The Warm Spitzer Mission: Opportunities to Study Galactic Structure and the Interstellar Medium

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Abstract. The Spitzer Space Telescope Warm Mission capability, specifically broadband IRAC imaging at 3.6 and 4.5μm, provides a unique opportunity to probe the content and structure of the Milky Way's disk, particularly along lines of sight that suffer significant interstellar obscuration. This white paper examines the factors that favor and constrain the application of a warm Spitzer to Galactic structure and interstellar medium science. Although the paper briefly discusses some specific survey choices, its primary purpose is to highlight the value of an extended Spitzer mission and outline the factors that might influence the construction of a large proposal focused on Galactic science in the future.

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1. INTRODUCTION

There is only one galaxy in the sky for which we can truly obtain a three dimensional view of its internal structure: the Milky Way. Our view from within the Galaxy removes many of the factors that limit the study of distant galaxies. With the high spatial resolution resulting from proximity one can resolve different stellar populations and spatial components of the Milky Way that appear only in the integrated light of other galaxies. Historically, the two principal difficulties in making progress in Galactic stellar structure have been the large area of the sky that must be covered uniformly and the presence of significant interstellar obscuration. The Spitzer/IRAC Warm Mission offers a unique solution to these issues.

Making the case, however, for extending Spitzer's Galactic plane coverage to the entire Galactic disk with warm mission observations is more difficult than it might seem. This difficultly does not arise from the shortcomings of Spitzer's warm capabilities, but instead arises from considering the *unique* contributions possible with Spitzer in the context of the wealth of existing, and soon to be available, space and ground-based survey data. For example:

- Visible and near-infrared wavelengths – SDSS and 2MASS have already provided detailed star count and population statistics. 2MASS, in particular, delivers diagnostics deep in the Galactic plane. Unlike Spitzer IRAC Bands 1 and 2, visual and near-infrared broadband colors are sensitive to stellar spectral and luminosity class, so these surveys support both star counts studies and true 3-dimensional reconstruction using selected populations as crude standard candles. 2MASS, for example, can detect and classify red clump stars at distances of $\sim$10kpc. On the other hand, Spitzer's IRAC Bands 1 and 2 fall in the Rayleigh-Jeans portion of most stellar spectral energy distributions, thus most stars have the indistinguishable IRAC colors and population analysis is not possible. Spitzer, nevertheless has a unique advantage over these "short" wavelength surveys in its ability to penetrate interstellar extinction. Combined with the available near-infrared data, Spitzer's warm capabilities provide a means of establishing the extinction to individual stars, and thus can be leveraged to inform a near-infrared view of the Milky Way largely free of Galactic extinction.

- Mid-infrared wavelengths – The Wide Field Infrared Survey Explorer (WISE) will launch in late 2009 and provide full-sky coverage at 3.3, 4.7, 12, and 23 μm during a 7-month primary mission. The two short-wavelength WISE bands effectively duplicate the available IRAC warm mission spectral bandpasses with 120 and 160 μJy (5σ) sensitivity in unconfused regions - essentially the same sensitivity as for GLIMPSE-style coverage. WISE, however, will have a 6 arcsecond FWHM PSF at 3.3 and 4.7 μm compared with 2 arcseconds for IRAC bands 1 and 2, giving Spitzer a substantial advantage in source confused regions.

In the context of these existing and future capabilities, the Spitzer warm mission still provides unique scientific opportunity to extend our knowledge of the structure of the Milky Way. Two significant examples are:

- Although WISE will survey the entire sky, Spitzer enjoys greater spatial resolution and can surpass WISE's sensitivity in modest integration time. Source confusion then defines the regions in which Spitzer will be most effective and, conversely, those in which WISE coverage alone may be sufficient for illuminating Galactic structure.
- Many regions of the Galactic plane suffer substantial extinction even at near-infrared wavelengths. At low Galactic latitude some of the most interesting features of the Milky Way's disk (e.g. bars, interacting dwarf satellites, and spiral arms) lie hidden behind the dust and are inaccessible or poorly defined in near-infrared surveys. With its ability to penetrate extinction, and to obtain higher sensitivity at higher spatial resolution than WISE, Spitzer has a unique niche to ally with near-infrared surveys such as 2MASS and UKIDSS to lift the veil of extinction in regions where extinction impairs the near-infrared surveys.

2. COMPARISONS OF PAST, PRESENT, AND FUTURE SURVEYS

Figure 1 shows the point source sensitivities and wavebands covered by several generations of infrared surveys. Since the ground-breaking IRAS survey, infrared surveys have delivered ever increasing sensitivity and improved angular resolution. Included in

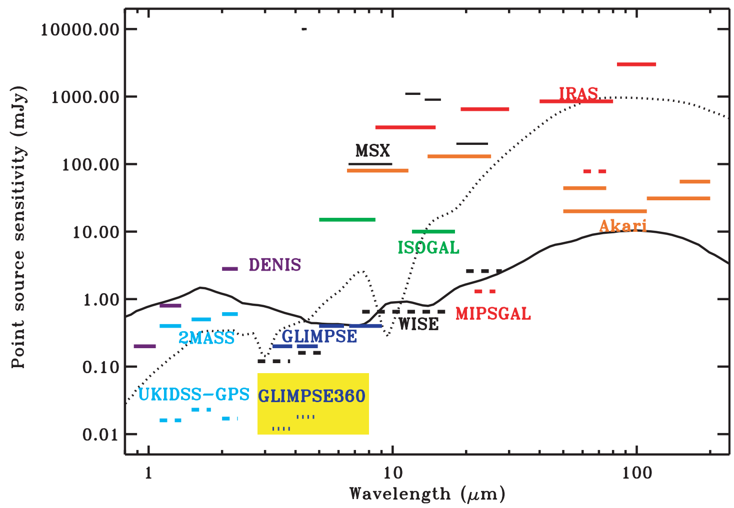

FIGURE 1. A comparison of GLIMPSE and GLIMPSE360 sensitivity limit to the sensitivity of other ground and space-based infrared surveys. This comparison shows the good match in sensitivity between GLIMPSE and 2MASS, and GLIMPSE360 and UKIDSS. The curves show model spectra of Whitney et al. [1] for a 1 L_o T Tauri star at a distance of 0.7 kpc (solid) and a deeply embedded 1 L_o protostar at a distance of 0.6 kpc(dotted).

this plot are the point source sensitivity of GLIMPSE, a shallow, but large area survey which consisted of (at least) two 2 second integrations over the galactic longitude range $|l| < 65^\circ$ and $|b| < 1^\circ$, with some selected vertical extensions at selected longitudes (See Figure 2). The depth of the four-band GLIMPSE survey is well matched to the three-band near-infrared sensitivity of 2MASS. This combined seven-band data set is especially powerful for analyzing Galactic stellar structure and identifying different classes of sources, such as carbon stars, AGB stars, red clump giants, Wolf-Rayet stars, etc.

Figure 1 also shows the point source sensitivity of a potential Warm Spitzer program, hereafter GLIMPSE360. This survey would be deeper than GLIMPSE, consisting of 12 second dithered HDR mode observations with two epochs of coverage, similar to the strategy used for the SAGE legacy project. This style of coverage takes approximately twice as long as GLIMPSE,[1] but goes significantly deeper. Like the GLIMPSE/2MASS combination, the combination of GLIMPSE360 data with data from the Northern hemisphere UKIDSS-GPS (UKIRT Infrared Deep Sky Survey-Galactic Plane Survey), will provide a five band combination to fainter than 17.5 mag in all bands.[2] It should also be noted that most of the UKIDSS-GPS survey region (see Table 1) has yet to be comprehensively covered by Spitzer in any wavelength range.

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[1] The GLIMPSE style observing strategy covers 0.55 square degrees/hour, while GLIMPSE360 style averages 0.227 square degrees/hour.

[2] The GLIMPSE360 5σ limits would be 18.4 and 17.5 magnitude in the 3.6 and 4.5 μm IRAC bands. The limiting magnitudes for UKIDSS-GPS are 20, 19.1, and 19.0 for J, H, and K bands respectively. See `www.ukidss.org` for more information.

TABLE 1. Summary of Infrared Galactic Plane and All-Sky Surveys

	Wavebands (μm)	Resolution (arcsec)	Sensitivity*
DENIS	0.97,1.22,2.16	1-3	0.2,0.8,2.8 mJy
2MASS	1.22,1.65,2.16	2	0.4,0.5,0.6 mJy
UKIDSS-GPS	1.2, 1.6, 2.2	0.5	0.016,0.023, 0.017 mJy
GLIMPSE	3.6,4.5,5.8,8.0	≤ 2	0.2,0.2,0.4,0.4 mJy
GLIMPSE360	3.6,4.5	≤ 2	0.012, 0.018 mJy
WISE	3.3, 4.7, 12, 24	6-10	0.12, 0.16, 0.65, 2.6 mJy
MSX	4.1,8.3,12,14,21	18.3	10000,100,1100,900,200 mJy
ISOGAL†	7,15	6	15,10 mJy
Akari**	9.1,18.3,62.5,80,155,175	5–44	20-100 mJy
IRAS	12,24,60,100	25–100	350,650,850 3000 mJy
Hershel/Hi-Gal‡	60-600	4 – 40	$\sim$100 mJy
COBE/DIRBE§	1.25–240	0.7°	0.01-1.0 MJy sr^{-1}

* 5σ point source sensitivity
† Survey covered non-continuous regions of Galactic plane
** Formerly Astro-F
‡ Galactic plane survey still being formulated
§ DIRBE photometric bands are 1.25, 2.2, 3.5, 4.9, 12, 25, 60, 100, 140, and 240 μm. We report the diffuse flux sensitivity rather than point source sensitivity due to the large beam size.

Also important to a Warm Spitzer Galactic plane survey is the coming deluge of complementary longer wavelength data from MIPSGAL, WISE, Akari, and Herschel (for which a galactic survey, Hi-Gal, is currently being developed; Molinari et al. [2]). While shorter wavelengths characterize stars and embedded sources, these longer wavelength bands are vital for the detection of circumstellar or interstellar dust. For YSOs, for example, data at all near- and mid-infrared bandpasses are necessary to provide meaningful constraints on the viewing geometry, stellar mass, accretion rate and disk geometries of these objects (Robitaille et al. [3]).

Angular resolution, and the related issue of source confusion, further distinguish existing and future surveys. Table 2 shows that the latitude-averaged confusion limit for GLIMPSE is approximately 0.5 to 1.0 magnitudes brighter than the sensitivity limit even for this shallow survey. Toward the Galactic center confusion abates rapidly with increasing Galactic latitude, and slowly (13.3 to 13.6 mag) with increasing longitude. Confusion estimates based on source counts from 2MASS, UKIDSS and previous IRAC observations will help inform the design of any large-area warm Spitzer survey.

For reference, if 6000 hours of warm mission time were devoted to a large-area Galactic plane survey, that allocation could enable:

- a GLIMPSE-style (two 2-second exposures for each sky location) survey of 3300 square degrees. Spread uniformly in longitude (resurveying the 388 square degrees already covered by GLIMPSE, GLIMPSE2, and GLIMPSE 3D), this survey would cover a latitude range of $|b| < 4.6°$.
- a GLIMPSE360-style (two 12-second exposures for each sky location) survey of 1360 square degrees, equivalent to a full-plane survey with $|b| < 1.9°$.

TABLE 2. GLIMPSE Catalog Information

IRAC band (μm)	S_0* (Jy)	A_λ/A_K†	m_{sens} (mag)	m_{sat} (mag)	m_{conf}** (mag)
3.55	277.5	0.56 ± 0.06	14.2	7.0	13.3−13.6
4.49	179.5	0.43 ± 0.08	14.1	6.5	13.3−13.6
5.66	116.5	0.43 ± 0.10	11.9	4.0	11.7−12.3
7.84	63.13	0.43 ± 0.10	9.5	4.0	11.0−12.4

* Vega isophotal wavelengths and IRAC zero magnitude flux from Reach et al. (2005)

† Extinction from Indebetouw et al. [4]

** Confusion limit varies over the longitude range $|l| = 10^\circ$ to $|l| = 65^\circ$.

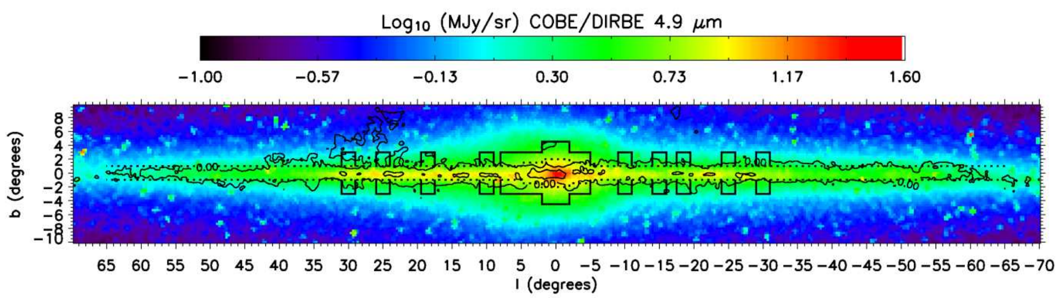

FIGURE 2. COBE/DIRBE 4.9 micron map of the Galactic plane. Irregular contours show regions of $A_K > 1$ ($A_V \sim 10$) as inferred from Dame CO maps. Straight lines show the area covered by GLIMPSE (dotted) and GLIMPSE-3D (solid) survey.

3. LIMITATIONS IMPOSED BY GALACTIC PLANE CONFUSION

Confusion plays a significant role in defining the characteristics and priorities for a warm Spitzer galactic structure campaign, especially when making direct comparisons with the capabilities of the upcoming WISE mission. In particular, the higest priority lines of sight for a Spitzer warm survey are those in which Spitzer's superior source confusion limit ($2''$ FWHM vs. $6''$ FWHM for WISE) yields significant advantage for Spitzer. One, however, must also account for directions in which confusion noise will thwart Spitzer's advantage of being able to improve sensitivity with longer integrations.

Estimating confusion noise for any direction requires either observations that extend to or below the flux limits under consideration or extrapolation of source counts at brighter flux limits with some knowledge of the power law coefficient, α, of the $\frac{\log N}{\log S}$ relation. Lacking the former for most lines of sight in the Galaxy, we have used the MSX 8 μm source counts as the normalization for the confusion noise estimate. Since stars have Rayleigh-Jeans spectral energy distributions at mid-infrared wavelengths we extend these confusion predictions to wavelengths other than 8μm by scaling by λ^2.

The distribution of Galactic stars is non-Euclidean. In the outer Milky Way, counts

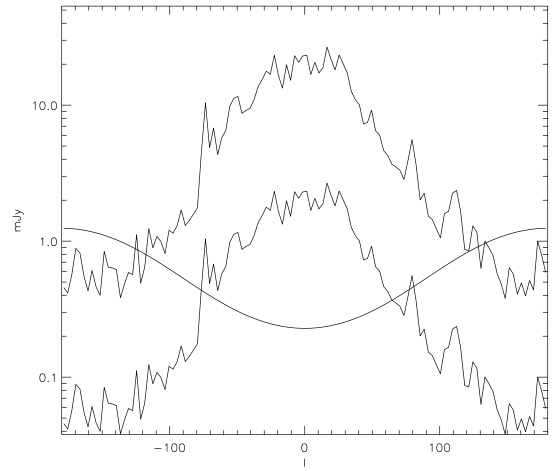

FIGURE 3. A plot of Galactic plane source confusion vs. longitude estimated from MSX 8μm source counts for a 2″ FWHM beam (lower jagged curve) and for a 6″ FWHM beam (upper jagged curve). The curve has been scaled to be representative of IRAC Band 1 assuming the primary source of confusion has a Rayleigh-Jeans spectral energy distribution. The smooth curve represents a K3III star at a galactocentric distance of 20 kpc - a red clump star in the outer Galactic disk.

increase less rapidly with decreasing flux compared with a uniform distribution of targets due to the decline in disk surface density with distance. Model estimates (T. Jarrett, personal communication)) and empirical measurements (based on 2MASS) of the $\frac{\log N}{\log S}$ power law coefficient yield a slope of $\alpha \sim -0.88$ - shallower than the Euclidian case. We have used this coefficient for our estimate of source confusion noise at the Spitzer/WISE flux density levels. In fact, at these flux density levels extragalactic populations begin to dominate over stars while at the same time Galactic star counts begin to decline in the outer disk leading to some uncertainty in the proper value of α for estimates of the confusion limit. The confusion analysis that follows should be considered uncertain to about a factor of two pending direct measurement of in-plane confusion in the outer Milky Way.

In the inner Milky Way confusion dominates and is well estimated by GLIMPSE at the flux levels of interest. Overall the plots suggest that there are two distinct confusion regimes of interest:

- *The inner Milky Way ($|l| < 90°$):* Spitzer and WISE are both confused near the plane over this range of longitudes. Spitzer enjoys nearly an order of magnitude better sensitivity relative to WISE owing to its better FWHM. At the same time, Spitzer achieves sensitivity better than the confusion limit in the two 2-second exposures characteristic of the original GLIMPSE survey. Gains from increasing the base exposure time to 12-seconds will be limited (except at high galactic latitude).
- *The outer disk ($|l| > 90°$):* WISE remains source confused at these longitudes. Spitzer again reaps significant gains over WISE in GLIMPSE-like exposure times, but more importantly Spitzer can take full advantage of pairs of 12-second frames.

4. GALACTIC SCIENCE IN THE WARM SPITZER MISSION

Three principal scientific goals motivated the GLIMPSE survey. Much of the science that will be accomplished with a Warm Spitzer mission will be extensions of these results to cover the whole plane to deeper magnitudes and higher latitudes. As of June 2007, data from the GLIMPSE project has been used in a total of 27 papers by members of the GLIMPSE team and 41 papers by the community at large. The principal goals of GLIMPSE were:

1. *To provide a uniform stellar census of the Galaxy.* Analysis of the GLIMPSE point source catalog (Benjamin et al. [5], Benjamin et al. in prep.) has provided convincing confirmation of two previously under-appreciated features of Galactic structure: (1) the presence of a long ($R = 4.5$ kpc), thin, stellar bar oriented at 45° with respect to the Sun-Galactic center line, *in addition to* the shorter, thicker bar oriented at $\sim 20^\circ$ characterized by COBE and microlensing studies (Nishiyama et al. [6], Cabrera-Lavers et al. [7]), (2) the lack of stellar counterpart for the Sagittarius arm (Drimmel [8]) together with a convincing detection of the Centaurus spiral arm tangency, supporting the hypothesis that the Milky Way is a two-armed spiral in mass density (traced by mid-infrared light) and a four-armed spiral in star formation. GLIMPSE data are also being used to characterize the scalelength of the stellar disk, the structure the Galactic bulge, and (to a limited extent) the vertical structure of the disk, bar, and bulge.
2. *To provide a unbiased survey of star formation in the inner galaxy.* The original GLIMPSE survey includes a uniform sample of thousands of star formation regions and stellar clusters, a large fraction of which were previously uncharacterized (Mercer et al. [9, 10], Churchwell et al. [11, 12]). Many of these star formation regions are close enough that the stellar clusters can be resolved into individual stars and protostars. The spatial and mass distribution of lower mass stars can be studied in the more nearby star formation regions (Churchwell et al. [13], Povich et al. [14], Indebetouw et al. in prep.), and the 4.5 μm band has allowed the detection of a few dozen new outflows/jets in star forming regions (Watson et al. [15]). This unbiased sample of star formation allows a study in the variation in star formation properties, i.e., cluster density, initial mass function, gas content, in a wide range of Galactic environments.
3. *To discover new objects hidden behind the dust and new classes of objects that are bright in mid-infrared wavelengths.* At the outset of the GLIMPSE survey, it was realized that there was likely to be a large component of serendipitous discoveries since high angular resolution mid-infrared observations would allow one to see through regions of the Galaxy that were obscured even at near-infrared wavelengths. Some of the surprises of GLIMPSE so far include (1) a new globular cluster (Kobulnicky et al. [16]), (2) an overdensity of bright ($> 3L_*$) galaxies associated with the Great Attractor (Jarrett et al. [17]), (3) identification of infrared counterparts for X-ray bright sources (Reynolds et al. [18]), and (4) mid-IR bright bowshocks surrounding single stars both in star formation regions and the field (Benjamin and GLIMPSE [19]).

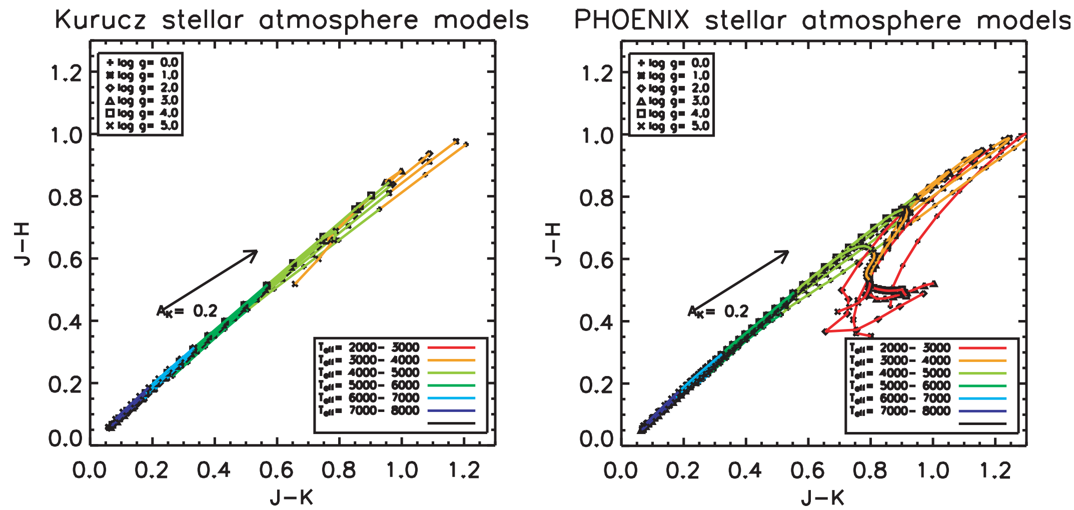

FIGURE 4. Infrared color-color plot showing the near-infrared colors as a function of T_{eff} and log g for two different stellar atmosphere models. Note the degeneracy between temperature and extinction for near-infrared colors.

4.1. Identifying Stellar Sources with Near/Mid-Infrared Data

The Galactic stellar structure goals of a Warm Spitzer mid-infrared Galactic plane survey are similar to the goals of near-infrared investigations. *However, the combination of Spitzer and 2MASS/UKIDSS-GPS data allows for two key improvements over near-infrared data alone:*

- **More sources:** Since $A_L = 0.06A_V = 0.6A_K$, for resolution/sensitivity matched Galactic plane surveys, mid-infrared data will yield a greater number of sources and any investigation using star counts with be far less limited by patchy extinction. For example, the 99.5% reliable GLIMPSE point source catalog yields approximately 50% more sources than the full 2MASS catalog over the same region. Since this ratio changes as a function of Galactic longitude, uncorrected near-IR and mid-IR star counts would give significantly different estimates of the radial scalelength of the Galactic exponential disk.
- **Accurate extinction corrections:** Figure 4 shows that, in theory, near-infrared colors (e.g J-K) are a strong diagnostic of spectral type/temperature. In practice, application of near-infrared colors for this purpose is quite effective in directions where interstellar extinction is low ($A_V < 2$ and thus $A_K < 0.2$). However, within the Galactic plane, even in the J, H, and K bands, extinction becomes significant and skews the ability to distinguish stellar temperature (Figure 5).
The addition of mid-infrared to near-infrared data allows for accurate extinction correction of near-infrared data. Estimation of extinction correction is extremely difficult at visible wavelengths because the wavelength dependence strongly depends on the dust density/composition. In the near/mid infrared this wavelength dependence is much reduced (Indebetouw et al. [4], but see Flaherty et al. [20]). With near-infrared data alone, however, the reddening and temperature loci are par-

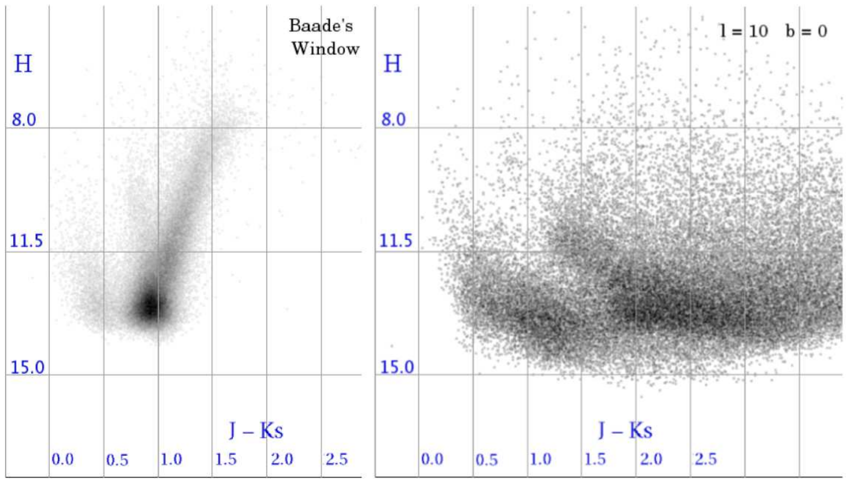

FIGURE 5. A comparison of 2MASS colors in an relatively low extinction region near the Galactic plane (Baade's Window - left) and a region at $l = 10$ where extinction is high (right). In Baade's Window stellar populations are evident, particularly the giant branch and asymptotic giant branch (with the red clump at the base of the giant branch - just above the 2MASS confusion limit). In the plot at right interstellar extinction skews the stellar populations. Reliable dereddening can restore stellar colors to enable population analysis.

allel in color-color space (see Fig. 4). The addition of the first two IRAC bands, however, provides measurement on the Rayleigh-Jeans tail of the stellar blackbody curve, so that (to first order) all near-mid IR colors should be zero. By picking an infrared color that remains fixed for a large range of stellar temperatures expected in the sample, e.g., H-[4.5] (see Fig. 6), one can accurately correct stellar fluxes for extinction (Nidever et al., in prep) and recover the temperature/spectral type information inherent in the near-infrared fluxes.

A Spitzer warm galactic plane survey would provide a powerful tool for dereddening surveys such as 2MASS and UKIDSS at low galactic latitudes, enabling population based (i.e. standard candle) reconstruction of Galactic structure and thus permitting the construction of a three-dimensional view of the Milky Way. Such a survey would be directly applicable to 2MASS and UKIDSS, and ultimately would serve as a legacy for application to any low-latitude near-infrared survey with overlapping sensitivity.

4.2. Galactic Stellar Structure Goals

Given the availability of near-infrared surveys, the highest priority focus for a Spitzer Warm Mission galactic plane survey should be those direction that suffer the greatest extinction. Given the utility of mid-infrared data for de-reddening and luminosity classification, coverage beyond the highest extinction regions is warranted as well, but of lower priority. A list of goals for Galactic stellar structure are as follows:

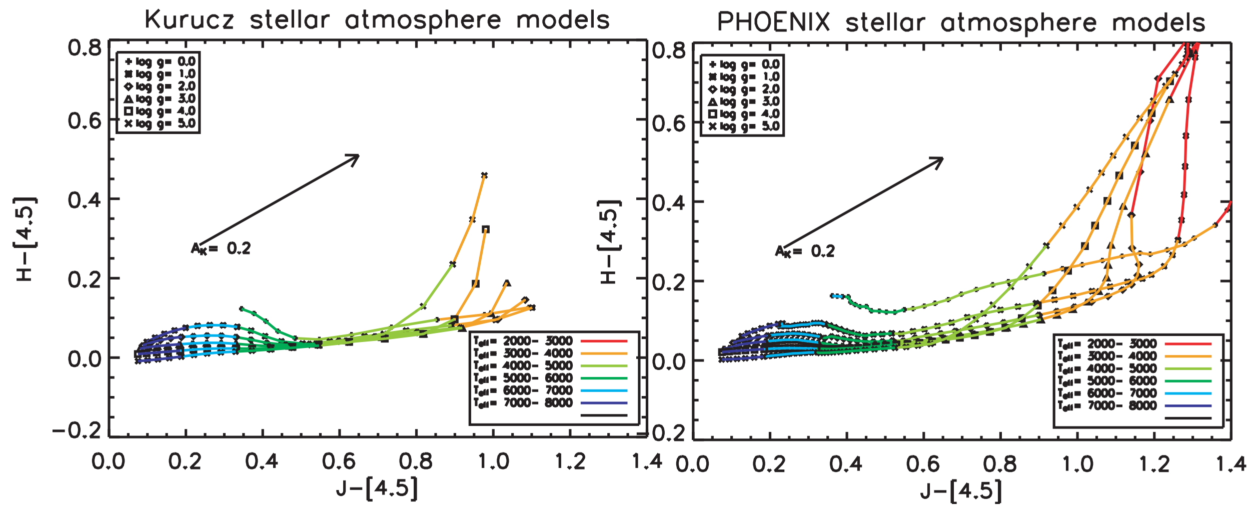

FIGURE 6. Infrared color-color plot showing how mid-infrared colors can be used to break the degeneracy between temperature, extinction, and (to a lesser extent) log g for ordinary stellar sources.

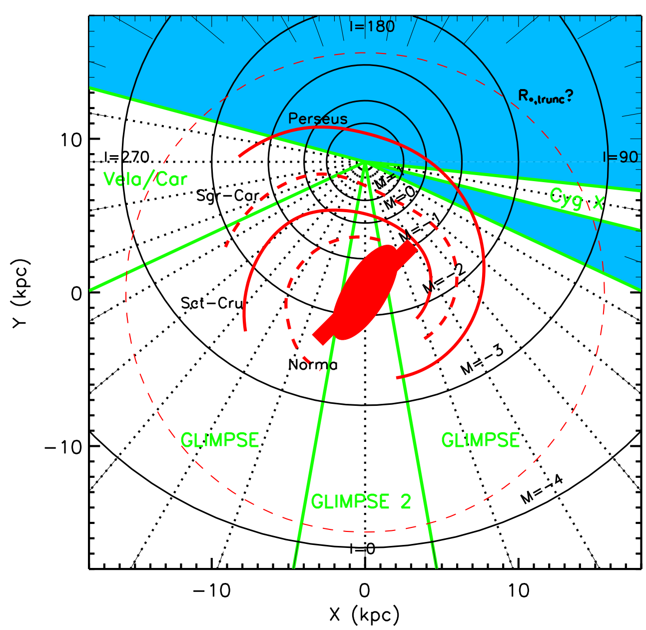

FIGURE 7. The Galactic Plane showing the areas covered by GLIMPSE, GLIMPSE2, Vela- Carina Survey (PI: Majewski), and Cygnus-X survey (PI: Hora). Solid circles indicate the GLIMPSE detection distances for objects with absolute magnitude M, assuming no extinction. The approximate positions of Galactic spiral arms (Taylor and Cordes [21]) are indicated in red. The central oval and bar represents the approximate extent of the central triaxial bulge/bar (Gerhard [22], Cole and Weinberg [23]) and the "Long" bar (Hammersley et al. [24], Benjamin et al. [5]). The expected truncation radius for the Galactic stellar disk is also shown with a dashed red line.

1. *The vertical structure of the stellar bar and disk:* Our own Galaxy is the *only* edge-on spiral galaxy in the universe in which we currently can hope to study the vertical distribution of stellar populations as a function of position within the Galaxy. The inner disk, bar, and bulge lie in the directions where interstellar extinction is at a maximum, complicating our ability to constrain scaleheights of the stellar components tracing these structures. To this end, GLIMPSE-3D (PI: Benjamin) was approved to add vertical coverage at selected longitudes. However, constraints on observing time precluded uniformly covering the latitude range $1 < |b| < 3^{\circ}$ (see Figure 2). *Experience shows that in the presence of patchy extinction, even in the mid-infrared, uniform coverage is vital to constrain galactic structure parameters.* To probe the thin disk, vertical coverage should extend to at least two scale heights at the distance of Galactic center which is approximately $|b| = 3^{\circ}$. Using COBE/DIRBE data, Binney et al. [25], for example, found evidence for the stellar disk scale height increasing from $z_o = 97$ to 220 pc ($0.69 - 1.57^{\circ}$ at a distance of R=8 kpc). Assuming the thick disk maintains a constant thickness of z_{th} =1060 pc (Cabrera-Lavers et al. [26]), latitude coverage of 7.6° would be needed to cover a single scaleheight. Finally, models of stellar bars are still under rapid development, but models of Debattista et al. [27], for example, predict a scaleheight of ~ 500 pc (3.6°).
2. *The edge of the stellar disk of the Galaxy:* The stellar disk of $\sim$ 80% of galaxies exhibit an outer truncation radius at approximately four scalelengths (van der Kruit and Searle [28]). Using stellar disk scalelength derived from GLIMPSE data (Benjamin et al. [5]), this result predicts that the Milky Way's truncation should lie at a galactocentric radius of 15.6 ± 2.4 kpc, putting our Sun about halfway between the center and edge of the Galaxy. If the thin disk does not flare at large radii (due to lower surface gravity), the edge of the thin disk would have the same angular height (1.57°) as at the Galactic center. A search for a deficit of red giant branch and red clump stars towards the outer galaxy could be used to constrain this outer truncation. Note, in Fig. 7, however, that the entire outer Galaxy is obscured by the Perseus arm; an accurate determination of the stellar edge of the Galaxy requires the combination of near/mid IR data to provide a reliable extinction correction.
3. *A survey of low latitude star clusters:* Star clusters are a particularly valuable commodity in stellar populations research because they are the only disk tracer for which reliable ages can be derived. This feature not only makes it possible to explore such attributes of the disk as the age-metallicity relation, age-velocity dispersion relation (where velocity dispersion is intimately correlated to the scaleheight of a stellar population through Poisson's equation), and the disk star formation history, but also to explore the dynamical evolution of the clusters themselves. Unfortunately, proper age-dating (via isochrone fitting) requires accurate distances to the clusters. For the typical globular cluster, a 10% uncertainty in the distance corresponds to about a 20% error in the age. A similarly small uncertainty in the extinction translates to a similar error in the ages, and one of the primary problems with studying low latitude clusters is the degeneracy of age, distance, and reddening/extinction in the isochrone fitting. The use of Spitzer+2MASS data can break this degeneracy and lead to unambiguous isochrone age-dating.

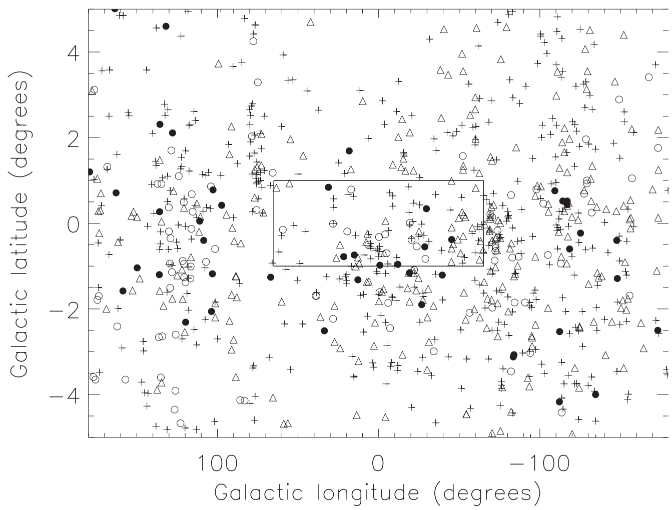

FIGURE 8. Location of open clusters within five degrees of the Galactic plane with the approximate GLIMPSE boundaries shown. Symbol type indicates the distance to the cluster: 0-5 kpc (open triangle), 5-10 kpc (open circle), 10-20 kpc (solid circle), and unknown distance (plus sign).

While a large fraction of star formation is tightly constrained to the inner Galactic plane, the majority of known open clusters are more distributed in both longitude and latitude, but generally still highly extinguished. In addition, the disk and bulge globular cluster population is broadly dispersed, but also lies behind significant dust. Only 2 globular clusters fall within the GLIMPSE survey, whereas a full quarter of known ~ 150 Galactic globular clusters lie within $|b| < 5$, and more than half of the known clusters lie behind more than $A_V = 1$ magnitude of dust, including the bulk of the disk and bulge clusters. Out of the 1100 known open clusters (taken from the WEBDA database), only 101 lie within the area currently covered by GLIMPSE data. A full plane galactic survey covering $|b| < 2^\circ, 3^\circ$ or 4° would increase this sample size to 529, 679, and 783 open clusters, respectively. Further strategic IRAC pointing, particularly on all highly reddened globular clusters, would provide substantial, definitive leverage on the age distribution of open and globular clusters. It is also likely that with a deep, general Galactic plane survey, where star-by-star dereddening would be enabled, new open clusters and stellar associations will be identified.

4. *The stellar spiral structure of the Galaxy:* One of the pleasant surprises of the GLIMPSE survey has been the detection of an enhancement in star counts in the direction expected for the Centaurus (or Crux) spiral arm tangency, combined with the lack of detection of the first quadrant tangency for the Sagittarius arm (Benjamin et al. [5]). This supports the Drimmel and Spergel [29] hypothesis that the Galaxy is a two-armed spiral galaxy in mass.[3] Given the positive identification

[3] In this hypothesis, the Perseus and Scutum-Crux spiral arms are traced by the old stellar mass, while the Sagittarius-Carina and Norma arms, while still star formation structures, are not associated with significant overdensities of mass.

of the stellar spiral structure of the Galaxy, it would be extremely desirable to map the vertical and azimuthal structure using stellar populations that trace both the mass (such as red clump giants), and the star formation. Since spiral arms are intrinsically regions of high gas density, the reduced extinction available at mid-infrared wavelengths is essential for such work.

5. *Galactic Satellites and Tidal Streams:* From high latitude, large-area photometric surveys like 2MASS and the Sloan Digital Sky Survey, it is now clear that the halo of our Galaxy is highly substructured, including networked streams of tidal debris from disrupting satellites (e.g., Majewski et al. [30], Belokurov et al. [31], Grillmair [32]). A number of the newly identified, diffuse substructures — such as the Monoceros Stream (Newberg et al. [33], Yanny et al. [34], Rocha-Pinto et al. [35]), the Triangulum-Andromeda star cloud (Rocha-Pinto et al. [36], Majewski et al. [37]), the Anticenter Stream(s) (Grillmair [32]), and the Hercules-Aquila cloud (Belokurov et al. [38]) — lie at low Galactic latitudes, and may be part of a vast complex of tidal debris accumulating around the disk of the Milky Way.

   The tidal disruption of satellites aligned with the disk has been used to explain a similar, diffuse set of features seen wrapping around the M31 disk (Ibata et al. [39]), and this may be a manifestation of the predictions from the prevailing ΛCDM models that Galactic disks grow inside out from the continued agglomeration of subhalos. Several "nuclei" for such accreted structures have been identified, including Canis Major (Martin et al. [40]) and Argo (Rocha-Pinto et al. [41]), but whether these nuclei as well as the "streams" identified above may actually be a misinterpretation of the heavily reddened, low latitude starcounts, further complicated by the presence of a stellar counterpart of the HI warp has been hotly debated (see below; Rocha-Pinto et al. [41], Momany et al. [42], Bellazzini et al. [43, 43], Martin et al. [44], López-Corredoira [45], Momany et al. [46]).

   What is known is that satellites on inclined, prograde orbits will dyamically couple to disks, suffer orbital decay and orbital plane tilting, and eventually lead to the accretion of these systems along the edge of the disk (Quinn et al. [47]). Eventually these systems will dynamically heat the outer disk as the satellite continues to spiral inward. Theoretically, then, it appears that the dust-obscured, outer disk is perhaps the most interesting place to look for the ongoing process of disk building and subhalo accretion. One key way to probe such structures is to analyze near-infrared CMDs of the stellar overdensities. In regions where extinction is significant, Spitzer data is necessary to provide reliable extinction corrections to the near-infrared fluxes.

   Even satellite systems that are on more polar orbits can have large critical patches obscured by the Zone of Avoidance. For example, a large fraction of the Sagittarius dSph core and its tidal stream lies behind the bulge of our Galaxy, in highly reddened regions, and this has made it difficult to follow with accuracy the shape of the tidal stream (e.g., Majewski et al. [30]), leading to disparate models of the system (e.g., Law et al. [48], Fellhauer et al. [49]). Indeed, the very distance of the Sgr core is still uncertain at about the 20% level in part because of the uncertainty on the reddening.

   Finally, it is estimated that if the distribution of satellites is uniform by latitude, then approximately 1/3 of all dwarf satellites of the Milky Way will be unaccounted for if we do not accurately probe the Zone of Avoidance (Willman et al. [50]). With the doubling of the known satellite population of the Milky Way just in the past year or two of study of the SDSS footprint (which covers 1/5 of the sky), one can estimate that at least another 40-50 satellites remain to be found around the Galaxy, and more than about 20 probably lie in highly reddened regions, perhaps some very close, according to the Quinn et al. mechanism. Thus, a thorough probe of the low latitude Galaxy with a warm mission IRAC survey may teach us a lot about the structure and continued evolution of the Milky Way and its subhalo system.

6. *The Stellar Warp:* The neutral hydrogen warp of the Galaxy has been well studied, but the relation of this to the stellar warp remains far from clear (Momany et al. 2006). Part of the difficulty in tracing the stellar warp with different stellar populations is the difficulty of identifying stellar populations in near-infrared CMDs that have been smeared out by extinction. In addition, there is ongoing debate on the connection between the warp and tidal streams known to be encircling the disk (e.g., López-Corredoira [45], Bellazzini et al. [43], Momany et al. [46]). Once again, the reddening estimates provided by mid-infrared observations are essential to reconstructing the extinction-free near-infrared CMD's of the outer Galaxy and disentangling the structure(s) there.

In addition to these global stellar structure goals, a full plane survey will allow for a global characterization of whole classes of stellar populations, including AGB stars, Wolf-Rayet stars, and carbon stars. Multi-epoch observations could allow for the identification of several classes of variable stars. Finally, one of the unanticipated uses of GLIMPSE data that will also hold true for a full-plane survey is the use of this data for the identification of infrared counterparts or companions for X-ray and gamma-ray sources resolved by Chandra or XMM; this has already added a few sources to the list of ~ 100 known high mass X-ray binaries.

4.3. Star Formation

The dependence of star formation on physical conditions in galaxies is critically important to understanding the evolution of those galaxies. We must search for any dependencies of the star formation process on large-scale physical conditions in our Galaxy, where star formation regions can be resolved and studied in detail. The average metallicity (measured in ionized gas) drops by at least a factor of 4 from the inner to outer Galaxy (Afflerbach et al. [51]). Theoretically, low metallicity should reduce the ability of molecular clouds to cool and collapse into stars. The cosmic-ray flux (which should also heat molecular clouds and affect their collapse) is also reduced away from the inner Galaxy (Bloemen et al. [52]). The average interstellar radiation field is observed to be more intense in the outer Galaxy (Cox and Mezger [53]) , and the interstellar phase balance shifts significantly in favor of atomic over molecular hydrogen. The radiation field produced near a given mass star which does form will be stronger and harder if the star has lower metallicity, hindering the formation of lower-mass stars in the proximity. The structure and temperature of the HII regions surrounding these more

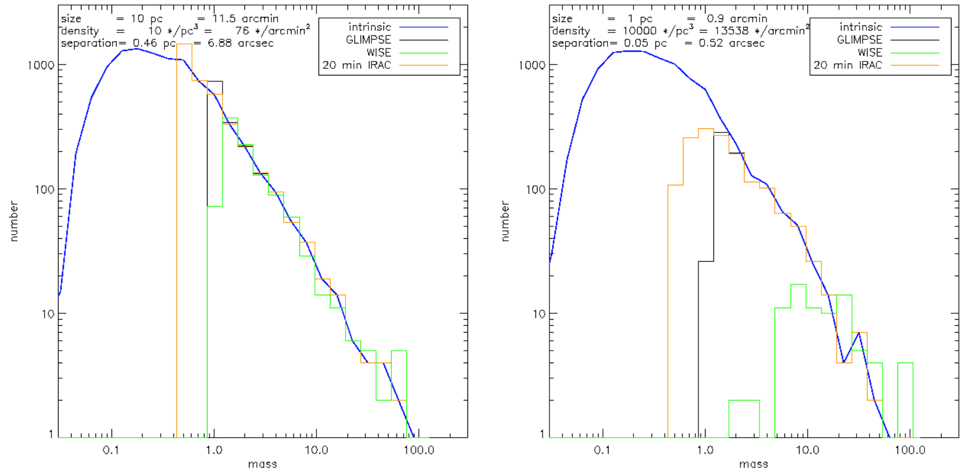

FIGURE 9. Simulated mass functions as "observed" by Spitzer and WISE for two different apparent source densities.

intensely radiating protostars should differ from that around high-metallicity protostars. The different physical conditions in outer Galaxy molecular clouds should also affect the spatial and luminosity distribution and stellar content of star forming regions, the IMF, and the radiation transfer in a nascent cluster, all of which can be studied with Spitzer's warm mission.

A full Galactic plane survey would extend an unbiased study of star formation to the entire plane, providing coverage of the Carina spiral arm tangency and most of the Perseus arm. Using the HII region compilation of Paladini et al. [54], 850 of the 1442 HII regions are in the current GLIMPSE coverage. Full coverage up to $|b| < 2^\circ, 3^\circ$ or 4° would increase this sample size to 1250, 1344, and 1393 cataloged HII regions. However, Churchwell et al. [12] have shown many of the star forming regions seen in GLIMPSE are not included in this catalog, so these numbers are lower limits.

Owing to local confusion in clustered regions, Spitzer has a clear advantage over WISE for clustered star formation studies. Figure 9 shows simulated mass functions (with the Kroupa and Weidner [55] functional form) for Galactic clusters, and the mass functions that would be observed with the existing Spitzer/GLIMPSE survey (2.4s exposure time), with IRAC for 20 minutes in a warm mission observation, and with WISE. The observed mass functions are derived from the 3.6μm observed flux density distribution and a polynomial fit to the spectral type-flux density relation (e.g. Bessell and Brett [56]). Poisson noise from the stars and from a uniform background of 200MJy/sr is included – the latter is a best case, since it is known from GLIMPSE that the diffuse background is highly structured, and in practice the faintest sources must be discarded to maintain reliability and exclude false sources extracted from knots in the background. It is clear that in the inner Galaxy and in even modestly crowded clusters (tens of stars per cubic parsec), that Spitzer will improve over WISE. It is less clear that significant improvement can be gained over GLIMPSE in the inner Galaxy and in clusters with significant diffuse background. The greatest impact of a warm mission survey will be in clusters, star formation regions, and regions of high extinction in the

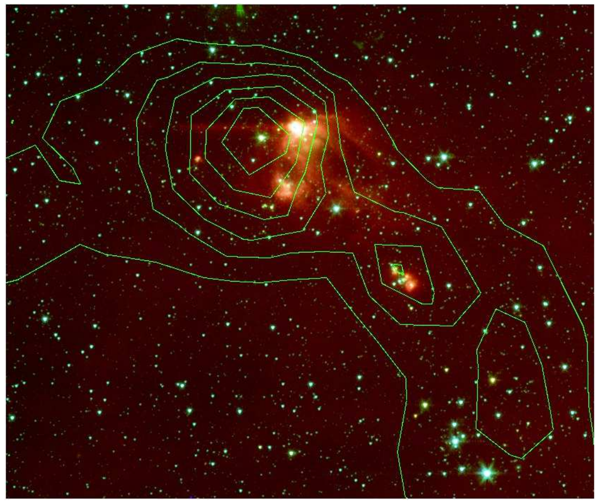

FIGURE 10. Three color composite of outer Galaxy star forming region G124 from a 72 sec integration with IRAC bands 1, 2, and 4.

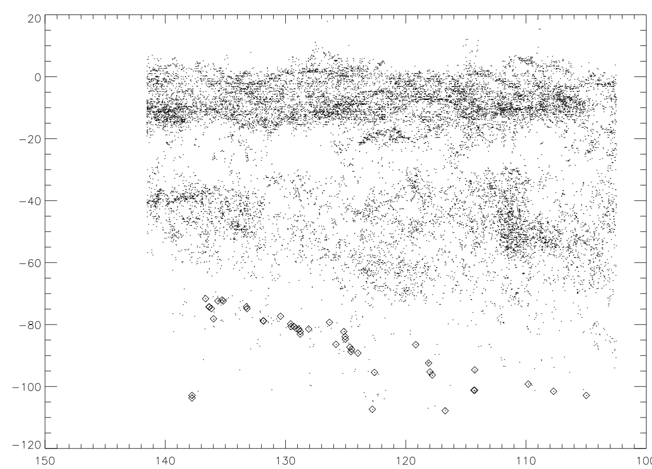

FIGURE 11. Longitude *vs.* V_{LSR} for IRAC/CO associations in the outer Milky Way from Kerton and Brunt [57]. The diamonds highlight the most distant regions in the outer disk.

outer Galaxy that have not yet been observed by Spitzer.

Figure 10 shows an example of an outer Galaxy star formation region, IRAC bands 1,2, and 4, with contours of ^{12}CO at the velocity range of the outer Galaxy cloud. The region was selected from Kerton and Brunt [57] and observed for 72 seconds. These observations are not yet confusion limited – clearly deep observations of outer Galaxy clusters will be useful for measuring the mass function with a large dynamic range in mass, and characterizing the stellar and protostellar population.

One can outline a type of project that would be worth pursuing: Outer Galaxy star formation regions have been identified by correlation of CO clouds with IRAS point sources by Kerton and Brunt [57] among others. Figure 11 shows a region in the outer galaxy with CO/IRAS associations, and the most distant outer galaxy regions marked with diamonds. The Sagittarius spiral arm is clearly visible at lower velocities. Their catalog has 6700 associations, each which could probably be observed with 1-2 IRAC pointings. If one wanted to observe all such regions for two minutes, a $\sim$300 hour program would ensue. Only observing the most distant regions (163 regions with V$<$-65) for 5 minutes each would require $\sim$15 hours.

4.4. Extragalactic Science

A deep Galactic plane survey may be of great interest to astronomers working outside the field of Galactic astronomy. In particular, a mid-infrared survey will serve to nearly eliminate the “Zone of Avoidance” found in surveys of extragalactic clusters. Several galaxies with $L \sim 3L_*$ have been found in the GLIMPSE survey, with many more appearing in the first analysis of GLIMPSE-3D galaxy. Redshifts have been obtained for some of these galaxies and it appears that these galaxies trace a part of the Great Attractor, a major overdensity of galaxies in the local Universe (Jarrett et al. [17]). The 2MASS extended source distribution indicates that a number of filaments, as well as some large voids, cross the outer plane, including the Local Supercluster and the Perseus-Pisces Supercluster.

5. THE INTERSTELLAR MEDIUM

5.1. Diffuse Interstellar Emission

PAH 3.3um emission (from the C-H stretching mode) makes a significant diffuse contribution in band 1. Emission from PAHs or other ultrasmall grains is thought to also contribute in IRAC band 2. If PAHs are heavily deuterated, as has been suggested (Peeters et al. [58], Draine [59, 60]) then the C-D stretching mode falls in the center of band 2. The 0-0 S(9) 4.695um, 0-0 S(10) 4.410um, and 0-0 S(11) 4.181um lines of H_2 also fall within IRAC band 2; these lines may be excited by outflows from protostars in molecular clouds (Noriega-Crespo et al. [61, 62]). Away from molecular clouds, the H_2 rotational emission should be insignificant, and PAH/ultrasmall grain emission is expected to be the principal source of diffuse emission.

In observations of the emission from other galaxies using IRAC bands 1 and 2, it is nearly impossible to separate the diffuse emission from dust and gas from the (generally much stronger) stellar continuum. However, in observations of the Milky Way, a large fraction of the stellar contribution can be removed by subtracting point sources from Spitzer images of the Milky Way. This has been done by Flagey et al. [63]), who were able to determine the emission in bands 1 and 2 that correlates with diffuse emission (due to PAHs) in IRAC band 4.

During a warm Spitzer mission, deeper observations of Milky Way fields may allow improved subtraction of point sources, due to higher signal/noise and perhaps also improved understanding of the instrumental p.s.f. If the regions in question have been previously imaged with IRAC bands 3 and 4, it may be possible to improve upon the results of Flagey et al. [63] concerning PAH+dust emission into IRAC bands 1 and 2, and how this correlates with diffuse emission in bands 3 and 4. One can also correlate diffuse emission in bands 1 and 2 with other interstellar tracers, such as 21 cm emission.

It is not clear at this time how much of an improvement can realistically be expected in terms of our ability to measure diffuse emission in bands 1 and 2, and this is perhaps best viewed as "added value" for imaging at moderate and high galactic latitudes that will be carried out for other reasons (e.g., deep imaging to detect high redshift objects). Such data can be "mined" to extract the diffuse emission from the Milky Way, which can then be compared to other tracers of the ISM, such as FIR emission (e.g., perhaps comparing with Akari sky maps at 80um , 140um, or 160um), 21cm emission, or CO 1-0 emission. Indeed, it might be of interest to select regions for observation for which imaging data from Akari will be available. [Note that Akari bands N3 and N4 have overlap with IRAC bands 1 and 2.] Prior ISO and MSX imaging would also provide context for IRAC band 1 and band 2 observations.

5.2. Infrared Extinction in Dense Cores

A specific interstellar medium topic that exploits Spitzer's mid-infrared capability to work at wavelengths that minimize interstellar extinction involves the ability to map the extinction profile of dense cores in molecular clouds. Even at near-infrared wavelengths these cores are sufficiently opaque that stars are not visible through the densest regions in deep exposures.

Quantitative knowledge of the detailed structure of dense cores is critical for both setting the initial conditions for star formation theory and directly testing predictions of protostellar collapse models. Extinction measurements toward background field stars are a very powerful, robust and quantitative probe of cloud structure. Deep ground-based near-infrared (JHK) observations obtained on large aperture telescopes enables extinction mapping of nearby dense cores to depths of typically $A_v \sim 30$ magnitudes and in very favorable circumstances extinctions as high as 40 magnitudes can be measured. This depth is often sufficient to probe the structure of starless cores with small or modest density contrasts. However, to penetrate more evolved starless cores on the verge of forming a star and typical protostellar cores requires the ability to reach depths of 75 - 100 magnitudes. Deep Spitzer observations in Bands 1 & 2 are capable of probing such depths.

A Spitzer Warm Mission survey of dense cores could obtain extinction maps of the inner regions of some of a comprehensive list of the most opaque dense cores known in molecular clouds in order to provide robust measurements of their structure which in turn will provide the initial conditions for, and direct tests of, star formation theories. It is in such regions that the early star formation process will exhibit its most significant structural evolution. An observational campaign to obtain deep, pointed band 1 & 2 images of a sample of nearby dense cores of different masses and in different stages of development would provide a quantitative empirical description of core evolution and yield direct tests of collapse calculations.

Because of the much longer integration times required, such a survey would be independent of the shallow Galactic plane surveys described to this point. Typical observations would require integration times of at least $\sim$10 minutes. Cores need to be of order ~ 2 arcminutes in angular size to produce meaningful morphological conclusions. The number of such nearby cores limits such a survey to a few dozen targets. A more extensive survey could be conducted on more distant cores but with limited angular resolution.

5.3. Extinction mapping of Infrared Dark Clouds

Infrared Dark Clouds (IRDCs) are distant, massive and dense molecular clouds that appear dark at mid-infrared wavelengths indicating relatively large opacities ($A_v > 40$ magnitudes). These objects are not typically sites of significant star formation and are consequently thought to be the future sites of cluster formation. Little is known about their physical conditions and infrared extinction mapping could provide robust estimates of some of their most fundamental properties, namely mass and structure.

A warm mission survey would obtain deep Spitzer observations in order to construct extinction maps of Infrared Dark Clouds to measure their structure and determine their masses and thus specify the initial conditions in objects that are likely the future formation sites of rich embedded stellar clusters. Such a survey would require deep IRAC pointed observations of a sample of IRDCs coupled with deep ground-based JHK observations necessary to mitigate strong foreground star contamination (IRDCs are sufficiently distant that foreground star contamination is significant and may be a serious impediment to extinction measurements). There are $\sim$100 objects known to be very dark with mean extinctions of tens of magnitudes. The maximum sizes of these clouds is $\sim$10 arcminutes. Integration times of $240-480$ seconds per field would be required to penetrate the highest extinction regions within the clouds with a sufficient number of background stars detected to provide reasonable angular resolution. Typical clouds could be covered with a few spatial pointings.

6. SUMMARY

Spitzer's Warm Mission capabilities enable legacy surveys of a substantially larger portion of the Galactic plane than was observed during the cryogenic mission. IRAC Bands 1 & 2 fluxes, with their relative immunity to interstellar extinction, can be combined with near-infrared surveys to exploit knowledge of individual stellar spectral types to construct a three dimensional view of the Milky Way. Given the existing and anticipated coverage of the Galactic plane during the cryogenic portion of the mission (Figure 7), and given knowledge of confusion as a function of Galactic longitude and latitude, the most natural focus of such programs are likely GLIMPSE-like (two 2s integrations per sky position) at latitudes extending up to $-5^\circ < b < 5^\circ$ that extend on the GLIMPSE coverage for longitudes $-90^\circ < l < 90^\circ$ and deeper (e.g. two 12s integrations per sky position) coverage for the outer Milky Way to $-1.5^\circ < b < 1.5^\circ$ with limited extensions to higher latitude to sample vertical structure as was done for GLIMPSE-3D.

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