EFFECTS OF DIFFUSE BACKGROUND EMISSION AND SOURCE CROWDING ON PHOTOMETRIC COMPLETENESS IN SPITZER SPACE TELESCOPE IRAC SURVEYS: THE GLIMPSE CATALOGS AND ARCHIVES

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Received 2013 March 1; accepted 2013 May 28; published 2013 June 26

ABSTRACT

We characterize the completeness of point source lists from Spitzer Space Telescope surveys in the four Infrared Array Camera (IRAC) bandpasses, emphasizing the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) programs (GLIMPSE I, II, 3D, 360; Deep GLIMPSE) and their resulting point source Catalogs and Archives. The analysis separately addresses effects of incompleteness resulting from high diffuse background emission and incompleteness resulting from point source confusion (i.e., crowding). An artificial star addition and extraction analysis demonstrates that completeness is strongly dependent on local background brightness and structure, with high-surface-brightness regions suffering up to five magnitudes of reduced sensitivity to point sources. This effect is most pronounced at the IRAC 5.8 and 8.0 μm bands where UV-excited polycyclic aromatic hydrocarbon emission produces bright, complex structures (photodissociation regions). With regard to diffuse background effects, we provide the completeness as a function of stellar magnitude and diffuse background level in graphical and tabular formats. These data are suitable for estimating completeness in the low-source-density limit in any of the four IRAC bands in GLIMPSE Catalogs and Archives and some other Spitzer IRAC programs that employ similar observational strategies and are processed by the GLIMPSE pipeline. By performing the same analysis on smoothed images we show that the point source incompleteness is primarily a consequence of structure in the diffuse background emission rather than photon noise. With regard to source confusion in the high-source-density regions of the Galactic Plane, we provide figures illustrating the 90% completeness levels as a function of point source density at each band. We caution that completeness of the GLIMPSE 360/Deep GLIMPSE Catalogs is suppressed relative to the corresponding Archives as a consequence of rejecting stars that lie in the point-spread function wings of saturated sources. This effect is minor in regions of low saturated star density, such as toward the outer Galaxy; this effect is significant along sightlines having a high density of saturated sources, especially for Deep GLIMPSE and other programs observing closer to the Galactic center using 12 s or longer exposure times.

Key words: infrared: stars – methods: data analysis – methods: statistical – techniques: image processing

Online-only material: color figures

1. INTRODUCTION

The Spitzer Space Telescope (Werner et al. 2004) has conducted numerous wide-area surveys, yielding a rich legacy of image data and point source catalogs that have become heavily used commodities. In terms of sky coverage, the largest of these are the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire programs (GLIMPSE, GLIMPSE II, GLIMPSE 3D; Benjamin et al. 2003; Churchwell et al. 2009) covering almost 400 deg2 of the Milky Way Plane in all four mid-infrared bands with the Infrared Array Camera (IRAC; Fazio et al. 2004). The Spitzer Mapping of the Outer Galaxy (SMOG; Carey et al. 2008), the Spitzer Legacy Survey of the Cygnus-X Complex (Hora et al. 2007), and the Vela-Carina large program (Zasowski et al. 2009) together cover another 120 deg2. The warm Spitzer mission program GLIMPSE 360 (Whitney et al. 2008) imaged ~511 deg2 of the outer Galactic Plane in the 3.6 and 4.5 μm bands. Deep GLIMPSE (Whitney et al. 2011) re-imaged a similar portion of the Galactic Plane as GLIMPSE I/II, but only at 3.6 and 4.5 μm, using a longer 10.4 s integration time. Other Galactic programs and numerous extragalactic legacy programs provided much deeper datasets but over relatively small fields of view. Our focus here is primarily the Galactic science programs that have yielded large lists of point sources.3 Table 1 summarizes the approximate coverages, exposure times, observational bandpasses, and total number of photometered point sources for these and other Galactic Spitzer surveys. There are two types of GLIMPSE source lists: a high reliability point source “Catalog” and a more complete point source “Archive.” The source lists are a result of doing photometry on each IRAC frame, averaging all detections made in a single band (in-band merge), then merging the photometry from all wavelengths, including Two Micron All Sky Survey (2MASS) JHKs, sources, at a given position on the sky (cross-band merge). The GLIMPSE source list criteria have been developed to ensure that each source is a legitimate detection and that the fluxes reported for the IRAC bands are of high quality. As of this writing, these Spitzer programs have generated nearly 158 million sources in the highly reliable GLIMPSE Point Source Catalogs (GPSC) and 229 million in the more complete GLIMPSE Point Source Archives (GPSA).

3 See http://irsa.ipac.caltech.edu/data/SPITZER/docs/spitzermision/observingprograms/ for a summary of Spitzer Legacy and other large programs. Data product and photometry documents for the GLIMPSE programs may be found at http://www.astro.wisc.edu/glimpse/docs.html and http://irsa.ipac.caltech.edu/data/SPITZER/docs/spitzermision/observingprograms/legacy/glimpse/.
Table 1

*Spitzer* GLIMPSE and Similar Galactic Wide-area Surveys

| Survey       | Coverage                  | Approx. Area | Instrument/Bands | Exp. Time | Reference          | Catalog Sources | Archive Sources |
|--------------|---------------------------|--------------|------------------|-----------|--------------------|-----------------|-----------------|
| GLIMPSE I    | $10^\circ < |\ell| < 65^\circ$; $|b| < 1^\circ$ | 220 deg$^2$  | IRAC [3.6],[4.5],[5.8],[8.0] | $2 \times 1.2$ s | Churchwell et al. (2009) | 31,154,438 | 49,133,194 |
| GLIMPSE II   | $|\ell| < 10^\circ$; $|b| < 1.5^\circ$ | 54 deg$^2$   | IRAC [3.6],[4.5],[5.8],[8.0] | $3 \times 1.2$ b | Churchwell et al. (2009) | 18,145,818 | 23,129,046 |
| GLIMPSE 3D   | $< |\ell| < 31^\circ$; $|b| > 1.5^\circ$ | 120 deg$^2$  | IRAC [3.6],[4.5],[5.8],[8.0] | $3(2) \times 1.2$ s c | Churchwell et al. (2009) | 20,403,915 | 32,214,210 |
| GLIMPSE 360  | $\ell = 65^\circ–76^\circ, 82^\circ–102^\circ, 109^\circ–265^\circ$; $|b| < 3^\circ$ | 511 deg$^2$  | IRAC [3.6],[4.5] | $3 \times 10.4$ s | Whitney et al. (2008) | 42,602,112 | 49,378,042 |
| Deep GLIMPSE | $\ell = 265–350^\circ$, $b' = -2^\circ–0^\circ$; $\ell = 25^\circ–65^\circ$, $b = 0^\circ–2^\circ$ | 208 deg$^2$  | IRAC [3.6],[4.5] | $3 \times 10.4$ s | Whitney et al. (2011) | 38,279,639 | 63,522,165 |
| SMOG         | $\ell = 102^\circ–109^\circ$; $b = 0^\circ–3^\circ$ | 21 deg$^2$   | IRAC [3.6],[4.5],[5.8],[8.0] | $4 \times 10.4$ s | Carey et al. (2008) | 2,512,099 | 2,836,618 |
| Cygnus-X     | $\ell = 76^\circ–82^\circ$; $b = -2;3–4;4^\circ$ | 24 deg$^2$   | IRAC [3.6],[4.5],[5.8],[8.0] | $3 \times 10.4$ s | Hora et al. (2007) | 3,913,559 | 4,455,066 |
| Vela-Carina  | $\ell = 255^\circ–295^\circ$; $b \approx -1;5–1;5^\circ$ | 80 deg$^2$   | IRAC [3.6],[4.5],[5.8],[8.0] | $2 \times 1.2$ s | Zasowski et al. (2009) | 2,000,188 | 4,547,327 |

Notes.

a Irregular region; see survey documentation for details.
b GLIMPSE II data products include the *Spitzer* Galactic Center survey (S. Stolovy; PID = 3677) which has five visits.
c Some portions of GLIMPSE 3D use two visits and others have three.
The utility of point source catalogs resulting from the Spitzer mission depends, partly, on understanding their completeness (i.e., the ratio of true sources detected to the number of all true sources). The stellar magnitude at which the GPSC or GPSA is nominally complete varies with bandpass. It also varies greatly as a function of background surface brightness and as a function of local source density where confusion with neighboring sources limits detection and photometry. Figure 2 of Robitaille et al. (2008) shows how high diffuse background levels inhibit the detection of point sources in the Spitzer 8.0 μm band, which is affected by strong, diffuse emission features arising from polycyclic aromatic hydrocarbons (PAHs) in and around regions of star formation. The IRAC 5.8 μm band, and to a much lesser extent the 3.6 μm band, also encompass these features, leading to strong spatial completeness variations, especially in complex fields near the Galactic Plane. It is widely recognized that sensitivity to point sources is significantly reduced in high-background fields and fields having high point source densities, but there has not yet been a general quantitative analysis of this effect.

Our goal in this contribution is to quantify the photometric completeness in the four Spitzer IRAC bandpasses, considering separately the effects of (1) high diffuse backgrounds and (2) high point source surface densities. In Section 2 we describe an artificial star analysis procedure for addressing the effects of incompleteness resulting from diffuse background emission. In Section 3 we provide plots and tables of completeness as a function of diffuse background level and stellar magnitude. In Section 4 we address the effects of incompleteness resulting from source crowding (i.e., confusion), and we provide plots and tables of the magnitude at which 90% completeness is achieved as a function of point source surface density. All magnitudes referenced herein refer to the Vega magnitude system used by the GLIMPSE pipeline and data products.

GLIMPSE I obtained two 1.2 s exposures of each object, while GLIMPSE II obtained three such 1.2 s exposures. GLIMPSE 3D utilized either two or three 1.2 s exposures at each location. GLIMPSE 360 and Deep GLIMPSE employed the high-dynamic-range (HDR) mode to obtain three 0.4 and 10.4 s exposures at each position. We adopt the GLIMPSE I/II/3D survey strategy and its resulting GPSC and GPSA as our baseline dataset, and we perform a similar analysis for the GLIMPSE 360/Deep GLIMPSE survey strategy. Although it is unrealistic to perform a completeness characterization for every possible survey strategy and sightline, we intend that these two results be general enough that consumers of source lists generated as part of GLIMPSE and similarly processed Spitzer IRAC surveys, such as SMOG, Cygnus-X, and Vela-Carina can infer completeness for those programs as well. This completeness analysis is pertinent only to point sources and is not appropriate for extended sources.

2. ARTIFICIAL STAR ANALYSIS PROCEDURE FOR DIFFUSE BACKGROUND COMPLETENESS

We selected a ~1.5 deg² region of the GLIMPSE I survey between 333:0 < ℓ < 334:5, -1° < b < 0°, exhibiting a large range in diffuse background level to use as a test region. This area contains some of the brightest mid-IR background regions in the Galactic Plane. Figure 1 shows a logarithmic grayscale representation of this region in the 8 μm IRAC band. This region of the Galactic Plane spans a large dynamic range from 20 MJy sr⁻¹ in the lower left to over 5000 MJy sr⁻¹. Yellow crosses show detected 8.0 μm point sources fainter than 12th magnitude as included in the GPSC. The varying density of cataloged sources from lower left to upper right dramatically illustrates the effects of high and complex background levels on completeness.

The GLIMPSE I data in this region is comprised of ~600 individual 1.2 s exposures in each of the four IRAC bandpasses. The IRAC pixel size is 1.2 at all four bandpasses. To each 256 × 256 pixel basic calibrated data (BCD) image we added roughly 600 artificial stars at random locations using an average point-spread function (PSF) appropriate for each band, as constructed by the GLIMPSE data processing team from an ensemble of IRAC point sources. The PSF was scaled to a random magnitude between $M_{\text{low}}$ and $M_{\text{up}}$, Gaussian noise ($\sqrt{N_{\text{photons}}}$) was added to each artificial star PSF on a pixel-by-pixel basis, and the artificial star was added at a (pseudo-) random location to the BCD image. The center locations of the artificial stars were constrained to (1) lie no closer than 5 pixels from the edge of the image, and (2) lie no closer than 3 pixels to a real star detected during previous processing by the GLIMPSE pipeline (dubbed the “Actual” list of point sources). This avoids both edge effects and the effects of confusion from neighboring point sources in order to focus on effects solely related to diffuse background levels. We set $M_{\text{low}} = 8$ $M_{\text{up}} = 15$ for all bands, spanning seven magnitudes in brightness to cover nearly the entire dynamic range of the GLIMPSE I survey in order to sample both very complete and very incomplete flux levels. The artificial stars have the same magnitude in each band. Effectively, this means that we are simulating sources having zero color, which comprise the vast majority (~94% of sources have $|m_2 - m_1| < 0.5$) of all GPSC sources having measurements in all four bands. However, it is not practical to conduct a general analysis for arbitrary spectral energy distributions. The GLIMPSE pipeline was run to generate a list of point sources from the Actual+Artificial images in the same manner as the published GPSC and GPSA. Inclusion in the highly reliable GPSC requires that a source be detected twice (i.e., in at least two individual IRAC exposures; detection is performed on the BCD frames) in any one IRAC band at S/N ≥ 5 and at least once in any adjacent band at

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4 This means that completeness for stars having unusual colors (e.g., very red objects such as young stellar objects or heavily reddened stars) is not accurately reported by our metric “Completeness” (defined below), but completeness of such red sources is tabulated meaningfully by the “Completeness2” metric.

5 Details of the detection algorithm implemented in the GLIMPSE pipeline appear in the Appendix.
S/N > 5, where the 2MASS Ks band is allowed as an adjacent band for IRAC 3.6 μm. Hence, it is possible for a source to be included in the GPSC but lack photometry in as many as two (or even three) of the four IRAC bands. Most commonly, non-detections occur at IRAC bands 5.8 and/or 8.0 μm as a result of the reduced instrumental sensitivity and the decreasing flux on the Rayleigh–Jeans tail of the spectral energy distribution for the majority of astrophysical sources. Objects with rising spectral energy distributions, such as protostars, evolved stars exhibiting circumstellar excesses, or heavily extincted objects, could have detections at IRAC 5.8 and 8.0 μm but not at the shorter wavelengths. Inclusion in the Catalog also requires that (1) a source does not fall within the PSF wings of a saturated source (as defined in the GLIMPSE data release documentation), (2) no hot or dead pixel lies within 3 pixels of the source center, (3) the source is not within 3 pixels of a frame edge, and (4) no Archive source lies within 2″ of the source. Furthermore, the sources used to identify and confirm a detection must be brighter than 0.6 mJy (14.2 mag), 0.4 mJy (14.1), 2 mJy (11.9), and 10.0 mJy (9.5) in the 3.6, 4.5, 5.8, and 8.0 μm bands, respectively. However, sources fainter than these limits at a particular band may appear in the Catalogs if they are identified and confirmed using other bands. Users should consult the GLIMPSE data release documentation⁵ for a full description of source selection and rejection criteria.

Inclusion in the less reliable but more complete GPA data requires that a source be detected at least once in any two bands at S/N > 3 and that there are no neighboring sources within 0″.5. Sources that lie within the PSF wings of a saturated star are included in the Archive. This last criterion means that the completeness we estimate for the Catalog is going to be suppressed relative to the Archive at all magnitudes and at all background levels because of the presence of saturated stars. The saturation limit for the short 1.2 s GLIMPSE I/II/3D frame times is approximately 7, 6.5, 4, and 4 mags (439, 450, 2930, and 1590 mJy) for IRAC bands 3.6, 4.5, 5.8, and 8.0 μm, respectively. The saturated source areal density is a strong function of Galactic position but is on the order of ~40 deg⁻² at ℓ = 36°, as estimated from 2MASS K-band source counts.⁷ Therefore, the effect of saturated stars on completeness in the GLIMPSE I/II/3D Catalogs and similar shallow survey Catalogs is minimal, given that the PSF wings (R < 24 pixels, but an irregular region given by the shape of diffraction spikes) comprise ≲1% of the survey area.

To characterize the completeness at each band the list of detected point sources from the “Actual+Artificial” images was compared to the input list of artificial sources (i.e., the Artificial list). Any detected source within 1.2 pixels of a source in the “Artificial” list was considered to be a successfully recovered source. We find that the magnitudes of recovered stars always match the magnitudes of inserted stars within the expected uncertainties, typically 0.05 mag at the bright end and ~0.5 mag at the faint end. Therefore, the matching process does not include a magnitude criterion. We found it necessary to develop two definitions of completeness. In the first definition, dubbed Completeness1, we define completeness as the number of artificial sources present in the resulting GPSC divided by the number of input artificial sources. This inclusive definition allows for the possibility that a given star may be included in the GPSC even though it may lack a detection at any given band, N. In the second definition, Completeness2, we require that a given source actually be detected in band N specifically, rather than being included in the Catalog only by virtue of its detection at other bands. The more restrictive Completeness2 values are always lower than Completeness1, especially at 5.8 and 8.0 μm where the deleterious effects of high and structured backgrounds on source identification are most severe.

3. DIFFUSE BACKGROUND COMPLETENESS RESULTS

3.1. GLIMPSE I, II, 3D Point Source Catalog
(and Vela-Carina)

Figure 2 (upper panel) plots Completeness1 versus background sky brightness in MJy sr⁻¹ for the IRAC 3.6 μm artificial star simulations. The ordinate is partitioned into logarithmically spaced sky brightness bins to increase the reliability of high-surface-brightness bins which comprise only a small fraction of the test area. Line styles indicate stellar magnitude bins from 8th to 15th magnitude, as shown by the legend. The heavy solid curve shows the cumulative distribution of the background sky brightness. For example, the solid curve shows that approximately 35% of the background regions in our test area are brighter than 5 MJy sr⁻¹ at 3.6 μm. The rapid decline in completeness at background levels greater than about 10 MJy sr⁻¹ is clear in all but the brightest magnitude ranges. Furthermore, the faintest magnitude bin, 14th–15th magnitude, is never more than 25% complete even in the regions of lowest sky brightness. We attempted to fit simple analytical formulae to these data to provide an easily integrable functional form for completeness as a function of magnitude and background level, but no simple form (Gaussian, exponential, trigonometric, polynomial) yielded good fits across the range of magnitudes and background levels pictured in Figure 2. We therefore elected to simply tabulate the results and allow end users to perform their own interpolation or fitting. Table 2 lists numerical values for Completeness1 as a function of magnitude and background level for the 3.6 μm bandpass as shown graphically in Figure 2. Note that the uncertainties on the tabulated completeness are at the level of 10%–15% for the bin at the highest background levels as a result of statistical limitations, but in the other bins uncertainties are typically <2%. Statistics in the lowest surface brightness bin are also uncertain at the level of a few percent as a result of the paucity of extremely dark regions in the Galactic Plane.

Figure 2 (lower panel) plots Completeness2 versus background sky brightness for the IRAC 3.6 μm. Table 3 lists these results in the same manner as for Completeness1 in Table 2. The results are nearly identical to the Completeness1 case because PAH emission from diffuse background sources is relatively minor at 3.6 μm and the flux from stellar photospheres is a maximum, thereby aiding source identification and extraction. Sources in the GPSC are most commonly included by virtue of having a detection at IRAC 3.6 μm.

Figure 3 plots Completeness1 and Completeness2 versus background sky brightness for the IRAC 4.5 μm artificial star simulations. The overall trends are similar to 3.6 μm where both Completeness1 and Completeness2 decline markedly in backgrounds above about 10 MJy sr⁻¹. Only the brightest stars, <11th magnitude, are readily detected and show a slower drop in completeness. The numerical results for Completeness2 are nearly identical to Completeness1. This results from the fact that background levels are low in the 4.5 μm band (no PAH

⁵ http://irsa.ipac.caltech.edu/data/SPITZER/GLIMPSE/doc/glimpse1_dataprod_v2.0.pdf
⁶ The 2MASS Ks band is used as a proxy for the IRAC 3.6 μm band because the GLIMPSE pipeline does not detect or extract saturated sources.
Figure 2. GLIMPSE I/II/3D Catalog Completeness1 (upper panel) and Completeness2 (lower panel) vs. sky brightness for IRAC 3.6 μm as a function of stellar magnitude, denoted by the line style from 8th to 15th magnitude. The heavy solid curve shows the cumulative fraction of sky background regions brighter than a given level. For example, approximately 35% of the background regions in our test area are brighter than 5 MJy sr⁻¹ at 3.6 μm.

Figure 3. GLIMPSE I/II/3D Catalog Completeness1 (upper panel) and Completeness2 (lower panel) vs. sky brightness for IRAC 4.5 μm as a function of stellar magnitude, with symbols as in Figure 2.

features) and that sources in the GPSC are almost always included by virtue of having a detection at 4.5 μm. Tables 2 and 3 record these numerical completeness data for the 4.5 μm analysis.

Figure 4 plots Completeness1 and Completeness2 versus background sky brightness for the IRAC 5.8 μm simulations. These histograms show dramatically decreased completeness levels for all but the brightest stars as the background levels exceed ~50 MJy sr⁻¹. The IRAC 5.8 μm band contains strong PAH features, and regions with specific intensities exceeding 200 MJy sr⁻¹ are not uncommon in this and other major star-forming complexes. A comparison of Figure 4 shows that Completeness2 is significantly lower than Completeness1 for stars fainter than about 11th magnitude for all background levels greater than ~100 MJy sr⁻¹. This results from sources being included in the Catalog (Completeness1) but not having...
a detection at 5.8 \( \mu \text{m} \) (Completeness2). Tables 2 and 3 record these numerical completeness data for the 5.8 \( \mu \text{m} \) analysis.

Figure 5 plots Completeness1 and Completeness2 versus background sky brightness for the 8.0 \( \mu \text{m} \) simulations. While the behavior of the calculated completeness is similar to the plots for 5.8 \( \mu \text{m} \) above, the difference between Completeness1 and Completeness2 is even more dramatic. Completeness2 shows a much more rapid decline than Completeness1, to the point where sources fainter than 12th magnitude are rarely detected in any but the darkest background regions. The difference between the upper and lower panels of Figure 5 illustrates why the number of 8.0 \( \mu \text{m} \) detections in GLIMPSE averages <30\% the number of
3.6 μm detections for a typical low-latitude sightline. In regions with background levels greater than 100 MJy sr⁻¹, the lower panel shows that only 11th magnitude and brighter sources are likely to be represented in the Catalog and have a measurement at 8.0 μm. However, on a more positive note, the upper panel shows that faint 8.0 μm sources are likely to be represented in the Catalogs by virtue of having measurements at other bands, principally at 3.6 and 4.5 μm.

In summary, Figures 2 through 5, in conjunction with Tables 2 and 3 provide a means of estimating the likelihood of detecting sources in a particular band and being included in the GPSC. These figures and tables should also be applicable to other Spitzer IRAC observations using similar short exposure times, low point source densities, and a small number of observations of each target, such as the Vela-Carina project which was processed by the GLIMPSE pipeline.
3.2. GLIMPSE I, II, 3D Point Source Archive

We performed the same analysis for the GPSA as for the GPSC. Figures 6 through 9 plot Completeness1 and Completeness2 as a function of background brightness for the Archive. Tables 4 and 5 summarize these results numerically. A comparison of Figures 6 through 9 with the corresponding sequence in Figures 2 through 5 reveals that more stars are recovered in the Archives versus the Catalogs at all bands. The typical difference is a few percent to as much as a few tens of percent, with the most dramatic improvement being at low background levels for the faintest stars.

3.3. GLIMPSE 360 and Deep GLIMPSE

GLIMPSE 360 and Deep GLIMPSE employed the IRAC HDR mode using 3.6 and 4.5 μm bands during the Spitzer warm mission to obtain three 0.4 and three 10.4 s exposures at each location along a large portion of the Galactic Plane following the warp of the disk in the outer Milky Way. We
employed the same artificial star methodology described above in order to generate completeness data for the 3.6 and 4.5 μm photometry obtained in the course of these large programs. The selected test region covers a wide range of background levels in the region $133.5 < \ell < 135.0$ and $0.0 < b < 1.9$ obtained during the GLIMPSE 360 observing program. The GLIMPSE 360 completeness analysis adds and recovers artificial stars only on the 10.4 s exposures, since we are interested primarily in completeness for the faint end of the observed magnitude range.

The GLIMPSE 360 and Deep GLIMPSE observing strategy is sufficiently different from the preceding GLIMPSE programs that slightly different criteria are applied to determine inclusion in the Catalogs and Archives. Given three HDR sequences (an HDR sequence means one 0.4 s exposure plus one 10.4 s exposure), there are six possible frames at each location in each of two bands where a source might be detected. In general, $M$ is the number of detections for a given source out of a possible $N$ detections. Inclusion in the GLIMPSE 360/Deep GLIMPSE

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**Figure 8.** GLIMPSE I/II/3D Archive Completeness1 (upper panel) and Completeness2 (lower panel) vs. sky brightness for IRAC 5.8 μm as a function of stellar magnitude, with symbols as in Figure 2.

**Figure 9.** GLIMPSE I/II/3D Archive Completeness1 (upper panel) and Completeness2 (lower panel) vs. sky brightness for IRAC 8.0 μm as a function of stellar magnitude, with symbols as in Figure 2.
Catalog requires $M/N > 0.6$ in one band (the selection band) and $M/N > 0.32$ in an adjacent band (the confirmation band), with $S/N > 5$ for both bands. Detection in the 2MASS $K_S$ band counts as a confirmation, but in practice, only a few percent of all GLIMPSE 360 sources are included in the Catalog by virtue of having a $K$-band detection in addition to a 3.6 μm detection.

Additionally, inclusion in the Catalog requires that (1) the source be fainter than the non-linear regime for the IRAC array (10.25 and 9.6 mag at 3.6 and 4.5 μm, respectively, for the IRAC 10.4 s exposure times; the HDR 0.4 s data has brighter limits but is not considered here in our simulations), (2) that the source not lie within $2''$ of an Archive source, (3) that the source not lie within $5''$ for both bands. Detection in the 2MASS $K_S$ band counts as a confirmation, but in practice, only a few percent of all GLIMPSE 360 sources are included in the Catalog by virtue of having a $K$-band detection in addition to a 3.6 μm detection.
Deep GLIMPSE Archive in lieu of the Catalog for applications requiring high completeness in the GLIMPSE 360 data. Users requiring a precise estimate of completeness in the GLIMPSE 360 data for the 3.6 and 4.5 μm band. Figure 13 shows the Completeness1 and Completeness2 results for 4.5 μm.

### Table 6
**GLIMPSE 360 and Deep GLIMPSE Catalog Completeness1**
As a Function of Band and Magnitude

| Background (MJy sr⁻¹) | 11–12 | 12–13 | 13–14 | 14–15 | 15–16 | 16–17 | 17–18 |
|------------------------|-------|-------|-------|-------|-------|-------|-------|
| 3.6 μm                 |       |       |       |       |       |       |       |
| 0.12–0.21              | 0.97  | 0.97  | 0.97  | 0.97  | 0.85  | 0.11  |
| 0.21–0.37              | 0.95  | 0.94  | 0.95  | 0.95  | 0.80  | 0.09  |
| 0.37–0.66              | 0.92  | 0.93  | 0.93  | 0.92  | 0.70  | 0.05  |
| 0.66–1.17              | 0.90  | 0.90  | 0.90  | 0.90  | 0.88  | 0.56  | 0.02  |
| 1.17–2.06              | 0.88  | 0.88  | 0.89  | 0.87  | 0.82  | 0.36  | 0.01  |
| 2.06–3.63              | 0.87  | 0.89  | 0.89  | 0.84  | 0.65  | 0.14  |
| 3.63–6.41              | 0.85  | 0.82  | 0.75  | 0.63  | 0.29  | 0.02  |
| 6.41–11.32             | 0.71  | 0.62  | 0.42  | 0.24  | 0.04  | 0.00  |
| 11.32–19.99            | 0.43  | 0.31  | 0.10  | 0.03  | 0.00  | 0.00  |
| 19.99–35.29            | 0.11  | 0.03  | 0.02  | 0.00  | 0.00  |
| 35.29–62.31            | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  |
| 62.31–110.00           | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  |
| 4.5 μm                 |       |       |       |       |       |       |       |
| 0.07–0.12              | 0.94  | 0.96  | 0.96  | 0.96  | 0.86  | 0.11  |
| 0.12–0.22              | 0.95  | 0.96  | 0.96  | 0.96  | 0.83  | 0.10  |
| 0.22–0.38              | 0.93  | 0.93  | 0.93  | 0.93  | 0.75  | 0.07  |
| 0.38–0.66              | 0.92  | 0.92  | 0.92  | 0.92  | 0.65  | 0.04  |
| 0.66–1.17              | 0.89  | 0.89  | 0.89  | 0.88  | 0.85  | 0.49  |
| 1.17–2.05              | 0.87  | 0.89  | 0.89  | 0.86  | 0.78  | 0.28  |
| 2.05–3.60              | 0.88  | 0.88  | 0.86  | 0.82  | 0.56  |
| 3.60–6.32              | 0.82  | 0.80  | 0.71  | 0.54  | 0.21  |
| 6.32–11.09             | 0.72  | 0.61  | 0.42  | 0.26  | 0.03  |
| 11.09–19.47            | 0.45  | 0.27  | 0.09  | 0.02  |
| 19.47–34.18            | 0.14  | 0.07  | 0.03  |
| 34.18–60.00            | 0.00  | 0.00  | 0.00  |

**Note.** a Completeness of the GLIMPSE 360/Deep GLIMPSE Catalogs is significantly reduced in some locations by the density of saturated stars and their extended PSF wings (R = 24 pixels). Saturated star density varies greatly with Galactic location, so these data should be regarded as illustrative of general trends rather than definitive for all regions. Users requiring a precise estimate of completeness in the GLIMPSE 360/Deep GLIMPSE Catalogs should conduct their own analysis of saturated star density specific to their region of interest and its impact on Catalog completeness. We recommend the GLIMPSE 360/Deep GLIMPSE Archive in lieu of the Catalog for applications requiring high completeness.

Figure 10 shows the Completeness1 and Completeness2 results for the GLIMPSE 360/Deep GLIMPSE Catalog for the 3.6 μm band. Figure 11 shows the Completeness1 and Completeness2 results for 4.5 μm. The histogram line styles indicate magnitude ranges from 11 to 18. Tables 6 and 7 report numerical data for the GLIMPSE 360/Deep GLIMPSE Catalog simulations for the 3.6 and 4.5 μm bands. These figures show that a similar trend to the 3.6 and 4.5 μm results from the GLIMPSE 1/II/3D simulations reported above. Completeness varies as a function of both magnitude and background level. Given the deeper exposures for GLIMPSE 360/Deep GLIMPSE compared to GLIMPSE 1/II/3D, the completeness is generally greater at any given magnitude at any given background level. One noteworthy feature of these histograms is the drop in completeness at all magnitudes, even at relatively faint sky background levels. This means that the GPSC for GLIMPSE 360/Deep GLIMPSE is almost never 100% complete, even at the brightest magnitudes and darkest sky backgrounds. The reason for this is described subsequently.

Figure 12 shows the Completeness1 and Completeness2 results for the GLIMPSE 360/Deep GLIMPSE Archive for the 3.6 μm band. Figure 13 shows the Completeness1 and Completeness2 results for 4.5 μm. Tables 8 and 9 report numerical data for the GLIMPSE 360/Deep GLIMPSE Archive simulations for the 3.6 and 4.5 μm bands. These figures and tables show that the Archive Completeness1 is very similar to Completeness2. This is expected, given that the lack of IRAC 5.8 and 8.0 μm data in GLIMPSE 360 and similar surveys essentially means that all of the sources must be detected both at 3.6 and 4.5 μm in order to appear in the Catalog or the Archive.

Notably, GLIMPSE 360 Archive completeness in Figures 12 and 13 is higher than Catalog completeness in Figures 10 and 11, even at bright magnitudes and low background levels. This results from the inclusion of sources in the Archive that lie within

For further understanding of source flags and subtle criteria that define the Catalog and the Archive sources, consult the GLIMPSE 360 Data Delivery Document8 for a full understanding of source flags and subtle criteria that define the Catalog and the Archive sources.

8 http://www.astro.wisc.edu/glimpse/glimpse360_dataprod_v1.1.pdf
Figure 10. GLIMPSE 360/Deep GLIMPSE Catalog Completeness1 (upper panel) and Completeness2 (lower panel) vs. sky brightness for IRAC 3.6 μm as a function of stellar magnitude, with symbols as in Figure 2.

Figure 11. GLIMPSE 360/Deep GLIMPSE Catalog Completeness1 (upper panel) and Completeness2 (lower panel) vs. sky brightness for IRAC 4.5 μm as a function of stellar magnitude, with symbols as in Figure 2.

the PSF wings of saturated stars. Such sources are rejected from the Catalog in order to ensure high reliability. Saturated stars are a much greater problem in the longer exposures used for GLIMPSE 360/Deep GLIMPSE compared to GLIMPSE I/II/3D. This means the photometry for a significant fraction of the areal coverage in GLIMPSE 360/Deep GLIMPSE Catalogs is nullified because it lies under the PSF wings of saturated stars. The GLIMPSE 360/Deep GLIMPSE Archives, by contrast, are significantly more complete because they include sources that lie in the PSF wings of saturated stars. The magnitude of this effect in the GLIMPSE 360/Deep GLIMPSE Catalogs varies dramatically with Galactic positions, being on the order of a few percent in the outer Galaxy but rises to many tens of percent in crowded regions of the inner Galaxy. Figures 14 and 15 show grayscale representations of the GLIMPSE 360/Deep GLIMPSE IRAC 3.6 μm mosaic near ℓ = 180° and ℓ = 030°, respectively. Red circles in the left panel of each figure mark sources included in the GPSC, while green circles
in the right panels mark sources included in the GPSA. The effect of “dead zones” around bright stars is dramatic in the left panel of Figure 15 where high stellar densities cause the removal of photometric results from the GPSC for a significant fraction of the survey area. By contrast, the effects of saturated sources in the GPSC in Figure 14 for the $\ell = 180^\circ$ field are rather subtle. Here and in other such fields having low stellar densities, the completeness of the Catalog and Archive will be more similar than for high-density fields, as only a few percent of the survey area falls under the wings of saturated stars. In summary, Catalog incompleteness in GLIMPSE 360/Deep GLIMPSE varies greatly with location, and users are encouraged to consider the merits of the GPSA where high levels of completeness are desired.

4. ROLE OF STRUCTURED BACKGROUNDS

Having empirically assessed the completeness simply as a function of one parameter, i.e., background level, we now...
consider the role that the structure of the diffuse background emission plays in limiting point source detection. Figure 1 shows that not only is the Galactic Plane filled with regions of high surface brightness (i.e., regions where Poisson noise from background photons is elevated), but the emission is also highly structured, having a variety of filamentary morphologies on scales all the way down to the IRAC PSF (and probably on smaller scales that would be significant in data having higher angular resolution). This structure further complicates source identification and extraction.

As a test of whether photon noise or structure from diffuse backgrounds is the more significant cause of incompleteness, we conducted the same artificial star test described in Section 2 using the “residual” images generated by the GLIMPSE pipeline after point sources have been removed. We smoothed these residual images in the $\ell = 333^\circ$ test region, first with a 101 pixel box and then a 27 pixel box to eliminate “structure” on scales smaller than about 25 times the PSF and 7 times the PSF, respectively. These smoothing scales represent large and moderate smoothing, respectively. To avoid edge-of-frame effects, we smoothed a mosaic image of the residuals and then reconstructed the original BCD images. To the smoothed residual BCD images we added Poisson noise, at a level appropriate for each pixel, and readnoise, according to the IRAC documentation: 11.8, 12.1, 9.1, and 7.1 electrons per pixel for the IRAC bandpasses 3.6, 4.5, 5.8, and 8.0 $\mu$m, respectively. Artificial stars were added at exactly the same positions and magnitudes as in Section 2 before running the GLIMPSE pipeline to extract sources and construct a Catalog and Archive. The input list of artificial stars was compared to the recovered list of stars to assess the completeness.

Figure 16 shows the resulting GPSC Completeness2 versus background level for 8.0 $\mu$m, in a way exactly analogous to Figure 5, except that now the effect of structure has been eliminated using a 27 pixel smoothing box. A comparison of Figure 16 with Figure 5 shows that the completeness is much greater for any given magnitude or sky brightness level once the diffuse background has been smoothed. Results for other bands are similar.

Figure 17 shows GPSC Completeness2 versus background level for the 8.0 $\mu$m band, in a way exactly analogous to Figure 5, except that now the effect of structure have been eliminated using a 101 pixel smoothing box. Comparison with Figures 5 and 16 reveals that a much greater fraction of sources at all magnitudes and background levels are recovered and recorded in the Catalog when the diffuse background structure is reduced even further.

We conclude that, at the magnitude ranges of interest to users of GLIMPSE and similar Spitzer IRAC surveys, incompleteness resulting from diffuse backgrounds is dominated by the

Figure 14. Grayscale image of the GLIMPSE 360 IRAC 3.6 $\mu$m mosaic near $\ell = 180^\circ$. In the left panel red circles mark the locations of GPSC sources, while in the right panel green circles designate GPSA sources. The subtle differences between these figures in the vicinity of saturated stars illustrates the greater completeness of the Archive (right) compared to the Catalog (left).

Figure 15. As in Figure 14, but for the crowded $\ell = 30^\circ$ region of the Deep GLIMPSE survey. The dramatic drop in Catalog source density (left panel) near saturated stars illustrates the reduced completeness of the Catalog (left) compared to the Archive (right) for such crowded regions.
Figure 16. GLIMPSE I/II/3D Catalog Completeness vs. sky brightness for IRAC 8.0 \( \mu \)m as a function of stellar magnitude, with symbols as in Figure 2. The background has been smoothed using a 27 pixel boxcar. A comparison with Figure 5 shows that the completeness is much greater at any given magnitude range or background level bin, indicating that background complexity rather than photon noise is the dominant factor limiting source detection.

Figure 17. GLIMPSE I/II/3D Catalog Completeness vs. sky brightness for IRAC 8.0 \( \mu \)m as a function of stellar magnitude, with symbols as in Figure 2. The background has been smoothed using a 101 pixel boxcar. A comparison with Figure 5 and with Figure 16 shows that the completeness is much greater at any given magnitude range or background level bin when the background is made smoother.

effects of “structure” in the background rather than purely by photon noise. The artificial star analysis performed in Section 2 implicitly includes both effects. In the absence of a simple, single parameter suitable for describing the complexity of structured background emission in the Galactic Plane, we retain the tables and figures, as previously presented, as a way to assess incompleteness as a function of mean background level.

5. ANALYSIS OF POINT SOURCE COMPLETENESS

Point source crowding (i.e., confusion) inhibits source detection and affects the reliability of photometry independently from the diffuse background effects addressed above. Point source densities in the GLIMPSE Archives range from <10 sources arcmin\(^{-2}\) at 5.8 and 8.0 \( \mu \)m in some local regions...
of the GLIMPSE I/II/3D surveys to over 150 sources arcmin$^{-2}$ at 3.6 and 4.5 μm in some portions of the GLIMPSE 360/Deep GLIMPSE surveys. In the first extreme, source densities are so low that their PSFs rarely overlap and confusion effects are negligible. In the latter extreme, confusion is of considerable consequence. Ability to detect any given source will depend on the proximity to a neighboring source (or sources) and on the flux ratio between the source in question and the neighboring source(s). As such, this issue involves one more free parameter than the diffuse background problem addressed above. Accordingly, we have elected to perform a more general and more empirical characterization of its effects using the GLIMPSE data itself rather than an artificial star analysis.

Figure 18 plots the base 10 logarithm of the point source number counts ($N$) in 0.05 mag wide bins versus magnitude (i.e., flux) from the GLIMPSE Archives. The log($N$)–mag plot in each panel shows a different IRAC band either for the GLIMPSE I/II/3D 1.2 s survey (all four bands) or the GLIMPSE 360/Deep GLIMPSE 10.4 s survey (two bands). Line styles denote GLIMPSE Archive data from three distinct Galactic longitude strips, as labeled. Only the sources having the specified range of diffuse background intensity within the local point source densities in the lowest quartile of all sources in each longitude segment were used in order to mitigate possible effects of confusion and ensure that results are comparable to the simulations detailed in Section 3 where artificial stars were added at locations devoid of known sources. The curves exhibit a quasi-linear rise toward fainter magnitudes and then a well-defined turnover. The bin having the maximum counts is designated as the “turnover” or “peak” magnitude bin and marks where the Archive completeness becomes appreciable, as quantified below. The turnover magnitude varies systematically with Galactic longitude in the sense that regions farther from the Galactic Center are complete to fainter magnitudes as the source density drops. The lower left panel shows that the turnover magnitude toward the Galactic anticenter is $[3.6] = 16.6$, while at $\ell = 328–330^\circ$ it is $[3.6] \simeq 14.9$. It is also clear that the 10.4 s GLIMPSE 360/Deep GLIMPSE data go deeper than the GLIMPSE I/II/3D surveys. The shapes of the curves, specifically the slopes as a function of magnitude, exhibit subtle but real differences reflecting variations in stellar populations along different sightlines. A detailed analysis of the log($N$)–mag plots can be used to infer features such as the Galactic “long bar” interior to $\ell = 30^\circ$ and spiral arm tangencies (e.g., Benjamin et al. 2005; Benjamin 2009), and additional analyses will be presented elsewhere. Nevertheless, Figure 18 serves to illustrate the point that the completeness of the GLIMPSE surveys as a function of stellar surface density may be estimated from the data itself using a series of similar plots where the log($N$)–mag curves are generated using subsets of Archive data selected by local source density$^9$ instead of longitude.

Figure 19 shows a grid of log($N$)–mag curves from the GLIMPSE I survey at $\ell = 332^\circ–333^\circ$. The four columns correspond to the four IRAC bands. The five rows correspond sources having the specified range of diffuse background intensity within the $\ell = 332^\circ–333^\circ$ segment, increasing from very low values (top row) to moderate–high values for each band (bottom row), as labeled in each panel in MJy sr$^{-1}$. The black

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**Table 8**

| Background | 11–12 | 12–13 | 13–14 | 14–15 | 15–16 | 16–17 | 17–18 |
|------------|-------|-------|-------|-------|-------|-------|-------|
|           | (mag) | (mag) | (mag) | (mag) | (mag) | (mag) | (mag) |
| 3.6 μm     |       |       |       |       |       |       |       |
| 0.12–0.21  | 1.00  | 1.00  | 1.00  | 1.00  | 1.00  | 1.00  | 1.00  |
| 0.21–0.37  | 1.00  | 1.00  | 1.00  | 1.00  | 1.00  | 1.00  | 1.00  |
| 0.37–0.66  | 1.00  | 1.00  | 1.00  | 1.00  | 0.99  | 0.75  | 0.06  |
| 0.66–1.17  | 1.00  | 0.99  | 0.99  | 0.98  | 0.96  | 0.60  | 0.03  |
| 1.17–2.06  | 0.99  | 0.98  | 0.97  | 0.95  | 0.88  | 0.40  | 0.01  |
| 2.06–3.63  | 0.98  | 0.98  | 0.96  | 0.91  | 0.71  | 0.16  | 0.00  |
| 3.63–6.41  | 0.96  | 0.93  | 0.85  | 0.71  | 0.33  | 0.03  | 0.00  |
| 6.41–11.32 | 0.90  | 0.79  | 0.51  | 0.32  | 0.04  | 0.00  | 0.00  |
| 11.32–19.99| 0.72  | 0.48  | 0.17  | 0.03  | 0.00  | 0.00  | 0.00  |
| 19.99–35.29| 0.27  | 0.09  | 0.02  | 0.00  | 0.00  | 0.00  | 0.00  |
| 35.29–62.31| 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  |
| 62.31–110.00| 0.00 | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  |

**Table 9**

| Background | 11–12 | 12–13 | 13–14 | 14–15 | 15–16 | 16–17 | 17–18 |
|------------|-------|-------|-------|-------|-------|-------|-------|
|           | (mag) | (mag) | (mag) | (mag) | (mag) | (mag) | (mag) |
| 3.6 μm     |       |       |       |       |       |       |       |
| 0.12–0.21  | 0.99  | 1.00  | 1.00  | 1.00  | 1.00  | 0.87  | 0.13  |
| 0.21–0.37  | 0.99  | 1.00  | 1.00  | 1.00  | 1.00  | 0.84  | 0.10  |
| 0.37–0.66  | 0.99  | 1.00  | 1.00  | 1.00  | 0.99  | 0.99  | 0.74  | 0.05  |
| 0.66–1.17  | 0.99  | 0.99  | 0.98  | 0.97  | 0.97  | 0.95  | 0.59  | 0.02  |
| 1.17–2.06  | 0.98  | 0.97  | 0.96  | 0.95  | 0.95  | 0.94  | 0.87  | 0.38  | 0.01  |
| 2.06–3.63  | 0.97  | 0.97  | 0.95  | 0.91  | 0.70  | 0.15  | 0.00  |
| 3.63–6.41  | 0.95  | 0.91  | 0.84  | 0.69  | 0.31  | 0.02  | 0.00  |
| 6.41–11.32 | 0.87  | 0.78  | 0.50  | 0.29  | 0.04  | 0.00  | 0.00  |
| 11.32–19.99| 0.68  | 0.45  | 0.14  | 0.03  | 0.00  | 0.00  | 0.00  |
| 19.99–35.29| 0.27  | 0.07  | 0.02  | 0.00  | 0.00  | 0.00  | 0.00  |
| 35.29–62.31| 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  |
| 62.31–110.00| 0.00 | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  |

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9 Local source density (attribute SRCDENS in the GPSC and GPSA) is computed within the GLIMPSE pipeline for each Catalog or Archive source, based on detections from the original BCD frames, averaged over 1.6 arcmin scales. The Appendix further describes the GLIMPSE pipeline source detection algorithm.
Figure 18. Source count vs. magnitude plot for the IRAC GLIMPSE I/II/3D Archive (1.2 s exposures) and the GLIMPSE 360/Deep GLIMPSE Archive (10.4 s exposures). Labels show the IRAC bandpass in each panel, and the Y axis indicates the log of number counts within 0.05 mag wide bins. Line styles demarcate distinct regions of Galactic longitude. The turnover in the curves indicates the magnitude at which incompleteness becomes significant, and the turnover point increases (becomes fainter) with distance from Galactic center as a result of decreasing stellar surface densities and decreasing diffuse background levels.

The solid curve shows source counts in 0.1 mag bins for areas having local source densities less than the indicated value, in units of source arcmin$^{-2}$. These correspond to relatively low surface densities where confusion should be minimized. Blue dotted curves, available in some panels, plot the source counts in regions of high point source density. The vertical black dashed and blue dotted lines mark the peak bin for the low-density and high-density curves, respectively. There is a clear progression of the peaks from right to left (from fainter to brighter magnitudes) as the mean sky level increases from top rows to the bottom rows. The blue dotted line always lies to the left (brighter magnitudes) of the solid line, showing that incompleteness affects brighter sources in regions of higher source density. Vertical red lines mark the magnitude range of approximate 90% completeness inferred from the simulations reported in Section 3. Figure 19 illustrates the excellent agreement between the vertical red lines and the vertical black lines, demonstrating that the peaks of the log($N$)–mag curves are reliable indicators of the 90% completeness level. As a secondary method of inferring completeness we fit lines to the linear part of the log($N$)–mag curve, extrapolated the line to the location of the peak, and then measured the ratio of the extrapolated $N$ to the actual peak $N$ in each plot as an estimate of the completeness. This method generally supports the claim that the completeness at the peak of the log($N$)–mag curve is 70%–95%, but the inherently non-linear nature of the curves, especially in bright magnitude bins having few sources, precludes more precise measurements.

Figure 20 is similar to Figure 19, but plots the log($N$)–mag curves for 3.6 μm and 4.5 μm from the GLIMPSE 360 survey coverage of the $\ell = 133^\circ$ region. This outer-Galaxy sightline exhibits lower source densities and suffers less from the effects of confusion, despite the same 10.4 s exposure time as in Figure 20. As in Figure 19, the peak magnitude shifts toward brighter sources as sky levels increase from top to bottom. There is good agreement between the completeness levels indicated by the simulations for GLIMPSE 360 90% completeness magnitudes (red vertical lines) and the peak of the histogram (vertical dashed line), except where sky brightness becomes large (lower rows). This supports the use of the peak in the log($N$)–mag as an indicator of the 90% completeness level with regard to effects of confusion.

Agreement between the simulated completeness levels and the peak of the log($N$)–mag histograms in the preceding figures allows us to empirically infer the approximate magnitude where the GLIMPSE Archives are 90% complete with respect to point source confusion. Figure 22 plots the log($N$)–mag turnover magnitude versus local point source density for each of the four IRAC bands and each of the two major survey modes. Symbols distinguish data from each of the five GLIMPSE legacy surveys.
Figure 19. A grid of log($N$)--mag curves at $\ell = 332^\circ$–$333^\circ$ with columns showing the four IRAC bandpasses and rows showing regions of increasing diffuse background intensity, as labeled in each panel in units of MJy sr$^{-1}$. Blue dotted curves show source counts for regions of high source density exceeding the labeled value in sources arcmin$^{-2}$. Black vertical dashed lines and vertical blue dotted lines mark the peak of the log($N$)--mag histograms, respectively. Red vertical lines designate the approximate 90% completeness inferred from the artificial star analysis described in Section 3.

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

At each band, only regions having sky brightness less than the indicated values (corresponding to the lowest quartile of sky values in each band) are used in order to minimize the impact of diffuse background on point source detection. Each data point in Figure 22 represents the peak of the log($N$)--mag plot for a specified range of source densities from 10–20 arcmin$^{-2}$ to 190–200 arcmin$^{-2}$ within a particular segment of the GLIMPSE surveys. In some cases, the full range of source densities is
not realized in a given band for a given survey. For example, source densities never exceed 50 arcmin$^{-2}$ at 8.0 $\mu$m (lower panel). The dispersion of measurements at a given source density bin reflects both the uncertainties in measuring the turnover magnitude and real variations that stem from the uniqueness of stellar population and extinction distributions along each sightline. The solid black curve connects the weighted mean turnover magnitudes in each source density bin.

Figure 22 illustrates that the limiting magnitude is a decreasing function of source density, most convincingly at 3.6 and 4.5 $\mu$m, where stellar photospheres are brightest and source densities are highest. On average, the GLIMPSE 360/Deep
Figure 21. A grid of log(N)–mag curves for the GLIMPSE 360 coverage of the outer-Galaxy $\ell = 133^\circ$ region, with notation as in Figure 19. (A color version of this figure is available in the online journal.)

GLIMPSE surveys go almost two magnitudes deeper than the GLIMPSE I/II/3D surveys, but the slopes are similar. The dispersion within a given bin is notably large in the Deep GLIMPSE data at 3.6 $\mu$m. In the lower two panels source densities almost never exceed 50 arcmin$^{-2}$, and the trends are less clear. The limiting magnitudes are nearly constant at [3.6] $\simeq$ 12.4 and [4.5] $\simeq$ 12.1 until the two highest density bins where the statistics become poor. The dispersion at a given source density is especially large for the 8.0 $\mu$m panel, reflecting effects from variable levels of diffuse sky emission that cannot be completely removed by limiting the analysis to the lowest quartile of sky backgrounds. Figure 22 provides the best general estimate yet available for
estimating point source completeness levels in GLIMPSE data products, as affected by confusion. The results should be broadly applicable to regions covered by the various GLIMPSE surveys. Users of GLIMPSE data products requiring high levels of completeness precision should conduct their own analysis in specific regions of interest by constructing log(N)–mag curves and making use of the SRCDENS attribute provided as part of the GLIMPSE Catalogs and Archives.

5.1. Limiting Magnitude of GLIMPSE Data Products: Diffuse Background versus Point Source Confusion

Consumers of GLIMPSE data products are advised that either diffuse background emission or point source confusion (or both!) limits the completeness of the GLIMPSE data products in various regimes. Figures 23 and 24 plot point source densities and diffuse background levels, respectively, as a function of longitude for each of the IRAC bands. Thin lines show the GLIMPSE I/II survey data and bold lines show the GLIMPSE 360/Deep GLIMPSE survey data. Red/black/blue colors denote the 99.9%/median/0.1% points of the distribution, respectively, at a given longitude. Discrepancies between surveys at the same longitude are the result of different exposure times and different latitude ranges for the GLIMPSE I/II surveys relative to the Deep GLIMPSE survey.

Figures 23 and 24 show that point source densities and sky levels generally increase toward the Galactic center. Median point source densities above 50 sources arcmin$^{-2}$ at 3.6 and 4.5 μm are common in the 1.2 s GLIMPSE I/II/3D surveys.
Figure 23. Point source density as a function of Galactic Longitude for the GLIMPSE I/II surveys (thin lines) and the GLIMPSE 360/Deep GLIMPSE surveys (bold lines). The two sets of lines may not agree at overlapping longitudes because latitude coverage of the surveys differs. Red/black/blue colors denote the 99.9%/median/0.1% source densities, respectively.

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

toward the inner Galaxy, but at 5.8 and 8.0 μm, densities rarely exceed 30 sources arcmin$^{-2}$. Median sky brightness levels vary between 0.1 and 2 MJy sr$^{-1}$ toward the inner Galaxy at 3.6 and 4.5 μm, but at 5.8 and 8.0 μm levels between 10 and 100 MJy sr$^{-1}$ are common. The outer Galaxy, by contrast, shows vastly reduced point source densities and diffuse sky levels. Source densities and diffuse levels also increase toward the mid-Plane, but these variations are not reflected in the latitude-averaged plots. Spatial variations in these quantities can be large over very small angular scales. For example, infrared dark clouds exhibit some of the lowest sky levels of <1 MJy sr$^{-1}$, and these often lie adjacent to bright-rimmed clouds and photodissociation regions with sky levels exceeding 100 MJy sr$^{-1}$. This means that a detailed description of how confusion or diffuse background affects photometry as a function of sky position would require a more complex analysis than undertaken here, but our simulations provide some insights specific to individual bandpasses.

5.1.1. GLIMPSE I/II/3D

3.6 μm. Figure 22 shows that, for regions with very low sky background <2.6 MJy sr$^{-1}$, the GLIMPSE I/II/3D Archives are complete to between [3.6] = 14–14.9 mag, depending on local source density. By comparison, Figure 6 (lower panel) reveals that completeness never exceeds 80% in this faintest magnitude bin, even at low sky levels, and it drops markedly in regions with sky brightness above 6 MJy sr$^{-1}$. Diffuse background significantly impacts completeness in brighter magnitude bins when it exceeds 10 MJy sr$^{-1}$. We conclude that for regions
with sky levels $\lesssim 3 \text{ MJy sr}^{-1}$, the limiting magnitude is set by confusion but is otherwise dominated by diffuse emission.

4.5 $\mu$m. Figure 22 shows that, for regions with background levels $<1.6 \text{ MJy sr}^{-1}$, the GLIMPSE I/II/3D Archives are complete to $[4.5] = 14–14.7$ mag, for source densities from 85 to 15 arcmin$^{-2}$. Figure 8 (lower panel), by comparison, shows that the Archives are, at most, 50% complete for the $[4.5] = 14–15$ mag bin even in the darkest regions. For sky levels exceeding about 6 MJy sr$^{-1}$, incompleteness becomes appreciable in the $[4.5] = 13–14$ mag range. We conclude that for the darkest regions and highest source densities, incompleteness is limited by confusion but for sky levels $\gtrsim 6 \text{ MJy sr}^{-1}$, diffuse background becomes the limiting factor.

5.8 $\mu$m. Figure 22 shows that the limiting magnitude is roughly constant at $[5.8] = 12.3$ across the range of observed source densities for sky brightness $<18.6 \text{ MJy sr}^{-1}$. Figure 9 (lower panel) indicates that the Archives are already no better than 55% complete in this magnitude range, and that by 40 MJy sr$^{-1}$, the $[5.8] = 11–12$ mag range has become substantially incomplete. We conclude that above 40 MJy sr$^{-1}$ the incompleteness is dominated by diffuse emission at all magnitude ranges. In the darkest areas having $<18.6 \text{ MJy sr}^{-1}$ the effects of confusion and diffuse background may be comparable for sources $[5.8] = 12–13$. Given the very low source densities and strong PAH emission at 5.8 $\mu$m we conclude that diffuse emission often limits the detection of point sources for typical Galactic Plane sightlines.

8.0 $\mu$m. Figure 22 shows that the limiting magnitude is approximately constant at $[8.0] \simeq 12$ across the small range of observed source densities for sky values $<49.5 \text{ MJy sr}^{-1}$. 

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

**Figure 24.** Diffuse background level as a function of Galactic Longitude for the GLIMPSE I/II surveys (thin lines) and the GLIMPSE 360/Deep GLIMPSE surveys (bold lines). The two sets of lines may not agree at overlapping longitudes because latitude coverage of the surveys differs. Red/black/blue colors denote the 99.9%/median/0.1% sky levels, respectively.
Figure 7 (lower panel) indicates that in the [8.0] = 11–12 range, the completeness has already dropped below 90% for sky values near 49.5 MJy sr$^{-1}$. By 100 MJy sr$^{-1}$, stars in the 10–11 mag range become substantially incomplete. Given the very low source densities and strong PAH emission at 8.0 $\mu$m we conclude that diffuse emission is frequently the limiting agent regarding the detection of point sources.

5.1.2. GLIMPSE 360/Deep GLIMPSE

3.6 $\mu$m. Figure 22 displays a range of limiting magnitudes from 16.6 at the lowest source densities (15 arcmin$^{-2}$) to 15.2 at densities approaching 155 arcmin$^{-2}$ for sky backgrounds $<2.6$ MJy sr$^{-1}$. By comparison, Figure 12 reveals that at these sky levels stars in the [3.6] = 15–16 bin are already less than 90% complete. We conclude that the effects of confusion are dominant for sightlines with the highest stellar densities, less than 90% complete. We conclude that the effects of sky backgrounds are significant for low source densities and at 15–16 mag bin are already less than 90% complete at these sky levels. We conclude that sky background effects dominate the incompleteness unless sky levels are $\lesssim$2 MJy sr$^{-1}$ and point source densities are $\gtrsim$80 sources arcmin$^{-2}$.

4.5 $\mu$m. Figure 22 illustrates that limiting magnitudes vary from [4.5] = 16.3 to 14.7 as source densities increase from 15 to 145 arcmin$^{-2}$ for sky backgrounds $<1.6$ MJy sr$^{-1}$. By comparison, Figure 13 shows that stars in the [4.5] = 15–16 mag bin are already less than 90% complete at these sky levels. We conclude that sky background effects dominate the incompleteness unless sky levels are $\lesssim$2 MJy sr$^{-1}$ and point source densities are $\gtrsim$80 sources arcmin$^{-2}$.

6. CONCLUSIONS

We have conducted an analysis of the completeness of point sources appearing in the various GPSC and GPSA to assess the impact of (1) high diffuse Galactic backgrounds and (2) high point source densities. With regard to the effects of diffuse backgrounds, we find:

1. Completeness is, as expected, a strong function of both stellar magnitude and background sky level, such that no simple characterization of the completeness is possible. Completeness drops rapidly with increasing stellar magnitude and sky brightness, especially in the IRAC 5.8 and 8.0 $\mu$m bands where strong PAH features produce large sky background brightnesses.

2. We provide figures and tabular data, suitable for interpolation, listing Completeness1 and Completeness2 values for each band for each of the two GLIMPSE survey strategies for both the Catalogs and Archives.

3. Completeness, as defined in two slightly different ways, is generally higher in the GPSA than in the Catalogs, at any given IRAC band. Completeness2 is always equal to or lower than Completeness1.

4. Catalogs resulting from the GLIMPSE 360/Deep GLIMPSE surveys may suffer significantly reduced completeness relative to the equivalent Archives because sources in the PSF wings of saturated stars are removed from the Catalogs. This effect is most severe in high-density regions toward the Inner Galaxy. Consumers of GLIMPSE 360/Deep GLIMPSE data products should consider using the Archive rather than the Catalog if high completeness is desired. GLIMPSE 1/II/3D surveys, by virtue of their shorter exposure times, exhibit a relatively minor completeness differences between Catalogs and Archives from this effect.

5. We assess whether background “brightness” or background “structure” is the limiting factor for point source detection. We conclude that both play a role, but that the effects of structure appear to dominate over pure photon noise in hindering the identification and extraction of point sources.

6. Although our artificial star recovery analysis is performed on images drawn from the GLIMPSE 1/II/3D (multiple 1.2 s exposures at all four IRAC bands) and GLIMPSE 360 and Deep GLIMPSE (three 10.4 s exposures at 3.6 and 4.5 $\mu$m) surveys, the results can be generalized to estimate completeness for other SpitzerIRAC programs that used similar observing strategies and have data products (Catalogs and Archives) constructed in the same manner. These include the SMOG, Cygnus-X, and the Vela-Carina surveys.

With regard to the effects of high stellar density on completeness, we conclude that only in the regions of low sky background do the effects of confusion limit the detection of point sources in the shallow GLIMPSE 1/II/3D surveys. The relative importance of diffuse background emission increases from 3.6 $\mu$m to 8.0 $\mu$m for a typical sightline and as the point source densities decrease, such as toward the outer Galaxy. In GLIMPSE 1/II/3D, confusion is the dominant source of incompleteness only at 3.6 and 4.5 $\mu$m and in regions of high point source density $\gtrsim$80 sources arcmin$^{-2}$, and where sky background levels are $\lesssim$2 MJy sr$^{-1}$. IRAC 5.8 and 8.0 $\mu$m are almost never limited by confusion as point source densities never exceed about 50 sources arcmin$^{-2}$. GLIMPSE 360/Deep GLIMPSE surveys reach several magnitudes deeper and are limited by both confusion and diffuse emission, to varying degrees. Confusion is the dominant source of incompleteness at 3.6 and 4.5 $\mu$m and regions of high point source density $\gtrsim$80 sources arcmin$^{-2}$, and where sky background levels are $\lesssim$2 MJy sr$^{-1}$. Figure 22 provides the best current estimates for confusion limits in each of the GLIMPSE surveys and bandpasses as a function of point source surface density. GLIMPSE data products include attributes for quantifying local point source density and diffuse sky levels for each detected source.

Finally, we caution that completeness in the GLIMPSE data products (and any higher-level data catalog products) is inevitably also affected by additional selection and matching criteria that are imposed to ensure high reliability (i.e., robustness against false sources). Therefore, completeness is necessarily a multi-faceted, non-trivial quantity that is unique to a particular survey strategy and source extraction paradigm. Consumers of GLIMPSE data requiring highly precise completeness estimates are urged to understand the details of the source detection and selection process for the data products in question.

We are grateful to Matt Povich, Bob Benjamin, and Dan Clemens for their assistance and advice on this analysis. We thank the extended GLIMPSE team and the IRAC instrument team members who, together, have helped deliver a genuinely “legacy” dataset to the astronomical community. We thank the anonymous referee whose astute suggestions improved this manuscript. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute
APPENDIX

THE GLIMPSE PIPELINE SOURCE DETECTION ALGORITHM

Source detection in the GLIMPSE team’s photometry pipeline utilizes a modified version of the DAOPHOT (Stetson 1987) FIND routine (see Appendix 2 of the DAOPHOT II User’s Manual; http://www.astro.wisc.edu/glimpse/daophot2.pdf) and is more fully described in the GLIMPSE documentation on point source photometry (http://www.astro.wisc.edu/sirtf/glimpse_photometry_v1.0.pdf). The GLIMPSE team modified the DAOPHOT II FIND routine in two ways to accommodate the high-reliability requirement of the GLIMPSE Catalogs. The original DAOPHOT FIND routine determines a global “sky” value from the entire input image. Since the GLIMPSE images contain highly variable diffuse structure, we first estimate the local sky level using a 5-pixel median-smoothed version of the input image. The “sky” value is measured locally in a $5 \times 5$ pixel box centered at each pixel location. In order to ensure that detected sources in high-background, high-structure regions are real, we adopt the maximum sky value within the box as the effective sky value. The maximum sky value, readout noise, and detector gain are then used to determine the local noise at each central pixel. Point source detection is then performed as a two-step process. Initial detections are conducted using a $3\sigma$ threshold. Detected sources are then fit with the instrument PSF and extracted from the input image. If the photometric signal-to-noise ratio (S/N) of the extracted source falls below two, the source is discarded. Once the initial set of sources are extracted, the residual image (input image minus the subtracted sources) is then used as a new input image. A new sky image is constructed from this image and secondary sources are then detected at a $5\sigma$ threshold. The second iteration of FIND is performed at a higher detection level because the initial source subtraction adds noise around extracted sources, requiring a higher subsequent detection threshold to avoid finding false sources while still detecting real sources hidden in the wings of the brighter stars. First-pass source extractions are then combined with the second-pass extractions to produce the final list which we designate as the “full” list of candidate sources for each BCD image. Candidate sources must still pass additional cross-band and multi-detection criteria before being included in the Catalogs or Archives, as described in Section 2 and in GLIMPSE data products documents referenced herein.

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