to have roughly circular orbits, and are included in this study.

3.5. Prior DPDFs for Kinematic Distance Discrimination

Prior DPDFs are required to discriminate between the kinematic probability peaks for objects within the solar circle. DPDF\(_{\text{kin}}\) is symmetric about the tangent point, so prior DPDFs based on ancillary Galactic plane data must be asymmetric to provide useful distance constraints.

The Galactic distribution of molecular gas serves as an envelope inside which molecular cloud clumps may form. The prior DPDF\(_{\text{H}_2}\) is defined to be proportional to the volume density from the molecular hydrogen model of Wolfire et al. (2003) along a line of sight. This model consists of a Molecular Ring component with a decaying exponential toward the outer Galaxy; the vertical distribution is Gaussian with a half-width at half-maximum (HWHM) of 60 pc (Bronfman et al. 1988), flaring outside the solar circle. While this distribution is symmetric about \(d_{\text{sun}}\) along the Galactic midplane, the narrow vertical extent of the molecular layer sets a strong prior on higher-latitude objects. The relative amount of \(\text{H}_2\) beyond the tangent point for lines of sight at \(|b| > 0^\circ.3\) is small, generating the needed asymmetric function for molecular cloud clumps at larger Galactic latitude.

The prior DPDF based on EMAFs was computed from a pixel-by-pixel morphological matching between millimeter dust-continuum emission and mid-infrared dust absorption features. The derivation of DPDF\(_{\text{emaf}}\) is described in detail in the next section.

4. INFRARED-MILLIMETER MORPHOLOGICAL MATCHING

Morphological matching is based on the comparison between synthetic 8 \(\mu\)m images computed from millimeter flux density measurements and GLIMPSE 8 \(\mu\)m maps processed to match the angular resolution of the BGPS. This section describes the creation of both the synthetic and processed 8 \(\mu\)m images, as well as the mechanics of computing DPDF\(_{\text{emaf}}\).

4.1. Creation of Synthetic 8 \(\mu\)m Images

4.1.1. Radiative Transfer Assumptions

Creation of synthetic 8 \(\mu\)m images explicitly assumes that the dust seen in emission in the BGPS is the same dust that extincts mid-infrared light. When converted into a mid-infrared optical depth, BGPS observations represent dark clouds which may be placed at different heliocentric distances within a model of diffuse Galactic 8 \(\mu\)m emission. A series of synthetic images generated in this manner were compared with mid-infrared observations to compute the DPDF\(_{\text{emaf}}\).

We assumed a simple radiative transfer model to describe the observed mid-infrared intensity absorbed by a cold molecular cloud clump immersed in a sea of diffuse emission (assuming that the absorbing cloud has no emission). The intensity observed within an EMAF (\(I_{\text{emaf}}\)) is

\[
I_{\text{emaf}} = I_{\text{back}} \ e^{-\tau_{8\mu m}} + I_{\text{fore}},
\]

where \(I_{\text{back}}\) and \(I_{\text{fore}}\) are the background (from the cloud to large heliocentric distance) and foreground (between the observer and the cloud) intensities, respectively, and \(\tau_{8\mu m}\) is the mid-infrared optical depth of the cloud. The total intensity along a line of sight in the absence of absorption is \(I_{\text{MIR}} = I_{\text{back}} + I_{\text{fore}}\). Defining the fraction of the total intensity that lies in front of the cloud as \(f_{\text{fore}} = I_{\text{fore}}/I_{\text{MIR}}\) allows Equation (6) to be written as

\[
I_{\text{emaf}} = [(1-f_{\text{fore}}) \ e^{-\tau_{8\mu m}} + f_{\text{fore}}] \ I_{\text{MIR}}.
\]

This parameterization frames the observed EMAF intensity in terms of decrements below the unextincted intensity in the vicinity, and provides the basis for creating synthetic 8 \(\mu\)m images. It follows quickly from Equation (7) that clouds optically thick in the mid-infrared (\(\tau > 1\)) will still have a 10% difference between \(I_{\text{emaf}}\) and \(I_{\text{MIR}}\) (i.e., easily detectable) for \(f_{\text{fore}}\) as large as 0.85. Calculation of \(\tau_{8\mu m}\) and \(f_{\text{fore}}\) are described below, and the estimation of \(I_{\text{MIR}}\) from GLIMPSE data is discussed in Section 4.2.

4.1.2. 8 \(\mu\)m Optical Depth from the Millimeter Flux Density

The mid-infrared optical depth of an EMAF cannot be measured directly from the GLIMPSE mosaics without significant assumptions, but it may be estimated from millimeter data. Thermal emission is optically thin at millimeter wavelengths, so the observed BGPS flux density \((S_{1.1})\) may be written as

\[
S_{1.1} = B_{1.1}(T_d) \ \tau_{1.1} \ \Omega_{\text{BGPS}},
\]

where \(B_{1.1}(T_d)\) is the Planck function evaluated at \(\lambda = 1.1\) mm and dust temperature \(T_d\), and \(\Omega_{\text{BGPS}} = 2.9 \times 10^{-8}\) sr is the solid angle of the BGPS beam. The millimeter optical depth (\(\tau_{1.1}\)) was computed assuming the dust opacity (\(\kappa_{1.1}\)) for grains with thin ice mantles, coagulating at \(10^6\) cm\(^{-3}\) for \(10^6\) yr (Ossenkopf & Henning 1994, Table 1, Column 5; called OH5 dust). Interpolation of OH5 dust opacities to the central frequency of the BGPS bandpass yields \(\kappa_{1.1} = 1.14\) cm\(^2\) g\(^{-1}\) of dust (A11). A molecular cloud clump with \(\tau_{1.1} = 10^{-3}\), which corresponds to \(S_{1.1} \approx 0.9\) Jy, has a beam-averaged molecular hydrogen column density \(\approx 2 \times 10^{22}\) cm\(^{-2}\).

The 8 \(\mu\)m optical depth is related to \(\tau_{1.1}\) by the ratio of the dust opacities in the two bandpasses, \(R_\kappa = \kappa_8/\kappa_{1.1}\). We calculated
the mid-infrared dust opacity by assuming a dust emission spectrum including PAH molecules (Draine & Li 2007), finding the average attenuation intensity across IRAC Band 4, and extracting a band-averaged opacity \( \kappa_8 \approx 825 \text{ cm}^2 \text{ g}^{-1} \) of dust (see Appendix A). At the 33'' resolution of the BGPS, the beam-averaged 8 \( \mu \text{m} \) optical depth is therefore

\[
\tau_8 = \frac{R_d}{B_{1.1}(T_d)} \Omega_{\text{BGPS}} S_{1.1} = \mathcal{Y}(T_d) S_{1.1} \approx 0.778 \left( \frac{e^{13.0 K/T_d} - 1}{e^{13.0 K/20.0 K} - 1} \right) (S_{1.1}/1 \text{ Jy}) \ . \tag{9}
\]

The function \( \mathcal{Y}(T_d) \) has units of inverse flux density, and is normalized to 20 \( K \) in Equation (9). Because \( \tau_8 \) is a function of \( R_d \) (i.e., both millimeter-wave emission and mid-infrared absorption depend only on the dust), the gas-to-dust ratio is not relevant to the distance estimation method. Owing to the nearly three orders of magnitude difference in dust opacity between the millimeter and mid-infrared, a value of \( \tau_8 \approx 0.1 \) corresponds to a column of only \( N(H_2) \approx 3 \times 10^{21} \text{ cm}^{-2} \), assuming \( A_V/\kappa_8 \approx 0.05 \) (Indebetouw et al. 2005; Román-Zúñiga et al. 2007). Therefore, molecular cloud clumps with column densities \( \gtrsim 10^{22} \text{ cm}^{-2} \) will be mostly opaque at \( \lambda = 8 \mu \text{m} \).

Using Equation (9) to obtain an 8 \( \mu \text{m} \) optical depth requires a dust temperature \( (T_d) \). Since we are ignorant of \( T_d \) within each molecular cloud clump used in this study, we assumed that all sources are at the same temperature. Battersby et al. (2011) showed that mid-infrared-dark molecular cloud clumps generally span the temperature range 15 \( K \leq T_d \leq 25 \ K \). Therefore, \( T_d = 20 \ K \) is a reasonable representation for BGPS sources as a group. Variation of the assumed \( T_d \) affects the KDA resolutions for some sources, and is discussed briefly in Section 6.1.1.

With molecular cloud clump dust temperatures derived from Herschel Hi-GAL data, more precise DPDFs for individual objects may be derived using the present methodology.

### 4.1.3. 8 \( \mu \text{m} \) Foreground Fraction from a Galactic Emission Model

Absorption features seen at \( \lambda = 8 \mu \text{m} \) are assumed to be the result of dense clouds immersed in a smooth emission distribution, punctuated by regions undergoing active star formation. While small-scale structures are difficult to model, the broader diffuse emission is a more tractable problem. Creation of synthetic 8 \( \mu \text{m} \) images via Equation (7) requires a three-dimensional model for the Galactic 8 \( \mu \text{m} \) emission distribution.

The recent numerical Galactic stellar and dust emission model of Robitaille et al. (2012, hereafter R12), computed using the Monte-Carlo three-dimensional radiative transfer code HYPERION\(^{12} \) (Robitaille 2011), offers a self-consistent estimate of diffuse Galactic emission that is well-matched to observed quantities. We used the final model presented in R12, whose parameters were chosen to fit the Galactic latitude and longitude intensity distributions from seven bandpasses in the mid- to far-infrared. This model features two major and two minor spiral arms with Gaussian radial profiles, a lack of dust in the inner few kiloparsecs of the Galactic disk (dust hole; correlated with the dearth of molecular gas in this region), and a modified PAH abundance relative to the favored model from Draine & Li (2007). An analysis of the contributions from various stellar populations and dust grain sizes to the total intensity in each bandpass indicates that some 96% of the emitted near-infrared light is from evolved stars.

### Table 2

Comparison of HYPERION Model Parameters

| Category       | Parameter | R12 | This Work |
|----------------|-----------|-----|-----------|
| Grid*          | \( N_E \) | 200 | 200       |
|                | \( N_O \) | 100 | 200       |
|                | \( N_L \) | 50  | 44        |
|                | \( |z|_{\text{max}} \) (pc) | 3000 | 1000 |
| Wavelength*    | \( N \) bins | 160 | 22        |
| Range (\( \mu \text{m} \)) | 3 \( \leq \lambda \leq 140 \) | 6 \( \leq \lambda \leq 10 \) |
| Image*         | Observer \( R_{\text{gal}} \) (kpc) | 8.5 | 8.5       |
|                | Observer \( \ell \) (pc) | +15 | +25       |
| Longitude Range (\( \circ \)) | 65 \( \geq \ell \geq -65 \) | 65 \( \geq \ell \geq 0 \) | 0 \( \geq \ell \geq -65 \) |

**Notes.**

* \( N \): number of grid cells in this dimension.

\(^{12}\) [www.hyperion-rt.org](http://www.hyperion-rt.org)
at $\lambda = 8 \, \mu m$ (such as H$\upiota$ regions) are sprinkled throughout the box according to the underlying stellar distribution model. Very nearby objects ($d_{\odot} < 0.5 \, kpc$) appear quite bright, and cause “hot-pixel” effects in the computed images of the Galactic plane. These objects blend into the background for images computed from large Galactocentric position (e.g., Figure 1), and are averaged out in collapsed longitude or latitude distributions (R12). To ameliorate the effect of these objects in the computed ($\ell, b$) images, we ran seven realizations of the model, each with a different random-number seed, then median-combined the realizations removes most of these outliers. To eliminate any remaining outliers and reduce noise, the combined ($\ell, b$) images were median smoothed with a 3 pixel $\times$ 3 pixel box.

The foreground fraction was computed from the intensity cubes by dividing each ($\ell, b$) image slice by the final slice. The final FITS data cubes of 8 $\mu m$ intensity and $f_{\text{fore}}$ for both the northern and southern Galactic plane ($|\ell| \leq 65^\circ$) are publicly available with the BGPS archive. To illustrate the Galactic features present in the modeled cube, $f_{\text{fore}}(\ell, d_{\odot})$ for the northern plane along $b = 0^\circ$ is shown in Figure 2, with contours and gray scale representing its value from 0 to 1. Since PAH molecules contribute the bulk of the model emission, the dust hole towards low longitude is visible as a flattening of $f_{\text{fore}}(d_{\odot})$. The Molecular Ring/Scutum tangent at $\ell \approx 30^\circ$ appears where $f_{\text{fore}}$ grows quickly as a function of distance. The limited distance range caused by the model box size is represented by the 1.0 contour for $\ell \gtrsim 48^\circ$. The tangent distance as a function of longitude (black dashed line) spans the range $0.45 \lesssim f_{\text{fore}} \lesssim 0.6$, implying that clouds that are optically thick in the mid-infrared should be visible beyond $d_{\text{tan}}$.

Figure 2. Foreground fraction of Galactic 8 $\mu m$ emission in the northern Galactic plane derived from the Hyperion model as a function of ($\ell, d_{\odot}$) along $b = 0^\circ$. Gray scale and contours represent $f_{\text{fore}}$, with the unlabeled 1.0 contour marking the edge of the box in Figure 1 for $\ell \gtrsim 48^\circ$. The thick black dashed line follows the tangent distance as a function of Galactic longitude, and the vertical dot-dashed line marks the $\ell = 7.5$ lower limit of this study.

4.1.4. Computing the Synthetic Images

Synthetic images ($I_{\text{ema}}$) for a given BGPS object is computed using Equation (7). The optical depth was modeled as a two-dimensional image, constructed by applying Equation (9) to the BGPS map data. The estimate of the total mid-infrared emission ($I_{\text{MIR}}$) is also a two-dimensional image, and its creation is discussed below. Because of the coarse resolution of the $f_{\text{fore}}$ model, we simply extracted the one-dimensional $f_{\text{fore}}(d_{\odot})$ at the ($\ell, b$) of the BGPS object. The combination of these elements yields a cube of synthetic data to be compared with the processed GLIMPSE images.

4.2. Processing of GLIMPSE 8 $\mu m$ Images

Mid-infrared properties of dust-continuum-identified molecular cloud clumps were derived from the Spitzer/GLIMPSE mosaics. Further processing of these images was required to estimate the total mid-infrared intensity ($I_{\text{MIR}}$) in the vicinity of an EMAF, and to produce a smoothed, star-subtracted map, containing features and angular scales comparable to (sub-)millimeter data. The example source G035.524−00.274 (BGPS 5647) is used to illustrate the processing products in Figure 3. The first step was to remove individual stars because they contaminate estimates of broader diffuse emission and (sub-)millimeter observations are not sensitive to them. Star locations were identified by searching for bright, unresolved objects in the 3.6-$\mu m$ mosaics using DADOFT (Stetson 1987; Landsman 1995) with a threshold of 20 MJy sr$^{-1}$. A Gaussian was fit to the 8 $\mu m$ image at the location of each identified star, then subtracted. This method of star subtraction was deemed optimal because PSF variations across the survey mosaics meant that PSF-based approaches could not be applied. Star subtraction in this manner did, however, leave clear low-level residuals (Figure 3(a)). Since later processing smoothes the resulting images to the BGPS resolution, residuals are largely unimportant. However, to ensure that poor star subtraction or other effects did not affect distance estimation, evaluation of each potential EMAF for contamination was performed by-eye.

For further processing of the GLIMPSE data, $6' \times 6'$ postage-stamp images were extracted from the star-subtracted 8 $\mu m$ mosaics for each Bolocat source. These postage stamps, centered
on the location of peak millimeter flux density, limit consideration of mid-infrared variations to the immediate vicinity of a molecular cloud clump in addition to providing computational expediency. The first postage-stamp image created for a given BGPS object is a version of the star-subtracted GLIMPSE mosaic, re-pixelated and aligned to the 7′/2 scale of the BGPS images. This image was used to ensure that locally bright emission did not interfere with derived mid-infrared intensities, and to determine the likely intensity range containing I_{MIR} around the object. A pixel intensity histogram of the image was constructed with 1 MJy sr^{-1}-wide bins, and the background was defined as intensities within its FWHM. Pixels within an 8′ × 8′ section of the native-resolution star-subtracted GLIMPSE mosaic having intensities in the defined range were used to fit a quadratic surface using a linear, least-squares optimization. This surface, re-pixelated and scaled as above, comprises the postage-stamp estimate of I_{MIR} (Figure 3(d)). This estimate of background pixels ignored high pixel values from star residuals and low pixel values from EMAFs.

The IRAC camera on Spitzer suffers from internal scattering of light which affects instrument calibration (Reach et al. 2005). Point-source photometry is unaffected by the scattering due to the calibration technique employed, but extended emission (such as the Galactic plane) will appear brighter due to scattering into each pixel. Correcting for this effect should be done on a frame-by-frame basis, but was not accounted for in the GLIMPSE pipeline (S. Carey 2010, private communication). To approximately correct for the scattering, an estimate of the scattered light was subtracted from the postage-stamp images for each BGPS source. The postage-stamp size was chosen to be near the 5′.2 × 5′.2 FOV of IRAC, and the I_{MIR} fit serves as the estimate of the light available to be scattered within a single IRAC frame. This estimate is only approximate, as the I_{MIR} fit explicitly excludes very bright and very dim emission within a frame; for frames with regions of bright emission, the derived correction factor will be a lower limit, and vice versa for frames containing extensive dark clouds. The infinite-aperture intensity correction for IRAC Band 4 is 0.737 (Reach

Figure 3. BGPS and processed GLIMPSE data for example object G035.524−00.274. All panels are 6′ × 6′ postage-stamp images (see the text), and the pink circle identifies the 40′′-top hat BGPS equivalent aperture, centered on the location of peak flux density. (a) Cutout of the star-subtracted GLIMPSE image at native resolution. Cyan ellipses mark IRDCs identified in the Peretto & Fuller (2009) catalog; note that the dark cloud associated with BGPS source G035.478 (lower right corner) is not included in that catalog. (b) BGPS map data with Bolocat source boundary (light cyan). (c) Star-subtracted GLIMPSE cutout smoothed to 33′ and resampled to 7′/2 pixels to match the BGPS maps. Color contours represent logarithmic flux density levels from BGPS (Jy beam^{-1}). (d) Estimate of the total mid-infrared intensity, I_{MIR}, as a quadratic surface fitted to background pixels as described in the text. Contours are drawn to show the variation in I_{MIR} over the postage stamp (MJy sr^{-1}); ticks point to higher values), and the cyan aperture marks the region used to estimate (I_{MIR}) for this source (see Section 5.1). The gray-scale color bar represents the common (logarithmic) intensity scale for all three GLIMPSE panels. (A color version of this figure is available in the online journal.)
et al. 2005), meaning that $\xi = 0.263$ is the scattered light fraction. Assuming that $f_{\text{MBR}}$ represents the total incident light, we subtracted $\xi \times \text{median}(I_{\text{MBR}})$ from each postage-stamp image to remove scattered light.

Reduction of the GLIMPSE angular resolution was necessary for direct comparison with the synthetic images created using Equation (7). Since bright emission in the vicinity is scattered into the EMAF, removal of the scattered light must be done prior to smoothing. The scattering-corrected extracted postage stamps were smoothed with a FWHM = 33′′ Gaussian kernel, then re-pixelated and aligned to match the BGPS images (Figure 3(c)).

4.3. Morphological Matching

Derivation of $\text{DPDF}_{\text{emaf}}$ relies upon the comparison of the (sub-)millimeter emission and mid-infrared absorption of dust in cold molecular cloud clumps. The series of synthetic images were matched against the smoothed GLIMPSE postage stamp images (Figure 3(c)). For small $d_\odot$, the synthetic cloud appears darkest, without foreground light filling in the absorption feature. At larger heliocentric distance, $f_{\text{core}}$ grows, and the synthetic image converges upon $I_{\text{MBR}}$ (Figure 3(d)).

The Galactic 8 $\mu$m emission model of Section 4.1.3 describes smooth, diffuse emission against which EMAFs are visible, but actual Galactic emission is more complex. To match more closely the assumption of the model, the angular region over which the synthetic and observed sky are compared must be restricted. As the observational definition of a single molecular cloud clump, we began with a source’s Bolocat contour delineating the maximum extent of the comparison region (Rosolowsky et al. 2010). Since the synthetic image can never be brighter than $I_{\text{MBR}}$, the matching process is adversely affected by bright mid-infrared emission in the vicinity of a BGPS source. To ameliorate this effect, pixels in the smoothed GLIMPSE postage stamp were excluded from the matching region if their value exceeded the corresponding value in the $I_{\text{MBR}}$ image.

An overview of the morphological matching process is presented in Figure 4 for the same object as in Figure 3. The synthetic 8 $\mu$m image is shown in panel (a) for the distance which maximizes $\text{DPDF}_{\text{emaf}}$ (see below). Panels (b) and (c) are identical to Figure 3, except that the source contour now marks the restricted matching region due to bright mid-infrared emission on the perimeter of the EMAF. Panels (a) and (c) are shown on a common linear gray scale to illustrate the match between the observed extinction and that predicted from millimeter-wave thermal dust emission. The various $\text{DPDF}_{\text{emaf}}$ for this source are shown in panel (d), and are described below.

Quantification of the match as a function of distance was accomplished by constructing a $\chi^2$ statistic from a pixel-by-pixel comparison within the matching region. The estimate of the error in each pixel was derived from Equation (7) by propagating the uncertainty in the optical depth map as

$$\sigma_{\text{syn}}(\ell, b) = I_{\text{MBR}}(\ell, b) e^{-\tau_{\text{syn}}(\ell, b)} \sigma_{S_{11}},$$

(10)

where Equation (9) defines $\tau_{\text{syn}}$ and $Y$, and $\sigma_{S_{11}}$ is the median absolute deviation of the BGPS postage-stamp image. This estimate of the uncertainty places more weight on the portions of the image with larger BGPS flux density. The comparison is computed for synthetic images at 100- pc intervals along the line of sight, yielding $\chi^2(d_\odot)$.

A preliminary $\text{DPDF}_{\text{emaf}}$ was computed using the formal probability of the $\Delta \chi^2$ statistic. The number of degrees of freedom was taken as the integer number of BGPS beams in the matching region ($N_{\text{pixels}}/23.8$ pixels beam$^{-1}$; A11) minus one, since only beam-scale structures are independent and distance is a fitted parameter. For most sources, the $\text{DPDF}_{\text{emaf}}$ has a broad peak (several kiloparsecs wide), and falls sharply where $(\Delta \chi^2)_{\text{emaf}}$ exceeds unity. Because of the sharp cutoffs, it tends to very strongly favor one kinematic distance peak over the other. If the Galaxy truly consisted of dark molecular cloud clumps embedded within broad diffuse mid-infrared emission, this formulation of $\text{DPDF}_{\text{emaf}}$ would be appropriate. However, the Galaxy is punctuated with regions of stronger 8 $\mu$m emission that violate the simple radiative transfer of Equation (6), and the $\text{DPDF}_{\text{emaf}}$ should contain a systematic uncertainty that allows non-vanishing probability at the non-favored kinematic distance peak.

Experimentation with alternative approaches that allow a systematic uncertainty led to the selection of $\text{DPDF}_{\text{emaf}} \propto (\chi^2 - \beta)^{-\gamma}$, where $\beta$ is a positive scalar of the order of unity. This class of $\text{DPDF}_{\text{emaf}}$ have FWHM comparable to the formal probability, but greater width at low likelihood, and hence rarely goes to zero probability until far from the peak. The parameter $\beta$ may be used to tune the width of the function, with larger values leading to narrower distributions. Since the sharp cutoff of the $\text{DPDF}_{\text{emaf}}$, not the width of the peak, is what appears problematic in light of complex Galactic emission, we selected $\beta = 2$ to reproduce the widths of the formal probability $\text{DPDF}$. To verify the validity of this choice, we computed the Galactic Ring Survey (GRS) distance matching success rate (see Section 5.3.2) as a function of $\beta$, and found no dependence on the width of $\text{DPDF}_{\text{emaf}}$.

The resulting $\text{DPDF}$s for object G035.524–00.274 (BGPS 5647) are shown in Figure 4(d). The prior $\text{DPDF}_{\text{H}}$ (blue dotted-dashed) favors the near kinematic distance, since this line of sight looks out the bottom of the molecular layer. The gray dotted line shows the $f_{\text{core}}(d_\odot)$ from the numerical model. The morphological matching process, represented by $\text{DPDF}_{\text{emaf}}$ (black solid), could not make the synthetic image dark enough to match the smoothed GLIMPSE image, forcing the prior to peak at $d_\odot = 0$ kpc. The posterior $\text{DPDF}$ (red) clearly reflects the distance selection, with the near peak containing $>95\%$ of the integrated probability, although there remains some probability contained in the far kinematic distance peak at $d_\odot \approx 11$ kpc.

5. RESULTS

5.1. EMAF-selected Molecular Cloud Clumps

5.1.1. Spatial and Kinematic Selection Criteria

We derived posterior $\text{DPDF}$s for the subset of BGPS sources that have a measured $v_{\text{LSR}}$ from molecular spectroscopy, and are selected by the presence of an EMAF. Spatially, this set is defined by the GLIMPSE-BGPS overlap, limiting the upper end of the Galactic plane at $\ell = 65:\!:\!25$ and a latitude spread of $|b| < 1:\!:\!0$. Kinematic considerations restrict the regions of the $\ell - v$ diagram (Figure 5) that may be considered at lower Galactic longitude down to the $\ell = 7.5$ limit of the spectroscopic surveys.

The colored image in Figure 5 is the latitude-integrated $^{12}\text{CO}(1-0)$ intensity from Dame et al. (2001), and is shown as an indicator of molecular gas location and kinematic conditions. The presence of a long Galactic bar ($R_{\text{bar}} \sim 4$ kpc; Benjamin et al. 2005) implies significant non-circular motion at $\ell \lesssim 30^\circ$. Regions at these longitudes in the $\ell - v$ diagram associated with the Molecular Ring feature (cf. Dame et al. 2001; Rodriguez-Fernandez & Combes 2008), however, are likely at $R_{\text{gal}} \gtrsim 4$ kpc.
To include the Ring but exclude bar-related gas, we disallowed the two hashed regions in Figure 5. The upper region is bounded by $v_{\text{LSR}} = (3.33 \text{ km s}^{-1})\times(\ell^\circ) + 15 \text{ km s}^{-1}$, and includes the higher-velocity gas inside the Ring. The lower region excludes the 3 kpc expanding arm, and is bounded by $v_{\text{LSR}} = (2.22 \text{ km s}^{-1})\times(\ell^\circ) - 16.7 \text{ km s}^{-1}$. Both regions are defined only for $\ell \leq 21^\circ$. The upper hashed region does not extend past this point because the Molecular Ring feature extends to the tangent velocity at larger longitudes; the lower region is limited because the 3 kpc arm has its tangency here (Dame & Thaddeus 2008). There is likely overlap between Ring objects with nearly circular motions and objects in bar-related streaming orbits at $21^\circ \leq \ell \leq 30^\circ$, so kinematic distance estimates in this range, including those derived here, should be used with caution.

Black circles mark the locations of the BGPS molecular cloud clumps for which a DPDF$^{\text{emaF}}$ was computed, and the histogram summarizes their longitude distribution. Stars mark the masers used for distance comparison (see Section 5.3.1).

5.1.2. Mid-infrared Selection Criteria

Automated classification of dust-continuum-identified molecular cloud clumps as EMAFs was achieved using the mid-infrared contrast computed from the smoothed GLIMPSE images at the location of the BGPS source. The peak contrast was defined as

$$C = 1 - \frac{I_{\text{min}}}{I_{\text{MIR}}}$$

where the intensity values were measured from the processed postage-stamp images described in Section 4.2 for each Bolocat object. Due to the varied sizes and shapes of EMAFs, standardized intensities were measured in a 40$''$ aperture around the location of peak BGPS flux density (pink circles in Figure 3). The value of $I_{\text{min}}$ is the minimum intensity within the aperture measured from the smoothed star-subtracted GLIMPSE image (Figure 3(c)), and $I_{\text{MIR}}$ is the mean of the $I_{\text{MIR}}$ postage-stamp image within 2' of the peak of millimeter flux density (cyan circle in Figure 3(d)). A preliminary contrast threshold of $C \geq 0.01$ was implemented in the automated source selection to minimize the number of spurious matches caused by unrelated variation in the GLIMPSE 8$\mu$m mosaics. This threshold also rejects BGPS sources that are mid-infrared bright, as those objects have negative contrast.

All molecular cloud clumps meeting the above selection criteria were examined by eye to ensure their suitability for...
deriving a DPDFemaf. Bolocat objects were not assigned a DPDFemaf for the following types of deficiencies: (1) there was evidence of poor star subtraction contaminating I_{mm}, (2) there was very bright mid-infrared emission (I_{8\mu m} \gtrsim 200 \, \text{MJy} \, \text{sr}^{-1}) within 2' of the location of peak BGPS flux density that could bleed into the 40'' aperture or significantly affect the IRAC scattering correction, (3) the postage-stamp estimate of I_{MBR} was contaminated by excessive bright emission or dark extinction, or (4) the morphology of dark regions in the GLIMPSE image clearly did not correspond to that of the millimeter emission. By-eye exclusion removed approximately 40% of sources meeting the initial automated selection criteria.

Properties of rejected sources were analyzed to reveal that nearly all very-low contrast sources were spurious matches (deficiency type 4, see above). Additionally, BGPS objects located in fields of locally very bright mid-infrared emission were almost all excluded from the final source list (types 2 and 3). As a result, the contrast cutoff was increased to C \geq 0.05, and two additional automated selection criteria were introduced. First, the restriction (I_{MBR} \leq 100 \, \text{MJy} \, \text{sr}^{-1}) was placed to remove sources whose background estimate indicates significant disagreement with the 8 \mu m emission model, as large discrepancies may lead to improper distance estimates (type 3). Second, to automatically reject sources near very bright emission, the re-pixelated unsmoothed postage-stamp images were checked for pixels with I_{8\mu m} \gtrsim 200 \, \text{MJy} \, \text{sr}^{-1} within 2' of the image center; sources with more than 10 such (7'2) pixels were removed from consideration (type 2). These additions to the automated selection criteria led to fewer sources (only 28%) requiring by-eye removal, primarily due to poor star-subtraction (type 1) or complex emission structures that caused morphological mismatch (type 4).

5.1.3. Source Properties

The final source list contains 770 BGPS objects, and is presented in Table 3. EMAF-selected BGPS molecular cloud clumps are not drawn uniformly from the BGPS catalog. Comparisons of Galactic latitude and 40'' flux density distributions between this sample and the full Bolocat (within the spatial limits defined above) are shown in Figure 6. The latitude distribution of this sample follows that of the BGPS as a whole, including peaking below b = 0°. The offset is related to the Sun’s vertical displacement above the Galactic midplane (Schuller et al. 2009; Rosolowsky et al. 2010). The only significant deviation is near b = 0°, where locally bright 8 \mu m emission along the midplane, excited by H II regions and OB stars, obscures more distant molecular cloud clumps. The BGPS 40'' flux density histograms (Figure 6(b)) show that this sample contains, on average, brighter sources (median = 0.252 Jy) than the full Bolocat (median = 0.135 Jy). There are two likely origins of this bias. First, sources must have a vLSR measurement from a dense-gas tracer; the HCO' detection fraction, in particular, is a strong function of BGPS flux density (<20% for S1.1 < 0.1 Jy; Y. L. Shirley et al. 2013, in preparation). Second, the selection criteria excluded sources with very low contrast or whose morphology does not correspond to dark regions in the GLIMPSE maps. Faint BGPS sources have low optical depth (S1.1 = 0.1 Jy corresponds to τ_8 \approx 0.07), and would be difficult to distinguish against the variable Galactic 8 \mu m background.

The distribution of measured mid-infrared source contrast is shown in Figure 6(c), and has a median of 0.19. For images without the IRAC scattering correction, this value corresponds to an uncorrected median contrast of 0.15 (see Appendix B), considerably lower than the minimum contrast (C \approx 0.20) used
by Peretto & Fuller (2009) in their catalog of Spitzer IRDCs (which did not correct for IRAC scattering in the same manner). The majority of our sample consists of “low-contrast” sources that are missing from published catalogs of Galactic IRDCs.

5.2. Source KDA Resolutions

5.2.1. Distance Estimates and Constraints

We derived posterior PDFs for the EMAF-selected BGPS sources by multiplying the kinematic distance PDF by the two priors, and normalizing to unit total probability. By design, the prior PDFs are broader than the peaks in PDF$_{\text{kin}}$, so the resulting maximum-likelihood distances generally do not differ from the simple kinematic distances by more than $\sim 0.1$ kpc. To gauge the strength of the KDA resolution, two statistics were defined: the maximum-likelihood probability ($P_{\text{ML}}$) as the integrated posterior PDF on the $d_{\text{ML}}$ side of the tangent point, and the full width of the 68.3% maximum-likelihood error bar (FW$_{68}$). The ranges of these statistics are $0.5 \leq P_{\text{ML}} \leq 1.0$ and $0.2$ kpc $\lesssim$ FW$_{68} \lesssim 15$ kpc, and a comparison between them for each object is shown in Figure 7. The nature of a double-peaked PDF$_{\text{kin}}$ leads to the sharp change in the distribution of FW$_{68}$ near $P_{\text{ML}} = 0.78$ (vertical dashed line). When the ratio of the peak probabilities of the kinematic distance peaks in the
at the far kinematic distance using mid-infrared absorption. The comparisons of latitude distribution, BGPS 40” flux densities, and mid-infrared contrast between the near and far subsets are shown in Figure 8. For the purposes of this discussion, objects at the tangent distance are grouped with those at the far kinematic distance. The latitude distributions (panel (a)) are very similar, with the near group being slightly wider, owing to the latitude-limiting effect of DPDF\textsubscript{emaf}.

The histograms of BGPS 40” flux densities (Figure 8(b)) show that the far subset has a flatter distribution with a higher median than the near set. Since the source list for this study is mid-infrared-contrast limited, we do not expect to see low flux-density BGPS sources at the far distance; the low column density would not produce enough attenuation to be seen behind the significant foreground emission. The expected contrast as a function of heliocentric distance (represented by \( f_{\text{fore}} \)) may be computed by combining Equations (7), (9), and (11) into

\[
C = (1 - f_{\text{fore}})(1 - e^{-YS_{1,1}}),
\]

where \( I_{\text{emaf}} \) and \( I_{\text{MIR}} \) from Equation (7) are equivalent to \( I_{\text{min}} \) and \( (I_{\text{MIR}}) \) from Equation (11), respectively. A source with larger flux density may be at a farther \( d_{0} \) and still meet the contrast selection criterion.

Indeed, sources at the far kinematic distance have a lower median mid-infrared contrast (\( C = 0.11 \)) than those at the near kinematic distance (\( C = 0.22 \)), as shown in Figure 8(c). Of the 313 objects with \( C \geq 0.2 \), only 12 (4%) are placed at the far kinematic distance, reinforcing the notion that dark mid-infrared absorption features must lie relatively nearby. For comparison, of the 63 sources with \( C < 0.1 \), 40 (63%) were placed at the far kinematic distance, indicating that the majority of EMAFs with very low contrast are at or beyond the tangent point.

An interesting empirical predictor of KDA resolution is shown in Figure 9. The ratio of resolved heliocentric distance over \( d_{\text{tan}} \) is plotted against the ratio of BGPS 40” flux density over the mid-infrared contrast. For BGPS data, there appears to be a boundary at \( S_{1,1}/C \approx 2.5 \) that divides KDA resolutions. The exact value of this cutoff is dependent upon the (sub-)millimeter survey used, and there exists scatter across the boundary. It nevertheless suggests an additional means for KDA resolution when DPDF\textsubscript{emaf} fails to return a well-constrained estimate.

5.2.3. Galactocentric Positions

With well-constrained distance estimates, it is possible to construct a face-on view of the Milky Way. Sources with well-constrained KDA resolutions are plotted atop a reconstruction of the Milky Way from Spitzer data in Figure 10 (R. Hurt: NASA/JPL-Caltech/SSC) using either \( d_{\text{ML}} \) or \( d \) as described in Section 5.2.1. For clarity, the error bars, which account for small deviations from circular motion, are not shown. Some spiral structure is evident in the map of BGPS sources, notably portions of the Sagittarius Arm at \( \ell \gtrsim 35^\circ \), the Scutum–Centaurus Arm/Molecular Ring at \( \ell \lesssim 30^\circ \), and the local arm/orion spur within about a kiloparsec of the Sun (Churchwell et al. 2009). The kinematic restrictions on our sample led to the absence of objects within a \( \approx 4.0 \) kpc radius of the Galactic center (dashed circle in the figure). Face-on views of the Galaxy derived from kinematic distances will not show narrow spiral features (like those in the background image) because of the local virial motions of individual molecular cloud clumps within larger complexes. Galactocentric positions are therefore “smeared-out” by approximately \( \pm 0.4 \) kpc about the true kinematic...
Figure 8. Comparison of source properties for objects with “near” vs. “far” KDA resolutions. Sources placed at the near distance are represented by open black histograms; tangent-point and far-distance sources are shown together with filled gray histograms. Panels are as in Figure 6. Vertical dot-dashed lines represent the median of each distribution.

Figure 9. KDA resolution vs. the ratio of BGPS 40'' flux density to mid-infrared contrast. The upper region represents the far kinematic distance, and the lower the near; the gray shaded region illustrates the band around \( d_{\text{bar}} \). Black dots mark the sources with well-constrained distance estimates; the subset of cyan squares are sources within W43 (see Section 6.1.1). The vertical dot-dashed line is drawn at \( S_{1.1}/C = 2.5 \).

(A color version of this figure is available in the online journal.)

Figure 10. Face-on view of the Milky Way for sources with well-constrained KDA resolutions, plotted atop an artist’s rendering of the Milky Way (R. Hurt: NASA/JPL-Caltech/SSC) viewed from the north Galactic pole. The image has been scaled to match the \( R_0 \) used for calculating kinematic distances. The outer dotted circle marks the solar circle, and the inner dotted circle the tangent point as a function of longitude. The dashed circle at \( R_{\text{gal}} = 4 \) kpc outlines the region influenced by the long Galactic bar (Benjamin et al. 2005), corresponding to the hashed regions in Figure 5. The straight dashed gray line marks \( \ell = 30^\circ \) as a guide. Various suggested Galactic features are labeled. For clarity, distance error bars are not shown.

(A color version of this figure is available in the online journal.)

distance for the complex as a whole. Each dot in the figure, however, should be thought of in terms of its DPDF, where the kinematic distance peaks have a FWHM of 1–2 kpc.

KDA resolutions also allow the derivation of the vertical distribution of sources about the Galactic midplane. Vertical position is particularly affected by the KDA for higher-latitude sources (\(|b| \gtrsim 0.4\)). Calculation of vertical height (\( z \)) requires a proper accounting of the Sun’s \( \approx 25 \) pc vertical offset above the Galactic plane (Humphreys & Larsen 1995; Jurić et al. 2008). The small scale height of Galactic molecular gas can lead to incorrect inferences about the vertical distribution of dense gas in the disk if \( z \) positions are calculated directly from Galactic coordinates without a correction for the solar offset.

The matrix needed to transform \((\ell, b, d)\) into \((R_{\text{gal}}, \phi, z)\) is derived in Appendix C.

The vertical distribution for the set of well-constrained BGPS sources is shown in Figure 11. A Gaussian fit to the distribution yields a HWHM of 25 pc, and a positive centroid offset of 7 pc. This scale height is approximately half that found by Bronfman et al. (1988) for \(^{12}\)CO. This narrow result may, however, be a result of the limited Galactic latitude coverage of the BGPS. Analysis of the recent compact source catalog from the \( \lambda = 870 \mu \text{m} \) ATLASGAL survey (Contreras et al. 2013), which extends to \(|b| = 1^\circ\), shows that \( \approx 20\% \) of their
objects lie outside the BGPS latitude limits. To gauge the effect of limited latitude coverage, the derived \( z \) are plotted against heliocentric distance in Figure 12, with \( |b| = 0.5 \) shown for \( \ell = 30^\circ \) (the limits rotate to slightly more positive \( z \) for larger \( \ell \)). For the region \( d_\odot \lesssim 6 \) kpc (which contains more than 80% of this sample), the BGPS does not fully probe the FWHM of the \(^{12}\)CO distribution (dot-dashed lines). Other indicators of a larger scale height for star-formation regions include \(^{13}\)CO clouds from the GRS (Roman-Duval et al. 2009), which have a FWHM \( \approx 80 \) pc, and Galactic H\( \Pi \) regions (FWHM \( \approx 100 \) pc; Anderson et al. 2012).

5.3. Distance Comparisons with Other Studies

The quality of KDA resolutions for EMAF-selected BGPS sources was characterized through a comparison of distance estimates with values from the literature. In particular, comparison sets were chosen that used mostly orthogonal methodologies so that distance comparisons are largely free of correlated effects. The three sets described below are the use of maser parallax measurements, \( \text{H \ensuremath{\alpha}} \) absorption features associated with molecular clouds, and near-infrared extinction measurements.

5.3.1. Maser Parallax Distances

Maser parallax measurements towards regions of high-mass star formation provide absolute distance validation comparisons. The Bar and Spiral Structure Legacy Survey (BeSSeL; Brunthaler et al. 2011) is conducting ongoing very long baseline interferometry (VLBI) parallax measurements of \( \text{CH}_3\text{OH} \) and \( \text{H}_2\text{O} \) maser emission in star-forming regions across the Galactic plane. Such measurements provide very accurate distances out to \( d_\odot \sim 10 \) kpc, but the present overlap between published results and the BGPS is small (see Table 4 for the comparison set of maser sources used).

The comparison set was defined as objects from our sample whose angular separations and velocity differences were \( \lesssim 15^\prime \) and \( \lesssim 10 \) km s\(^{-1} \), respectively, from those of a published maser.

These masers tend to be in regions of high-mass star formation, and such regions are on the order of 0.25' in size. The velocity limit is related to the spread of virial velocities within such regions. A collection of 12 BGPS objects were associated with one of five masers; the distribution is noted in Table 4. To visualize the distance comparison, distances from Table 3 for each BGPS object are plotted against the measurements from the BeSSeL literature as magenta triangles in Figure 13. The gray dashed lines in the left panel represent \( \pm 1 \) kpc error margins, used for qualitative purposes. An object falling outside this region is said to have a “mismatching” distance estimate. For clarity in the figure, only mismatching objects have error bars shown; horizontal bars are from Table 3, and vertical bars are from the reference. The right panel is a zoom-in on the \( \Delta d = \pm 1 \) kpc region of the left panel (i.e., within the dashed lines).

For the maser comparison set, only three sources fall outside the \( \pm 1 \) kpc region. Two BGPS objects (overlapping triangles in

---

**Figure 11.** Vertical distribution of sources about the Galactic midplane. The filled gray histogram shows the distribution, while the black line represents a Gaussian fit to the histogram.

**Figure 12.** Derived vertical position of sources vs. heliocentric distance. Diagonal cyan dashed lines represent the nominal \( |b| = 0.5 \) limit of the BGPS at \( \ell = 30^\circ \) for a vertical solar offset above the Galactic midplane of 25 pc. Horizontal dot-dashed lines mark the FWHM of the \(^{12}\)CO layer (Bronfman et al. 1988).

(A color version of this figure is available in the online journal.)

**Table 4**

| Source | \( \ell \) (\(^{\circ}\)) | \( b \) (\(^{\circ}\)) | \( v_{LSR} \) (km s\(^{-1}\)) | Distance (kpc) | \( N_{BGPS} \) | Reference |
|--------|----------------|----------------|----------------|----------------|----------------|-----------|
| G23.0–0.4 | 23.01 | -0.41 | 81.5 | 4.6\(^{+0.4}_{-0.3}\) | 6 | 1 |
| G23.4–0.2 | 23.44 | -0.18 | 97.6 | 5.9\(^{+1.4}_{-0.9}\) | 2 | 1 |
| G23.6–0.1 | 23.66 | -0.13 | 82.6 | 3.2\(^{+0.5}_{-0.4}\) | 2 | 2 |
| W51 IRS2 | 49.49 | -0.37 | 56.4 | 5.1\(^{+2.9}_{-1.4}\) | 1 | 3 |
| W51 Main\(^b\) | 49.49 | -0.39 | 58.0 | 5.4\(^{+3.3}_{-0.3}\) | 1 | 4 |

**Notes.**

\(^a\) Number of EMAF-selected BGPS sources within 15' and 10 km s\(^{-1}\) of the maser location. See Figure 13 for comparison.

\(^b\) \( \text{H}_2\text{O} \) maser; all others are \( \text{CH}_3\text{OH} \) masers.

**References.** (1) Brunthaler et al. 2009; (2) Bartkiewicz et al. 2008; (3) Xu et al. 2009; (4) Sato et al. 2010.
Absorption features caused by cold neutral hydrogen within molecular clouds are also called “narrow” self-absorption (HINSA) to distinguish them from the broader self-absorption features of diffuse H\textsubscript{i} clouds (cf. Li & Goldsmith 2003).

5.3.2. Galactic Ring Survey KDA Resolutions

For a larger distance comparison set, we used the KDA resolutions from the BU-FCRAO GRS (Jackson et al. 2006). By matching $^{13}$CO(1–0) emission morphology and spectra with H\textsubscript{i} absorption features, Roman-Duval et al. (2009) estimated the distances to some 750 molecular clouds in the inner Galaxy. Those authors used a combination of H\textsubscript{i} self-absorption (HINSA)\textsuperscript{13} and 21 cm continuum absorption features to positively resolve the KDA. These techniques exploit the spectroscopic dimension of H\textsubscript{i} surveys, where cold atomic hydrogen within dense molecular gas absorbs line emission from warm gas at the same ν\textsubscript{LSR} on the far side of the Galaxy or continuum radiation from H\textsc{ii} regions. Distance resolutions from this method are subject to uncertainties from non-circular and radial streaming motions, but are directly comparable with the KDA resolutions of the DPDF method.

EMAF-selected BGPS objects were associated with cataloged $^{13}$CO clouds based on spatial and kinematic proximity. The association volume was defined as a circle of radius 10′ (approximately the median size of a GRS cloud; Roman-Duval et al. 2009), and a velocity spread equal to the $^{13}$CO velocity dispersion, centered on the (ℓ, b, ν\textsubscript{LSR}) coordinates from the GRS catalog. A total of 213 EMAFs lie within the association volume of one or more GRS clouds. To ensure the accuracy of the associated GRS KDA resolution, BGPS flux density maps were compared to both $^{13}$CO intensity maps integrated over the velocity of the appropriate dense-gas tracer from Table 1, and H\textsubscript{i} 21 cm “on”–“off” integrated intensity (HISA) maps. For a handful of sources (~7%), a strong HISA signature was present within the BGPS source contour even though the associated GRS cloud was placed at the far kinematic distance. None of these objects was listed as having a 21 cm continuum source, so the absorption signature is the result of cold gas at the near distance. These discrepant objects may be the result of line-of-sight confusion, a slight velocity offset between the parent cloud and the BGPS object, or incorrect association with a $^{13}$CO cloud. Whatever the cause, the KDA resolution for the associated GRS cloud was amended to “near” to reflect the HISA signature.

Roman-Duval et al. used the Clemens (1985) curve to derive heliocentric distances, and differences in rotation curve definition can cause distance-comparison discrepancies unrelated to the KDA (see Figure 5). To eliminate potential systematic effects, the KDA resolution and ν\textsubscript{LSR} of each associated GRS cloud were mapped to a new heliocentric distance using the Reid et al. (2009) rotation curve. In the comparison between the GRS-derived distance and those from the DPDFs (black dots in Figure 13) are associated with the maser object G23.66−0.13, which has a parallax distance that disagrees with the derived (near) kinematic distance. Bartkiewicz et al. (2008) find that this object has a proper motion consistent with the parallax distance and the assumption of a flat rotation curve, but has a ≈35 km s\textsuperscript{−1} peculiar motion toward the Galactic center. This radial streaming motion makes its kinematic distance appear larger, and provides a cautionary example of the effects of non-circular motion on kinematic distance methods. The other mismatching source has a DPDF distance estimate skewed away from the simple kinematic distance due to the sharply peaked DPDF\textsubscript{emaf} caused by its bright millimeter flux density (S\textsubscript{1.4} = 3.9 Jy). The W51 region lies near the tangent point, so correct DPDF placement for these objects merely implies that the region’s circular velocity is consistent with the rotation curve. The remaining EMAF-selected BGPS objects in this set have KDA resolutions that agree with the trigonometric parallax distance.

(A color version of this figure is available in the online journal.)
Figure 13), nearly 92% of our distance resolutions match those
of the GRS. This success rate is robust for the entire EMAF
set, as enforcing a minimum mid-infrared contrast of $C \geq 0.15$
only increases the matching rate to 94%.

The 17 BGPS objects with mismatching distance resolutions
are shown with horizontal error bars from the DPDFs. Those in
the upper left of Figure 13 have a large apparent mid-infrared
absorbing column, but Roman-Duval et al. (2009) did not find
evidence of self-absorbing H I. Conversely, those in the bottom
right have HISA signatures but were placed beyond the tangent
point by the posterior DPDF. Examination by eye of this latter
group showed that the two sources farthest from the one-to-
one line have slight underestimates of $I_{8.0}$ around the EMAF;
the values in the postage-stamp image reflect dimmer nearby
regions. The DPDF$_{emat}$ in these cases selects the far kinematic
distance peak despite the presence of HISA for these objects.

There are four objects whose GRS distance estimate is
5.5 kpc $\geq d_0 \geq 8$ kpc and disagree with the DPDF-derived
distance. These all lie within $\sim 1.5$ kpc of the tangent point.
Since the kinematic distance DPDFs do not have two fully
distinct peaks in this region, the particular shape of DPDF$_{emat}$
can have a significant impact on the derived single-distance
estimators. The mismatches are due to the source being near
d$_{tan}$, and not an incorrect KDA resolution. The remaining 11
mismatching sources in the upper left of Figure 13 (GRS-far,
DPDF$_{emat}$-near) are moderately dark EMAFs ($0.1 \leq C \leq 0.3$)
that show no signs of HISA at the velocity of the molecular
cloud clump. About half of these lie at $|b| \geq 4^\circ$, and may not
have enough H I backlighting at the far kinematic distance for
a HISA signature to be visible; although Gibson et al. (2005)
found self-absorption features out to more than $|b| = 2^\circ$
in the Canadian (H I) Galactic Plane Survey. For sources in this
quadrant of the figure, it is unclear which kinematic distance is
correct. The future application of additional prior DPDFs may
solve the small number of conflicting KDA resolutions, but the
present method achieves very good correspondence with other
distance estimates for molecular cloud clumps.

5.3.3. Near-infrared Extinction Distances

Using a technique for measuring three-dimensional near-
infrared Galactic extinction (NIREX; Marshall et al. 2006),
Marshall et al. (2009) estimated the distances to over 1200
IRDCs identified by the Midcourse Space Experiment (MSX)
in the inner Galactic plane (Simon et al. 2006, hereafter S06).
This approach compares the stellar colors of a section of sky
with a Galactic stellar distribution model, and searches for
sharp changes in color excess as a function of distance. Ex-
tinction measurements, like maser parallaxes, offer a kinematic-
independent means of distance determination.

MSX dark clouds have a typical size of about an arcminute,
so BGPS sources lying within $60^\prime$ of the centroid of a NIREX
cloud were included in this comparison set. While there are
about 275 objects from Marshall et al. (2009) within the spatial
bounds of this study, only 38 EMAF-selected BGPS sources
could be associated with a NIREX cloud. Peretto & Fuller (2009,
hereafter PF09) noted that only a quarter of MSX IRDCs appear
in their catalog of $Spitzer$ dark clouds for a variety of reasons.
This selection effect, in combination with our requirement that
an object be detected in one or more molecular line transitions,
makes the number of matching clouds reasonable.

Objects from the NIREX comparison set are shown as cyan
diamonds in Figure 13. Most of the points lie within 2 kpc
of equality. Only one object has a wildly divergent distance
estimate, G31.026$-$0.113 (BGPS 4653; $d_{NIREX} \approx 9.5$ kpc),
which has $C = 0.4$ and should have been detected with a
strong near-infrared absorption signature at the near kinematic
distance of $d_0 = 4.5$ kpc. The collection of cyan diamonds with
a systemic positive offset of 1.5 kpc warrants attention. There
is a cluster of objects placed 2$-$4 kpc from the Sun. Most of
these are at $\ell \lesssim 15^\circ$, and uncertainties in both the rotation
curve and stellar model in that region may be contributing to the
offset. Mismatching NIREX distances beyond $d_0 = 4$ kpc have
divergent distance estimates of order the difference between the
Clemens (1985) and Reid et al. (2009) rotation curves for objects
at that velocity.

6. DISCUSSION

6.1. Kinematic Distance Discrimination

6.1.1. EMAFs as Distance Discriminators

The combination of millimeter-wave thermal dust emission
observations with mid-infrared extinction is a powerful method
for resolving the KDA for molecular cloud clumps. By starting
from a catalog of (sub-)millimeter sources, this method is not
limited to mid-infrared-identified IRDCs (catalogs of which
often have large minimum contrast). We are therefore able
to include low-column nearby sources as well as more distant
objects. The 92% success rate compared to distances resolutions
by the GRS team indicates that EMAFs can provide a powerful
means for distance discrimination. Additionally, BGPS objects
placed at the far kinematic distance that agree with the GRS
distance indicate that EMAFs are visible beyond the tangent
point with sufficient backlighting. In comparison with the HISA
KDA-resolution technique employed by Roman-Duval et al.
(2009), only 4% of BGPS objects were placed at the near
kinematic distance yet had no evidence of a HISA signature.
Application of additional prior DPDFs may help to resolve these
discrepancies.

The mid-infrared contrast distributions (Figure 8(c)) of ob-
jects on either side of $d_{tan}$ clearly show that objects placed
at or beyond the tangent point have lower collective contrast,
and would likely not be included in catalogs of IRDCs. These
distributions are consistent with the notion that dark IRDCs
($C \geq 0.2$) are nearby. Since the matching rate between DPDF-
derived distances and those of the GRS is nearly independent
of mid-infrared contrast, the present method extends robust KDA
resolution to EMAFs with lower contrast, roughly doubling the
number of molecular cloud clumps for which well-constrained
distances may be derived.

In addition to improving upon the axiom “if IRDC then
near” for KDA resolution, this method automatically accounts
for the profile of the $8 \mu m$ intensity as a function of Galactic
longitude (Figure 2). The morphological matching process does
not consider $d_{tan}$, and therefore offers a prior probability that is
independent of the kinematic signature of a given object. The
$f_{true}$ limit of visibility for a molecular cloud clump is simply a
function of optical depth (Equation (12)); for instance, an object
with $S_{1.1} = 0.3$ Jy will have $C \geq 0.05$ for $f_{true} \leq 0.76$, but one
with $S_{1.1} = 0.1$ Jy will not meet this contrast threshold if $f_{true}$
exceeds 0.33.

Heightened star-formation activity, which produces excess
$8 \mu m$ emission in its immediate vicinity, does constitute a
complicating factor in application of simple radiative transfer
(Equation (6)). These regions strain the assumption of smooth,
axisymmetric Galactic emission. As an example, we analyzed
the distance resolutions of objects in the W43 region. W43
is defined here by $31.5 \leq l \leq 29.5$, $-0.5 \leq b \leq 0.3$, and $80 \text{ km s}^{-1} \geq v_{LSR} \geq 110 \text{ km s}^{-1}$ (as in Nguyen Luong et al. 2011), and is marked by a white box in Figure 5. Of the 43 EMAF-selected BGPS sources with well-constrained distance estimates in this region, 9 are placed at or beyond the tangent distance by the DPDF method. This is a slightly higher rate than the general sample, but is not significant. The W43 objects are plotted as cyan squares in Figure 9, and obey the empirical $S_1/C = 2.5$ limit for near versus far distance discrimination (Section 5.2.2). Only eight objects could be associated with a GRS-identified $^{13}$CO cloud (Section 5.3.2), and all but one have matching KDA resolutions; the outlier is one of the BGPS objects near the tangent point, where $d$ is used, causing the $> 1 \text{ kpc}$ distance discrepancy. Although the observed Galactic plane consists of clumpy emission atop a more smooth Galactic emission pattern, the simple model used here still returns consistent KDA resolutions, even in more active regions.

While the KDA resolutions for EMAF-selected BGPS objects compare favorably with previously published distance estimates, they are still based upon the assumption of circular orbits about the Galactic center. As highlighted by the case of CH$_3$OH maser G23.66$-$0.13, radial streaming motions can have a significant impact upon the derived kinematic distances. Anderson et al. (2012) presents a detailed analysis of uncertainties involved with the use of kinematic distances in the presence of non-circular motions. Future improvements in kinematic distance measurements will require a full three-dimensional vector model of Galactic motions.

Throughout this analysis we used $T_d = 20 \text{ K}$ for converting BGPS flux densities into $8 \mu\text{m}$ optical depths. The effect of different assumed dust temperatures on KDA resolutions is not a priori predictable. Generating a new set of DPDF$_\text{emaf}$ based on different temperatures, however, is straightforward. The results of KDA resolutions from the posterior DPDFs and GRS distance comparison statistics are shown in Table 5 for the range of $T_d$ found by Battersby et al. (2011). A warmer dust temperature pushes more objects to the near kinematic distance to compensate for a smaller derived $\tau_0$. Interestingly, the GRS success rate is unchanged for $T_d = 25 \text{ K}$, but there are likely many unconsidered systematic effects at play.

The use of EMASs as prior DPDFs for kinematic distance discrimination is directly applicable to all current and future (sub-)millimeter surveys of the Galactic plane. The advantage of starting with a sample of continuum-identified molecular cloud clumps is that mid-infrared extinction may be used to resolve the KDA for many objects that may not be dark enough to be included in IRDC catalogs (e.g., S06, PF09).

Table 5

| $T_d$ (K) | $N_{WC}^a$ | KDA Resolution$^b$ | GRS Comparison |
|----------|------------|------------------|----------------|
|          |            | N | F | T |             |
| 15       | 625        | 416 | 175 | 34 | 218 | 77.5% |
| 20       | 618        | 523 | 70  | 25 | 213 | 91.9% |
| 25       | 605        | 547 | 33  | 25 | 198 | 91.9% |

Notes.

$^a$ Number of well-constrained distance estimates.

$^b$ N: near; F: far; T: tangent point.

$^c$ Distance matching success rate.

is depicted in Figure 14(a). These objects fall under the “well-constrained” KDA resolution criterion (as in Nguyen Luong et al. 2011). A warmer dust temperature pushes more objects to the near kinematic distance, and the probability ratio of the two peaks is also large (i.e., $P_{ML} \geq 0.78$). The example BGPS 4484 (G030.629$+$00.029) is depicted in Figure 14(a). These objects fall under the “well-constrained” condition described in Section 5.2.1, whereby the maximum-likelihood error bars encompass only one kinematic distance peak. For this set of objects, $d_{ML}$ is a reasonable collapse of the DPDF into a single value (with uncertainty). The second set of objects are those with kinematic distances within a kiloparsec of the tangent point. The kinematic distance DPDF for these objects have a shallow saddle feature at $d_{tan}$, as seen in Figure 14(b) for BGPS 4357 (G030.321$+$00.292). Since the main peak of the posterior DPDF is not symmetric, $d_{ML}$ is not a robust reflection of the distance estimate. Therefore, we recommend using $d$ for these sources (listed in Table 3 for this class of object) to more accurately reflect the available distance information. Thus, as long as the full-width of the error bars is less than 2.3 kpc (Section 5.2.1), these sources are considered to have well-constrained distance estimates. The final set of sources are those not meeting either of the above criteria, such as

Figure 14. Example DPDFs for three possible cases. Shown in each panel are DPDF$_{emaf}$ (dashed gray), DPDF$_{emaf}$ (solid cyan), DPDF$_{emaf}$ (dot-dashed gray), and posterior DPDF (solid black). The vertical dot-dashed line in each panel marks the tangent distance along that line of sight. The single-distance estimates are marked as black triangles ($d_{ML}$) and magenta diamonds ($d$). Panel (a) represents a well-constrained KDA far from $d_{tan}$; (b) shows a source near $d_{ML}$; (c) illustrates a source with an unconstrained KDA resolution.

(A color version of this figure is available in the online journal.)

6.1.2. Use of Different Distance Estimates

The DPDF formalism encodes all information about distance determinations for molecular cloud clumps, including likely distance and uncertainty. For some purposes, however, it is useful to have a single distance; Section 3.2 describes two possible options. In the use of the DPDFs produced here, it became apparent that different distance estimates were best applied to different situations. Examples of these situations are shown in Figure 14 to illustrate the difficulties encountered in extracting a single distance from a DPDF. For each panel, the black triangle and magenta diamond mark $d_{ML}$ and $d$, respectively.

The most common situation has well-separated kinematic distance peaks (i.e., the molecular cloud clump is far from $d_{tan}$) and the probability ratio of the two peaks is also large (i.e., $P_{ML} \geq 0.78$). The example BGPS 4484 (G030.629$+$00.029) is depicted in Figure 14(a). These objects fall under the "well-constrained" condition described in Section 5.2.1, whereby the maximum-likelihood error bars encompass only one kinematic distance peak. For this set of objects, $d_{ML}$ is a reasonable collapse of the DPDF into a single value (with uncertainty). The second set of objects are those with kinematic distances within a kiloparsec of the tangent point. The kinematic distance DPDF for these objects have a shallow saddle feature at $d_{tan}$, as seen in Figure 14(b) for BGPS 4357 (G030.321$+$00.292). Since the main peak of the posterior DPDF is not symmetric, $d_{ML}$ is not a robust reflection of the distance estimate. Therefore, we recommend using $d$ for these sources (listed in Table 3 for this class of object) to more accurately reflect the available distance information. Thus, as long as the full-width of the error bars is less than 2.3 kpc (Section 5.2.1), these sources are considered to have well-constrained distance estimates. The final set of sources are those not meeting either of the above criteria, such as
distance options are well-separated, but the DPDFemaf does not.

represents objects associated with neither catalog.

black dotted shows those associated with S06 (×5 for clarity); filled gray
represents objects associated with neither catalog.

BGPS 3352 (G024.533−00.182; Figure 14(c)). The kinematic
distance options are well-separated, but the DPDFemaf does not
place a strong discriminatory constraint. If it is desirable to use
the distances for these sources, we recommend Monte Carlo
sampling distances from the full DPDF in order to include all
distance information about the source (see Section 3.3).

Regardless of the method used, however, care should be taken
to properly propagate the uncertainty in the distance placement.
If only sources in the first category are used, it is important
to remember that matching success rate with GRS-derived
distances was ≈92%. This may be interpreted either as two
sources in 25 were placed at the wrong distance or that there is
a 92% confidence in each of the distance placements.

6.2. EMAF versus IRDC

In this paper, we introduce the nomenclature EMAF for dust-
continuum-identified molecular cloud clump whose emission
morphology matches an absorption feature in mid-infrared maps
of the Galactic plane. Many of these objects are quite dark (C ≳ 0.2) and are identified in IRDC catalogs. To better understand
the overlap between the EMAF and IRDC designations, we
searched through both the S06 and PF09 catalogs to find the
closest IRDC to the location of peak BGPS flux density.
A total of 361 (46%) EMAF-selected BGPS sources lay within
the semi-major axis distance of the centroid of a cloud from one
or both of the catalogs.

By definition, IRDCs have a large mid-infrared contrast, but
EMAFs are selected from thermal dust emission catalogs. As
such, the two groups have different contrast distributions, as seen
in the histograms of Figure 15. BGPS sources that are associated
with an object in the PF09 or S06 catalogs are plotted as black
solid and dotted lines, respectively. The filled gray histogram
represents EMAFs not associated with any IRDC. The bulk of
the non-IRDC objects have C ≳ 0.2, once again confirming that
the EMAF designation allows the use mid-infrared observations
for KDA resolution for objects with low contrast. Of particular
interest are the higher-contrast (C ≳ 0.2) BGPS sources
which do not appear in either IRDC catalog (filled gray).

striking example is the source G035.478−00.298 (BGPS 5631),
shown in the lower-right corner of Figure 3(a). These objects
suggest that it is easier to identify molecular cloud clumps from
(sub-)millimeter data than to try to find intensity decrements in
λ = 8 μm images.

The EMAF-derived KDA resolutions of the IRDC objects
place only a small fraction at the far kinematic distance (3% and
7% for S06 and PF09, respectively). The measured EMAF
contrast for such objects is generally C ≲ 0.2, reinforcing
the notion that dark IRDCs are nearby. Since the fractions of
IRDCs placed beyond dgal are comparable to the GRS distance
mismatch rate (Section 5.3.2), these subsets are not significant.

6.3. Implications for Galactic Structure

6.3.1. Galactic 8 μm Emission

A quick glance at the GLIMPSE mosaics suggests that
the Galactic distribution of 8 μm light cannot be described
simply by a smooth, diffuse model. Distances derived using
the assumption of smooth emission, however, compare favorably to
those derived from 21 cm H i absorption (GRS; Roman-Duval
et al. 2009) and near-infrared extinction mapping (NIREX;
Marshall et al. 2009). These results suggest that Galactic 8 μm
emission may be primarily composed of a diffuse component
punctuated by regions of active star formation. The R12 model
of mid- and far-infrared emission is a greatly simplified reflection
of the Galaxy, neglecting to account for individual small-scale
features. Yet its match, spatially and spectrally, to existing
Galactic plane observations indicates its power. The model,
therefore, provides a solid basis for our distance estimation
technique based on using a broad distance prior to distinguish
between kinematic distance peaks.

While the R12 model was constructed to broadly match
the multi-band observations of the Milky Way, it is useful
to also compare it with external galaxies. Spitzer observations
of SINGS galaxies (Kennicutt et al. 2003) yield a surface density
of in-band emission. Figure 16 depicts the IRAC Band 4 surface
brightness, normalized to Rgal = 8.5 kpc, for a collection of
17 SINGS galaxies, with galaxies represented by their Hubble
stage (T).14 To enable comparison, the R12 model was viewed
externally (see Figure 1) and emission was annularly integrated,
following the SINGS analysis; plotted as a thick black line.
The slope of the Milky Way model at Rgal ≳ 4 kpc is comparable
to the ensemble, but the drop in emission due to the dust hole
carved out by R12 near the Galactic center does not seem to
match extragalactic observations. The model was designed to
match observations from within the disk from the Sun’s location,
however, so discrepancies in the integrated 8 μm emission
profile in the inner Rgal ≲ 3 kpc are likely not relevant.

6.3.2. Spiral Structure

Recent large (sub-)millimeter Galactic plane surveys are
making it possible to trace the spiral structure of the disk.
Comparing the well-constrained KDA resolutions of BGPS
sources with an artist’s conception of the Galaxy based on
Spitzer data (Figure 10), glimmers of organization begin to
appear. While the regions that trigger the collapse of molecular
cloud clumps are likely very localized along spiral density
waves, features in the face-on map of the Galaxy derived

---

14 Hubble stage is a continuous numerical representation of the Hubble type
for a galaxy. T = 0 corresponds to an S0 galaxy, and the Milky Way (SBB-c) is
T ≈ 4 (Binney & Merrifield 1998, p.155).
The Astrophysical Journal, 770:39 (24pp), 2013 June 10

ELLSWORTH-BOWERS et al.

misplace molecular cloud clumps at the far kinematic distance, so distinguishing between the possibilities is unclear.

7. CONCLUSIONS

We developed DPDFs as a new method for distance determinations to molecular cloud clumps in the Galactic plane. Starting from a kinematic distance derived from molecular line observations as the likelihood, prior DPDFs may be applied in a Bayesian manner to resolve the KDA. In this study, we used two external data sets as priors: mid-infrared absorption features, and the Galactic distribution of molecular gas.

The dust in molecular cloud clumps detected by (sub-)millimeter Galactic plane surveys should absorb mid-infrared light and be visible against the broad diffuse PAH emission near \( \lambda = 8 \mu m \). Starting from the BGPS catalog of dust-continuum-identified molecular cloud clumps, we identified 770 EMAFs in the Spitzer/GLIMPSE mosaics. EMAFs may be thought of as generalized IRDCs, and are characterized by their selection from (sub-)millimeter data. With this collection of objects, simple radiative transfer arguments, and a model of Galactic mid-infrared stellar and dust emission, we developed a morphological matching scheme to compare dust emission and absorption. When using the GLIMPSE mosaics to measure apparent absorption features, it is imperative to account for scattering of light within the IRAC camera. This scattering, in concert with the instrumental calibration method, means that diffuse emission will appear brighter than it really is; bright emission will tend to fill in absorption features. The scattered light changes the apparent contrast of absorption features, in addition to any derived properties (such as optical depth, mass, etc.).

Well-constrained KDA resolutions were obtained for 618 objects in this sample: 523 at the near kinematic distance, 25 at the tangent point, and 70 at the far kinematic distance. To corroborate our distance discriminations, we used VLBI maser parallax measurements, KDA resolutions from the GRS, and near-infrared extinction distances as comparison sets. Of the 12 objects associated with maser parallax measurements, none had a discrepant KDA resolution. Distance comparisons with the GRS yielded a 92% success rate nearly independent of mid-infrared contrast. Comparison with the NIREX distances showed only one discrepant KDA resolution, with the remainder being within identified systematic effects. These comparisons illustrate the validity of the present method, including the placement of some EMAFs at the far kinematic distance (approximately 12 distance-matched GRS sources are beyond \( d_{\text{tan}} \)).

Approximately half of the set of EMAFs are associated with an object from the IRDC catalogs of S06 and PF09. Objects associated with IRDCs are mostly relatively dark \( (C \gtrsim 0.2) \); the remainder being largely low-contrast \( (C \lesssim 0.2) \). Interestingly, there are a handful of moderately dark \( (C \gtrsim 0.3) \) EMAFs that are absent from these IRDC catalogs. This suggests that it is perhaps easier to identify molecular cloud clumps first in (sub-)millimeter data, then investigate their mid-infrared properties.

KDA resolutions for EMAFs from the BGPS catalog reveal hints of Galactic structure. Foremost, most detectable Galactic molecular cloud clumps are in the Molecular Ring/Scutum–Centaurus Arm feature between the Sun and the Galactic center. The Sagittarius Arm outside \( \ell = 30^\circ \) is suggested by a collection of EMAFs beyond the tangent point, visible due to backlighting from the more-distant Perseus Arm.
The derivation of DPDFs allows for probabilistic determination of distances to molecular cloud clumps across the Galactic plane. By introducing the concept of an EMAF, we were able to use the mid-infrared GLIMPSE data to resolve the KDA for many more sources than is possible with extant catalogs of IRDCs. Although this method applies only to $\sim 10\%$ of the BGPS catalog, the DPDF framework allows for the incorporation of additional prior DPDFs to expand the number of molecular cloud clumps with well-constrained distance estimates.

The authors thank N. Halverson and J. Kam netzky for useful discussions, S. Carey for help with understanding the scattering within the IRAC camera, and T. Robitaille for assistance with using Hyperion. This work was supported by the National Science Foundation through NSF grant AST-1008577. The BGPS project was supported in part by NSF grant AST-0708403, and was performed at the Caltech Submillimeter Observatory (CSO), supported by NSF grants AST-0540882 and AST-0836826. The CSO was operated by Caltech under contract from the NSF. Support for the development of Bolocam was provided by NSF grants AST-9980846 and AST-0206158. E.R. and S.M. are supported by a Discovery Grant from NSERC of Canada. N.J.E. is supported by NSF grant AST-1109116. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by JPL, Caltech under a contract with NASA. This work utilized the Janus supercomputer, which is supported by the NSF (CNS-0821794) and the University of Colorado, Boulder. Janus is a joint effort of CU-Boulder, CU-Denver, and NCAR. The GRS is a joint project of Boston University and Five College Radio Astronomy Observatory, funded by the NSF under grants AST-9800334, AST-0098562, AST-0100793, AST-0228993, and AST-0507657.

APPENDIX A

COMPUTING A BAND-AVERAGED DUST OPACITY: SPITZER IRAC BAND 4

The apparent dust opacity of extinction features in broadband images is related to the dust opacity as a function of frequency and the spectrum of the light being absorbed. The IRAC Band 4 bandpass includes several distinct emission features from PAH molecules, as well as the complex behavior of the dust opacity near the 10 $\mu$m silicate feature. In this appendix, we derive a band-averaged dust opacity $\langle \kappa \rangle_{\text{band}}$ for use with the GLIMPSE mosaics.

Given the simple radiative transfer model of Equation (6), the intensity transmitted through a dust cloud is

$$I_{\text{trans}} = I_{\text{back}} e^{-\tau_{\text{band}}}, \quad (A1)$$

where $I_{\text{back}}$ is the background light (from the cloud to large heliocentric distance), and $I_{\text{trans}}$ is the transmitted light exiting the cloud on the near side (i.e., not including emission between the cloud and the observer). The band-averaged optical depth is related to the apparent dust opacity by $\langle \tau \rangle_{\text{band}} = \Sigma \langle \kappa \rangle_{\text{band}}$, where $\Sigma$ is the mass surface density of dust. The band-averaged dust opacity is therefore

$$\langle \kappa \rangle_{\text{band}} = -\frac{1}{\Sigma} \ln \left( \frac{I_{\text{trans}}}{I_{\text{back}}} \right). \quad (A2)$$

The ratio of intensities is computed from the band average over each quantity,

$$\frac{I_{\text{trans}}}{I_{\text{back}}} = \frac{\langle I_{\text{back},v} e^{-\tau_{\text{band}}} \rangle_{\text{band}}}{\langle I_{\text{back},v} \rangle_{\text{band}}} = \frac{\int R_{\text{band}}(v) I_{\text{back},v} e^{-\tau_{\text{band}}}}{\int R_{\text{band}}(v) I_{\text{back},v} dv}, \quad (A3)$$

where the $v$ subscript denotes that quantity as a function of frequency, and $R_{\text{band}}(v)$ is the relative frequency response per unit power for the instrument. Since both averages are over the same response bandpass, the usual normalization terms cancel.

The typical radius of an IRDC is small ($\sim 1$ pc; Rathborne et al. 2006) compared to the accumulated path length ($D$) for the diffuse background (several kiloparsecs), so the intensity $I_{\text{back},v} = \int j_{v} ds$ may be approximated by $I_{\text{back},v} = j_{v} D$, where $j_{v}$ is the emission coefficient. Additionally, the relative response per unit power, $R_{\text{band}}(v)$, is proportional to $(1/hv) S_{\text{band}}(v)$, where $S_{\text{band}}(v)$ is the relative response per photon.\(^{15}\) Cancelling frequency-independent quantities and inserting the intensity ratio into Equation (A2) yields the desired band-averaged dust opacity,

$$\langle \kappa \rangle_{\text{band}} = -\ln \left[ \frac{\int v^{-1} S_{\text{band}}(v) j_{v} e^{-\kappa_{\text{band}}}}{\int v^{-1} S_{\text{band}}(v) j_{v} dv} \right]. \quad (A4)$$

For the emission spectra ($j_{v}$), we used the dust emission models of Draine & Li (2007), which contain a mixture of grain sizes in addition to a variable PAH mass fraction ($q_{\text{PAH}}$). The various emission spectra were derived by irradiating the dust with starlight intensity fields having a tunable minimum value $U_{\text{min}}$ relative to the local interstellar radiation field ($U = 1$).

The choice of dust opacity model ($\kappa_{\text{v}}$) has a nontrivial effect on the derived band-averaged opacity. Three different models were analyzed, and are shown in Table 6. First is the OH5 model (dust grains with thin ice mantles, coagulating at $10^{6}$ cm$^{-3}$ for

\(^{15}\) Obtained from http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/calibrationfiles/spectralresponse.
10^7 yr; Ossenkopf & Henning 1994) used for determining the dust opacity at \( \lambda = 1.1 \) mm for the BGPS. The remaining models were presented in Weingartner & Draine (2001, hereafter WD01), with updated normalizations given by Draine (2003).16 The second of the three models is the \( R_V = 3.1 \) Milky Way model, tried even though this value of the color excess per magnitude extinction is consistent with the diffuse ISM and does not hold for regions of dense gas. The final model utilizes case A for \( R_V = 5.5 \) (consistent with observations of molecular clouds), which sought to minimize the extinction differences between observation and model, while also including a penalty term to keep dust grain volume from exceeding abundance/depletion limits (WD01). For each dust model, \( \langle \kappa \rangle_{\text{band}} \) was computed for three values of each \( q_{\text{PAH}} \) and \( U_{\text{min}} \) (Table 6).

The minimum value of the starlight intensity field has very little effect on the band-averaged dust opacity, meaning that the derived \( \langle \kappa \rangle_{\text{band}} \) are valid for a wide range of environments. An order of magnitude change in the assumed PAH mass fraction causes only a 2% difference in the derived opacity for the OH5 model, but the spread is 10% for the others. Draine & Li (2007) cite \( q_{\text{PAH}} = 4.58\% \) as best matching observations of the Milky Way.

The OH5 model is the preferred description of dust at (sub-)millimeter wavelengths (cf. Rathborne et al. 2006; Schuller et al. 2009; Aguirre et al. 2011), and has been used by previous studies for estimating \( \langle \kappa \rangle_{\text{band}} \) for IRAC Band 4 images (Butler & Tan 2009; Battersby et al. 2010). That model was computed from theory for coagulated grains (aggregates of smaller particles, with some voids) surrounded by an ice mantle. In contrast, the WD01 dust models utilized simple geometry (PAH molecules for very small grains, and graphite and olivine spheres for larger grains) and sought to fit a dust size distribution to parameterized observed extinction.

The connection to observed extinction in the infrared led us to choose the WD01 \( R_V = 5.5 \) model for this work. Following Draine & Li (2007), we used \( q_{\text{PAH}} = 4.58\% \) and \( U_{\text{min}} = 1.0 \) to compute \( \kappa_8 = \langle \kappa \rangle_{\text{band}} = 825 \text{ cm}^2 \text{ g}^{-1} \) of dust. For comparison, the corresponding value from the OH5 model yields \( \kappa_8 = 1167 \text{ cm}^2 \text{ g}^{-1} \), a \approx 40% difference. We note that the preferred WD01 model predicts a BGPS dust opacity \( \kappa_{11} = 0.272 \text{ cm}^2 \text{ g}^{-1} \) of dust, approximately one quarter the value from OH5.

**APPENDIX B**

**Spitzer IRAC SCATTERING CORRECTION FACTORS**

The IRAC camera on the *Spitzer Space Telescope* suffers from internal scattering within the detector arrays, particularly Bands 3 and 4. The scattering is such that a fraction of the incident light on a pixel is distributed throughout the entire array (Reach et al. 2005; IRAC Instrument Handbook). Image frames are converted into physical units (MJy sr^{-1}) using point-source calibration data; point-source aperture photometry is therefore accurate because the calibration takes into account the light scattered out of the aperture and into blank sky pixels. Observed extended emission, however, has light from other areas of the array scattered into each pixel as well, and so will appear brighter than it really is given the point-source calibration. For the broad, diffuse emission of the Galactic plane in IRAC Band 4, there is a roughly constant positive offset of the measured intensity in each frame.

For absorption features in the Band 4 images (EMAFs), however, the scattering cannot be corrected for by simple multiplicative aperture corrections. Because bright emission from surrounding regions is scattered into an EMAF, it will have a lower apparent contrast. To correct for this effect, an estimate of the scattered light in a frame must be subtracted from each frame (S. Carey 2010, private communication), as was done in this study for a pixel-by-pixel comparison between GLIMPSE and synthetic \( 8 \mu \text{m} \) images.

Quantities such as contrast and optical depth for EMAFs may be derived from the GLIMPSE mosaics (e.g., Butler & Tan 2009; PF09), but a scattering correction must be applied (cf. Battersby et al. 2010). Because careful subtraction of scattered light is not always necessary for a given application, correction factors may be derived for quantities measured directly from the IRAC Band 4 data. In this appendix, we derive correction factors for mid-infrared contrast \( (C) \), \( 8 \mu \text{m} \) optical depth \( (\tau_8) \), and foreground fraction of \( 8 \mu \text{m} \) emission \( (f_{\text{fore}}) \).

For regions of broad diffuse emission punctuated by dark clouds, the observed intensities \( I_0 \) and \( I_1 \) of the background and EMAF, respectively, are related to the actual intensities \( S_0 \) and \( S_1 \) by

\[
I_0 = S_0 + X, \quad \text{and} \quad I_1 = S_1 + X, \quad (B1)
\]

where \( X = \xi S_0 \) is the amount of scattered light, approximated by the fraction \( \xi = (1 - 0.737) = 0.263 \) of incident diffuse light scattered throughout the array, and 0.737 is the infinite-aperture correction for Band 4 from Reach et al. (2005). Rearranging to compute the true intensities from observed quantities yields

\[
S_0 = \frac{I_0}{(1 + \xi)}, \quad \text{and} \quad S_1 = \frac{I_1 - I_0}{(1 + \xi)}. \quad (B3)
\]

While the subtractive correction (Equation (B1)) for the diffuse background is equivalent to a multiplicative correction (Equation (B3)), correcting for the intensity within the EMAF is more complicated. To compute the true contrast of an EMAF, we begin with Equation (11): \( C_{\text{true}} = 1 - \frac{S_i}{S_0} \).

Inserting Equations (B3) and (B4), the true contrast becomes

\[
C_{\text{true}} = \left(1 - \frac{I_1}{I_0}\right)(1 + \xi) = C_{\text{meas}} (1 + \xi), \quad (B6)
\]

where \( C_{\text{meas}} \) is the quantity measured directly from the GLIMPSE images. The measured contrast will be smaller than reality, leading to an underestimate of optical depth and other quantities.

With a measured EMAF contrast, it is possible to estimate the optical depth of a cloud or the foreground fraction of diffuse emission, given an assumption about the other. Equation (12) may be rearranged to solve for either quantity in terms of

\[16\] http://www.astro.princeton.edu/~draine/dust/dustmix.html
The local coordinates are transformed to the Galactocentric coordinates, where the +z axis is directed along the Sun–Galactic center line, and z points north out of the plane,

\[
\begin{pmatrix}
 x_1 \\
y_1 \\
z_1
\end{pmatrix} = \begin{pmatrix}
d_\odot \\
d_\odot \\
d_\odot
\end{pmatrix} \begin{pmatrix}
 \cos l \cos b \\
 \sin l \cos b \\
 \sin b
\end{pmatrix}.
\]

The local coordinates are transformed to the Galactocentric frame by (1) rotation by 180° in the x–y plane to place the +x-axis pointing away from the GC, (2) translation of the coordinate axes to place the origin at the GC, and finally (3) rotation by the angle θ in the x–z plane to place the +x-axis along the Galactic midplane (rather than along the Sun–Galactic center line). The transformation may be written as

\[
\begin{pmatrix}
x_{\text{gal}} \\
y_{\text{gal}} \\
z_{\text{gal}}
\end{pmatrix} = \begin{pmatrix}
 \cos \theta & 0 & -\sin \theta \\
 0 & 1 & 0 \\
 \sin \theta & 0 & \cos \theta
\end{pmatrix} \begin{pmatrix}
 1 & 0 & 0 \\
 0 & 1 & 0 \\
 0 & 0 & 1
\end{pmatrix}
\times \begin{pmatrix}
 -1 \\
 0 \\
 0
\end{pmatrix}.
\]

where the lateral translation requires an augmented (affine translation) matrix. The resulting Galactocentric Cartesian coordinates are

\[
\begin{pmatrix}
x_{\text{gal}} \\
y_{\text{gal}} \\
z_{\text{gal}}
\end{pmatrix} = \begin{pmatrix}
 R_0 \cos \theta - d_\odot (\cos l \cos b \cos \theta + \sin b \sin \theta) \\
 -d_\odot \sin l \cos b \\
 R_0 \sin \theta - d_\odot (\cos l \cos b \sin \theta - \sin b \cos \theta)
\end{pmatrix}.
\]

The actual foreground fraction will be smaller than that measured directly from GLIMPSE images, with the difference being less at large f_{fore}. Any f_{fore,true} ≤ 0.2 maps to zero true foreground fraction, as negative values are not physical; such values arise from uncertainty in C and the derivation of τ_b from (sub-)millimeter data.

APPENDIX C

THE VERTICAL SOLAR OFFSET AND CONVERTING (ℓ, b, d_\odot) INTO (R_{gal}, φ, z)

Deriving Galactocentric positions of objects in the Milky Way requires a coordinate transformation of the triad (ℓ, b, d_\odot), where d_\odot is the heliocentric distance along the line of sight toward (ℓ, b). The Galactic coordinate system was defined assuming the Sun is at the midplane of the disk (Blauw et al. 1960), but more recent studies have measured a vertical solar offset of ≈25 pc above the midplane (Humphreys & Larsen 1995; Juric et al. 2008). Since the vertical scale height of the molecular gas layer in the disk is small (HWHM ≈ 60 pc; Bronfman et al. 1988), neglecting to account for the solar offset may introduce a systematic bias in the derived vertical distributions of components of the Galactic disk.

The coordinate transformation is done in Cartesian coordinates. First the triad (ℓ, b, d_\odot) is converted into local Cartesian coordinates, where the x-axis is directed along the Sun–Galactic center line, and z points north out of the plane,

\[
\begin{pmatrix}
x_1 \\
y_1 \\
z_1
\end{pmatrix} = \begin{pmatrix}
d_\odot \\
d_\odot \\
d_\odot
\end{pmatrix} \begin{pmatrix}
 \cos l \cos b \\
 \sin l \cos b \\
 \sin b
\end{pmatrix}.
\]

The rotation angle θ = sin^(-1)(z_0/R_0), where z_0 = 25 pc, corrects for the Sun’s vertical displacement above the midplane. Galactocentric positions in the cylindrical coordinates (R_{gal}, φ, z) may be extracted from Equation (C3) in the usual manner. The rotation by θ is most important for the derived z_{gal}, and has negligible effect on R_{gal} and φ.

REFERENCES

Aguirre, J. E., Ginsburg, A. G., Dunham, M. K., et al. 2011, ApJS, 192, 4 (A11)
Anderson, L. D., & Bania, T. M. 2009, ApJ, 690, 706
Anderson, L. D., Bania, T. M., Balser, D. S., & Rood, R. T. 2012, ApJ, 754, 62
Bally, J., Anderson, L. D., Batterby, C., et al. 2010, A&A, 518, L90
Bartkiewicz, A., Brunthaler, A., Szymczak, M., van Langevelde, H. J., & Reid, M. J. 2008, A&A, 490, 787
Battersby, C., Bally, J., Ginsburg, A., et al. 2011, A&A, 535, A128
Battersby, C., Bally, J., Jackson, J. M., et al. 2010, ApJ, 721, 222
Benjamin, R. A., Churchwell, E., Babler, B. L., et al. 2003, PASP, 115, 953
Benjamin, R. A., Churchwell, E., Babler, B. L., et al. 2005, ApJL, 630, L149
Binney, J., & Merrifield, M. 1998, Galactic Astronomy (Princeton: Princeton Univ. Press)
Blaauw, A., Gum, C. S., Pawskey, J. L., & Westerhout, G. 1960, MNRS, 121, 123
Bronfman, L., Cohen, R. S., Alvarez, H., May, J., & Thaddeus, P. 1988, ApJ, 342, 248
Brunthaler, A., Reid, M. J., Menten, K. M., et al. 2009, ApJ, 693, 424
Brunthaler, A., Reid, M. J., Menten, K. M., et al. 2011, AN, 332, 461
Butler, M. J., & Tan, J. C. 2009, ApJ, 690, 484
Dame, T. M., & Thaddeus P. 2008, ApJ, 683, L143
Dobbs, C. L., & Burkert, A. 2012, MNRAS, 421, 2940
Draine, B. T. 2003, ARA&A, 41, 241
Dobbs, C. L., & Burkert, A. 2012, MNRAS, 421, 2940
Draine, B. T., & Li, A. 2007, ApJ, 657, 810
Dunham, M. K., Rosolowsky, E., Evans, N. J. II, Cyganowski, C., & Urquhart, J. S. 2011, ApJ, 741, 110
Eden, D. J., Moore, T. J. T., Plume, R., & Morgan, L. K. 2012, MNRAS, 422, 3178
Enoch, M. L., Glenn, J., Evans, N. J. II, et al. 2007, ApJ, 666, 982
Enoch, M. L., Young, K. E., Glenn, J., et al. 2006, ApJ, 638, 293
Evans, N. J. II 1999, ARA&A, 37, 311
Foster, J. B., Stead, J. J., Benjamin, R. A., Hoare, M. G., & Jackson, J. M. 2012, ApJ, 751, 157
Fukui, R. 1999, A&A, 345, 787
Gibson, S. J., Taylor, A. R., Higgs, L. A., Brun, C. M., & Dewdney, P. E. 2005, ApJ, 626, 195
Ginsburg, A. G., Rosolowsky, E., Glenn, J., et al. 2013, ApJS, submitted
Humphreys, R. M., & Larsen, J. A. 1995, AJ, 110, 2183
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
Johnstone, D., Fiege, J. D., Redman, R. O., Feldman, P. A., & Carey, S. J. 2003, ApJ, 588, L37

Ellsworth-Bowers et al.

The local coordinates are transformed to the Galactocentric coordinates with the formula for the optical depth (from which follows surface mass density) given by

\[
\tau_{b,\text{true}} = -\ln \left[ 1 - \frac{C_{\text{true}}}{1 - f_{\text{fore}}} \right] = -\ln \left[ 1 - \frac{C_{\text{true}}(1 + \xi)}{1 - f_{\text{fore}}} \right], \quad (B7)
\]

assuming a model that yields f_{fore} (as in Butler & Tan 2009). The true value of τ_b will be larger by up to a factor of two for C_{true} ≳ 0.5. If, instead, the foreground fraction is desired given an external estimate of τ_b (such as from (sub-)millimeter thermal dust continuum data; as in PF09), the true value is given by

\[
f_{\text{fore,true}} = 1 - \frac{C_{\text{true}}(1 + \xi)}{1 - e^{-\tau_b}} = \left( 1 - \frac{C_{\text{true}}(1 + \xi)}{1 - e^{-\tau_b}} \right) (1 + \xi) - \xi = f_{\text{fore,meas}} (1 + \xi) - \xi. \quad (B8)
\]

The rotation angle θ = sin^(-1)(z_0/R_0), where z_0 = 25 pc, corrects for the Sun’s vertical displacement above the midplane. Galactocentric positions in the cylindrical coordinates (R_{gal}, φ, z) may be extracted from Equation (C3) in the usual manner. The rotation by θ is most important for the derived z_{gal}, and has negligible effect on R_{gal} and φ.
