A 24 μm POINT SOURCE CATALOG OF THE GALACTIC PLANE FROM SPITZER/MIPS GAL

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ABSTRACT

In this contribution, we describe the applied methods to construct a 24 μm based point source catalog derived from the image data of the MIPS GAL 24 μm Galactic Plane Survey and the corresponding data products. The high quality catalog product contains 933,818 sources, with a total of 1.353,228 in the full archive catalog. The source tables include positional and photometric information derived from the 24 μm images, source quality and confusion flags, and counterpart photometry from matched 2MASS, GLIMPSE, and WISE point sources. Completeness decay data cubes are constructed at 1° angular resolution that describe the varying background levels over the MIPS GAL field and the ability to extract sources of a given magnitude from this background. The completeness decay cubes are included in the set of data products. We present the results of our efforts to verify the astrometric and photometric calibration of the catalog, and present several analyses of minor anomalies in these measurements to justify adopted mitigation strategies.

Key words: catalogs – Galaxy: stellar content – infrared: stars

1. INTRODUCTION

The MIPS GAL Survey is a Legacy Program of the Spitzer Space Telescope that imaged the 24 and 70 μm emission along the inner disk of the Milky Way (Carey et al. 2009). These mid-infrared bands are sensitive to the thermal emission radiated by interstellar dust grains that reside within a broad range of environments such as the envelopes of evolved stars, circumstellar disks, and infalling envelopes surrounding young stellar objects (YSOs), H n regions, supernova remnants, and the extended domains of dense, interstellar clouds. As a wide area survey, MIPS GAL is an important component to the infrared-to-millimeter reconnaissance of the Galaxy, which includes recent, all-sky missions: 2MASS (Skrutskie et al. 2006), WISE (Wright et al. 2010), and Planck (Planck Collaboration et al. 2011) as well as surveys targeted along the Galactic plane: GLIMPSE (Churchwell et al. 2009), ATLAS-GAL (Schuller et al. 2009), the Bolocam Galactic Plane Survey (Aguirre et al. 2011; Ginsburg et al. 2013), and the Herschel Infrared Galactic Plane Survey (Molinari et al. 2010). With its primary 24 μm band, MIPS GAL provides a critical wavelength measurement, which links the near-infrared data from 2MASS and GLIMPSE to the far-infrared/submillimeter information for both point sources and diffuse emission.

The processed, 24 μm MIPS GAL image mosaics have been available since 2008 (Carey et al. 2009). This data product is comprised of flux calibrated FITS images of 24 μm surface brightness with astrometric header information, images of the surface brightness standard deviations of the coadded data, data coverage, and locations of problematic data. Each mosaic field (hereafter, a tile) covers ~1 x 1 deg2 area.

As much of the measured MIPS GAL 24 μm signal resides within an unresolved component (evolved stars, YSOs, compact clusters), a previously missing yet critical data product is a point source catalog derived from the image tiles. The value of a source catalog lies within the uniformity of the source extraction and photometry algorithms applied to all image data and the evaluation of source completeness. The compilation of source positions, fluxes, flux errors, and completeness limits enables a more comprehensive, condensed examination of 24 μm emitting objects in the Galaxy. When merged with photometry from other surveys, one can further select for certain types of objects based on the shape of the spectral energy distribution and flux amplitude.

In this contribution, we describe the construction of a 24 μm based source catalog derived from MIPS GAL data. In Section 2, the source extraction and aperture photometry methods are summarized. The photometric accuracies, calibration, and catalog completeness are evaluated in reference to the literature in Section 3. In Section 4, we describe the method to derive 24 μm source completeness limit for each MIPS GAL tile. The columns of the source catalog table are defined in the Appendix.

2. BUILDING THE 24 μm POINT SOURCE CATALOG

Here we describe in detail the methods used in the construction of the inclusive “archive” and high reliability “catalog” photometry tables using the MIPS GAL 24 μm image tiles. In summary, we find compact sources in all tiles, measure their 24 μm photometric properties, merge the tile lists together, and link the results to external catalogs. Astrometric systematics are examined in order to correct calibration offsets by tile and establish conditions for a confusion flag that is internal to our source list.

2.1. Source Extraction

The MIPS GAL image tile products are extremely uniform integration depth maps of 24 μm flux density, but robust point source detection is nontrivial because of nonuniform background emission across the Milky Way. For a large survey such as MIPS GAL, automated data analysis techniques are essential. However, many automated point source detection techniques produce substantial numbers of false detections among the filamentary emission structures of the nebulae surrounding recent star forming events. Here, we have adopted the IDL
program PhotVis (version 1.10) to robustly identify point-like sources regardless of the complexity of the background (Gutermuth et al. 2008).

PhotVis employs a modified version of the DAOFIND source detection algorithm (Stetson 1987), as implemented in the IDL Astronomy Users’ Library (Landsman 1993). In summary, the DAOFIND technique involves convolving each image with a “sunken” two-dimensional Gaussian function sized to match the beam size of the observations (for this work, 6′/25 FWHM). This convolution concentrates the flux of unresolved structure into the central pixels of that structure, while large scale structure effectively convolves to a value near zero. Ideally, the convolved image makes stellar sources easy to identify with a simple threshold search. Unfortunately, numerous false sources are found by this algorithm among filamentary and other nonuniform structure in the bright nebulosity associated with the Galactic plane, and regions of star formation more generally (e.g., Megeath et al. 2004). In PhotVis (v1.10), the standard DAOFIND algorithm has been enhanced to include empirical estimation of a noise map for the Gaussian-convolved source detection image. Specifically, the absolute value of the convolved image is boxcar median-smoothed with a box size of five times the FWHM of the point-spread function (PSF). The original Gaussian-convolved image is then divided by this noise map, effectively converting the search threshold from a signal-based threshold into an approximate local signal-to-noise ratio (S/N)-based threshold.

We use a threshold value of seven in the local noise map scale, based on considerable testing on MIPS 24 μm data of star-forming regions (e.g., Gutermuth et al. 2008, 2009; Beerer et al. 2010; Megeath et al. 2012). The resulting algorithm simultaneously achieves excellent sensitivity in dark, uniform, uncrowded regions of images and automatic adaptation to less sensitive local conditions, largely mitigating the production of false sources associated with nebulous structure (Gutermuth et al. 2008).

Once sources are found, their flux is measured using synthetic aperture photometry via aper.pro from the IDL Astronomy Users’ Library (Landsman 1993). The MIPSGAL tiles are made of merged observations at a range of spacecraft rotation angles, thus we chose to use aperture photometry rather than PSF-fitting photometry due to its computational simplicity and measurement robustness under that circumstance. We adopt aperture inner and outer sky annulus radii of 6′/57, 7′/62, and 17′/78 respectively, and a magnitude zero point of 14.525 mag (Vega standard) for a 1 Digital Number per second (DN s⁻¹) source observed at 24 μm (Gutermuth et al. 2008). The photometric uncertainty is derived from calculations of the shot noise in the aperture and shot noise and internal variance in the sky annulus pixels that are used to compute the background emission per pixel for subtraction from the aperture flux. An internal noise floor of 0.02 mag is enforced to prevent rare data anomalies from yielding untenable uncertainty estimates.

Finally, as a characterization of source quality, we compute the FWHM of each source. As noted above, calibration of aperture photometry includes a correction for the finite sampling of the PSF set by the choice of aperture and sky radii. If an object is intrinsically resolved beyond the instrument resolution, then the source would be of relatively poor photometric quality in our catalog because the aperture correction would be incorrect. The measurement algorithm used is entirely empirical, extracting the half of peak flux radial distance from a cubic spline interpolation of the radial profile (Barth 2001). We azimuthally average (by median) the radial profile before running this algorithm to improve measurement success probabilities near structured nebulosity.

2.2. Archive Construction

Once the source lists and photometry have been obtained from all of the individual tiles, we combine them into a unified survey “archive” data product. The tiles were constructed with some degree of overlap, thus duplicate detections near tile edges are common and must be identified and removed. Once astrometry systematics were treated (see Section 2.3), a simple angular offset tolerance of 1° is used to identify all inter-tile duplicates. For each set, the instance of the source that is furthest from tile edges is selected to represent that source in the final combined source list as this maximizes the coverage of the sky annulus and the surrounding area for the noise map calculation. The resulting tally of detections in the final archive that have <0.33 mag uncertainty at 24 μm is 1,353,228. This requirement is approximately a S/N of 3, significantly lower than the approximate S/N >7 limit mentioned above for our empirically derived noise map in the source identification process. The photometrically determined uncertainty is generally somewhat higher because it includes photon shot noise. Ultimately, the photometric S/N limit is a sensitivity limit, but not where the survey is complete, as we will explore in Section 4, below. In Figure 1, the variations of magnitude uncertainties (top) and FWHM (bottom) with magnitude for

![Figure 1. Magnitude uncertainty (top) and FWHM (bottom) vs. 24 μm magnitude for the entire MIPSGAL archive, plotted as a source density map. The grayscale is inverted log scale, where white is <1 and black is >10^4 sources per bin. Dashed lines mark the stricter limits imposed on those sources included in the “catalog” data product.](image-url)
the archive sources are expressed as two-dimensional histograms. The spread in magnitude uncertainty for a given value of 24 μm simply reflects the variation of backgrounds throughout the MIPSGAL field.

Via automated queries to the Vizier online catalog service, we obtain all of the 2MASS, GLIMPSE, and WISE sources that fall within each tile. These are matched to our MIPSGAL archive such that the closest match within an angular tolerance of 2″ is linked to each 24 μm source. The matching tallies for each data source are summarized in Table 1. A counterpart is typically that this includes the matched source. Thus if this is a true match, we will be overestimating the field density somewhat (10–50% for GLIMPSE and 2MASS, 100% for WISE, typically). We then multiply that density by the area corresponding to the smaller 2″ matching radius to determine a mean number of contaminators to expect for that source. Using the mean contaminator rate, we pull random Poisson deviate numbers of potential contaminators for each object. For each object with a non-zero synthetic contaminator count \( n_i \) in a given realization, we draw that number of uniform, area-weighted deviates \( i.e., \text{radius PDF} = 2r, \) per the classic dartboard problem \( i.e., \text{radius PDF} = 2r, \) and compare the smallest value to the radial separation, \( r_{\text{match}} \) of the actual match for the archive source. If the nearest false source is within \( r_{\text{match}} + 0.1" \) we count that as a possible contamination event in the test. We then integrate contamination counts over the entire archive, over 1000 trials. The resulting estimated mismatch rate is ~0.1% for each catalog (see Table 1).

Source quality flags are compiled for each source, including the FWHM (described above), a binary flag to note sky annulus overlap with image edges, coverage edges, or saturated pixels, and source proximity among nearest neighbor archive members, in arcseconds. An internal confusion flag based on the nearest neighbor distance and the difference in 24 μm magnitude between source and neighbor is described in Section 2.3. We also tabulate the number of objects in each external catalog that fall within 6′35 of the source’s centroid position.

### 2.3. Astrometric Systematics

Initial efforts to incorporate publicly available external catalogs with our 24 μm archive revealed systematic offsets in the astrometric calibration of the MIPSGAL tiles. These offsets are shown in Figure 2 as astrometric residuals between the GLIMPSE and 24 μm centroid positions. We identify a secondary issue related to astrometry in the archive’s nearest neighbor distance \( d_{\text{NN}} \) distribution shown in Figure 3. The functional form of the distribution is approximately log-normal, with a narrow true normal excess centered on 10″ angular separation. This distribution corresponds to the central radius of the first diffraction ring outside of the Gaussian core of the MIPSGAL 24 μm PSF, suggesting that one of the pair could be a false identification. Moreover, such a feature can skew the photometry and astrometry of faint sources that fall near the feature. The magnitude difference between each source and its nearest neighbor in the archive versus \( d_{\text{NN}} \) is displayed in Figure 4(a). The same data are plotted for those objects without and with GLIMPSE counterparts within 2″ in Figures 4(b) and (c), respectively. The distribution of magnitude differences for sources without GLIMPSE counterparts exhibits clear excess source counts in three distinct locations: \( -0.2 < \Delta[24] < 0.2 \) and \( d_{\text{NN}} < 8" \), \( \Delta[24] > 0.8 \) and \( 9" < d_{\text{NN}} < 11" \), and \( \Delta[24] > 2.8 \) and \( 25" < d_{\text{NN}} < 27.5" \). This excess is further illustrated in Figure 4(d), which shows the ratio of the magnitude differences of sources without and with GLIMPSE counterparts and normalized by the expected ratio uncertainty, assuming Poisson counting statistics. Guided by this figure, where the grayscale has been set to mark \( >3\sigma \) regions as black, we define the conditions for the internal confusion flag. The conditions and the source counts affected are listed in Table 3.

### 2.4. Catalog Construction

The archive data product is meant to be an inclusive list of 24 μm point-like sources extracted from the MIPSGAL survey. A higher reliability subset of the archive sources, the “catalog” data product, is selected to mitigate the systematic issues in the archive discussed in Sections 2.2 and 2.3. First, we impose a
surveys such as 2MASS (Skrutskie et al. 2006). Here we perform several analyses of our methods by comparison to other previous studies and surveys in order to bootstrap some measures of reliability for extracted sources.

In Figure 5, we present the magnitude versus uncertainty distribution and magnitude histogram for the entire survey, as well as for two regions of the survey that are chosen to demonstrate the extremes in sensitivity changes set by location within the Galactic plane: the densely populated regions of the inner bulge and central disk, and the less densely populated off-plane areas of the wider survey. We have defined Galactic coordinate cuts of $|b|<0.5$ and $l<10$ for the “Central Bulge” region, and $|b|>0.5$ and $l>15$ as the “Disk, Off-Plane” zone. We use these divisions in several figures through the rest of this paper. In summary, the one magnitude relative shift (7 versus 8) in the locations of the peaks of the magnitude histograms is an initial demonstration of the substantially reduced sensitivity of the bulge area of the survey relative to the off-plane zone. With reduced crowding, less bright sources, and less nebulosity, the off-plane portion of the survey is much more sensitive to fainter objects.

3.1. Robitaille et al. (2008)

In order to verify the photometric performance and calibration of our source extraction process, we merged the MIPS 24 μm photometry of red sources provided in Robitaille et al. (2008, R08) with our catalog. The base image data set is the same in both cases, but R08 used the original Spitzer Science Center pipeline-reduced mosaics for their photometry instead of the enhanced MIPSGAL-reduced tiles. Regarding source extraction, they also used PSF fitting photometry by hand, instead of automated aperture photometry as we have done here. Of the 18,949 red GLIMPSE sources in the R08 catalog, 16,469 have reported MIPS 24 μm fluxes and uncertainties. Matches for 16,079 of those sources are made within the archive product (97.6%), and 14,926 matches...
Table 2: MIPSGAL Tile Astrometry Offsets and Residuals Summary

| Tile Name     | ∆R.A.  | ∆Decl. | σR.A.  | σDecl. |
|---------------|--------|--------|--------|--------|
| MG0000n005    | 0.123  | 0.296  | 0.412  | 0.528  |
| MG0000n015    | -0.021 | 0.665  | 0.299  | 0.316  |
| MG0000p005    | 0.011  | 0.583  | 0.379  | 0.499  |
| MG0000p015    | -0.263 | 0.274  | 0.315  | 0.334  |
| MG0010n005    | 0.105  | 0.410  | 0.410  | 0.575  |
| MG0010n015    | -0.217 | 0.118  | 0.301  | 0.321  |
| MG0010p025    | -0.176 | 0.056  | 0.302  | 0.327  |
| MG0060n005    | 0.122  | 0.625  | 0.362  | 0.513  |
| MG0060p015    | -0.167 | 0.233  | 0.299  | 0.324  |
| MG0080n025    | -0.229 | 0.089  | 0.316  | 0.343  |
| MG0080n005    | 0.005  | 0.160  | 0.376  | 0.598  |
| MG0090n025    | -0.187 | 0.066  | 0.313  | 0.311  |
| MG0090n015    | -0.127 | -0.039 | 0.313  | 0.326  |
| MG0100p005    | -0.009 | 0.679  | 0.338  | 0.521  |
| MG0100p015    | -0.054 | 0.183  | 0.301  | 0.316  |
| MG0100p025    | -0.207 | 0.242  | 0.311  | 0.325  |
| MG0300n005    | -0.121 | 0.018  | 0.377  | 0.499  |
| MG0300n015    | -0.204 | 0.063  | 0.306  | 0.311  |
| MG0300p025    | -0.142 | -0.040 | 0.345  | 0.338  |
| MG0300p005    | 0.034  | 0.402  | 0.335  | 0.601  |
| MG0300p015    | -0.046 | 0.096  | 0.317  | 0.325  |
| MG0300p025    | -0.143 | 0.149  | 0.316  | 0.340  |
| MG0400n005    | -0.287 | 0.060  | 0.367  | 0.382  |
| MG0400n015    | -0.212 | 0.021  | 0.307  | 0.318  |
| MG0400n025    | -0.140 | -0.006 | 0.318  | 0.322  |
| MG0400p005    | -0.045 | 0.009  | 0.344  | 0.461  |
| MG0400p015    | -0.092 | 0.078  | 0.319  | 0.327  |
| MG0500n015    | -0.211 | 0.151  | 0.351  | 0.336  |
| MG0500n025    | -0.402 | 0.095  | 0.345  | 0.344  |
| MG0500n035    | -0.227 | 0.007  | 0.303  | 0.314  |
| MG0500n015    | -0.125 | 0.028  | 0.333  | 0.327  |
| MG0500n005    | -0.237 | 0.102  | 0.361  | 0.378  |
| MG0500n015    | -0.071 | 0.065  | 0.309  | 0.317  |
| MG0500n025    | -0.147 | 0.153  | 0.331  | 0.329  |
| MG0600n005    | -0.390 | 0.161  | 0.390  | 0.383  |
| MG0600n015    | -0.204 | 0.054  | 0.358  | 0.351  |
| MG0600n025    | -0.108 | 0.096  | 0.333  | 0.318  |
| MG0600p005    | -0.411 | 0.094  | 0.351  | 0.333  |
| MG0600p015    | -0.086 | 0.068  | 0.307  | 0.310  |
| MG0600p025    | -0.081 | 0.120  | 0.303  | 0.327  |
| MG0700n005    | -0.291 | 0.264  | 0.372  | 0.376  |
| MG0700n015    | -0.157 | 0.116  | 0.322  | 0.331  |
| MG0700n025    | -0.082 | 0.120  | 0.338  | 0.342  |
| MG0700n035    | -0.448 | 0.119  | 0.346  | 0.350  |
| MG0700n015    | -0.115 | 0.007  | 0.351  | 0.342  |
| MG0700n025    | -0.092 | 0.099  | 0.312  | 0.331  |
| MG0800n005    | -0.203 | 0.305  | 0.338  | 0.397  |
| MG0800n015    | -0.118 | 0.181  | 0.312  | 0.334  |
| MG0800n025    | -0.067 | 0.187  | 0.324  | 0.335  |
| MG0800p005    | -0.400 | 0.205  | 0.358  | 0.363  |
| MG0800p015    | -0.168 | -0.022 | 0.385  | 0.397  |
| MG0800p025    | -0.070 | 0.020  | 0.296  | 0.326  |
| MG0900n005    | -0.211 | 0.410  | 0.333  | 0.423  |
| MG0900n015    | -0.135 | 0.317  | 0.330  | 0.335  |
| MG0900p005    | -0.269 | 0.294  | 0.331  | 0.387  |
| MG0900p015    | -0.091 | -0.094 | 0.307  | 0.340  |
| MG1000n005    | -0.329 | 0.593  | 0.355  | 0.456  |
| MG1000n015    | -0.250 | 0.412  | 0.328  | 0.424  |
| MG1100n005    | -0.470 | 0.707  | 0.357  | 0.453  |
| MG1100n015    | -0.388 | 0.564  | 0.346  | 0.448  |
| MG1200n005    | -0.537 | 0.556  | 0.375  | 0.458  |
| MG1200n015    | -0.426 | 0.635  | 0.329  | 0.434  |
| MG1300n005    | -0.532 | 0.450  | 0.381  | 0.444  |
| MG1300p005    | -0.448 | 0.571  | 0.343  | 0.433  |

(Continued)
| Tile Name      | ΔR.A. | ΔDecl. | σR.A. | σDecl. |
|---------------|-------|--------|-------|--------|
| MG0460n005    | -0.57 | 0.66   | 0.37  | 0.41   |
| MG0460p005    | -0.71 | 0.58   | 0.37  | 0.42   |
| MG0470n005    | -0.62 | 0.64   | 0.32  | 0.39   |
| MG0470p005    | -0.59 | 0.62   | 0.37  | 0.40   |
| MG0480n005    | -0.67 | 0.67   | 0.37  | 0.38   |
| MG0480p005    | -0.59 | 0.67   | 0.37  | 0.38   |
| MG0490n005    | -0.73 | 0.65   | 0.42  | 0.45   |
| MG0490p005    | -0.60 | 0.62   | 0.37  | 0.42   |
| MG0500n005    | -0.67 | 0.65   | 0.41  | 0.42   |
| MG0500p005    | -0.76 | 0.67   | 0.37  | 0.40   |
| MG0510n005    | -0.74 | 0.64   | 0.37  | 0.39   |
| MG0510p005    | -0.72 | 0.70   | 0.37  | 0.42   |
| MG0520n005    | -0.74 | 0.69   | 0.35  | 0.40   |
| MG0520p005    | -0.73 | 0.67   | 0.39  | 0.42   |
| MG0530n005    | -0.63 | 0.71   | 0.35  | 0.40   |
| MG0530p005    | -0.81 | 0.64   | 0.38  | 0.43   |
| MG0540n005    | -0.72 | 0.80   | 0.36  | 0.39   |
| MG0540p005    | -0.85 | 0.70   | 0.41  | 0.42   |
| MG0550n005    | -0.63 | 0.75   | 0.35  | 0.40   |
| MG0550p005    | -0.77 | 0.69   | 0.37  | 0.42   |
| MG0560n005    | -0.59 | 0.63   | 0.36  | 0.40   |
| MG0560p005    | -0.64 | 0.67   | 0.36  | 0.40   |
| MG0570n005    | -0.52 | 0.49   | 0.53  | 0.45   |
| MG0570p005    | -0.60 | 0.74   | 0.33  | 0.39   |
| MG0580n005    | -0.66 | 0.36   | 0.32  | 0.40   |
| MG0580p005    | -0.61 | 0.73   | 0.38  | 0.39   |
| MG0590n005    | -0.65 | 0.27   | 0.37  | 0.40   |
| MG0590p005    | -0.60 | 0.56   | 0.34  | 0.43   |
| MG0600n005    | -0.60 | 0.23   | 0.38  | 0.41   |
| MG0600p005    | -0.63 | 0.36   | 0.39  | 0.41   |
| MG0610n005    | -0.59 | 0.18   | 0.37  | 0.38   |
| MG0610p005    | -0.63 | 0.34   | 0.38  | 0.39   |
| MG0620n005    | -0.61 | 0.20   | 0.32  | 0.38   |
| MG0620p005    | -0.62 | 0.28   | 0.35  | 0.39   |
| MG0630n005    | -0.54 | 0.18   | 0.36  | 0.39   |
| MG0630p005    | -0.58 | 0.26   | 0.36  | 0.40   |
| MG0640n005    | -0.48 | 0.23   | 0.34  | 0.39   |
| MG0640p005    | -0.57 | 0.17   | 0.37  | 0.39   |
| MG0650n005    | -0.47 | 0.26   | 0.35  | 0.37   |
| MG0650p005    | -0.54 | 0.15   | 0.33  | 0.40   |
| MG0660n005    | -0.41 | 0.24   | 0.36  | 0.46   |
| MG0660p005    | -0.51 | 0.19   | 0.37  | 0.39   |
| MG0670n005    | -0.156| -0.362 | 0.445 | 0.430  |
| MG0670p005    | -0.199| -0.464 | 0.405 | 0.402  |
| MG0680n005    | -0.208| -0.246 | 0.421 | 0.432  |
| MG0680p005    | -0.085| -0.432 | 0.380 | 0.334  |
| MG0690n005    | -0.250| -0.019 | 0.414 | 0.403  |
| MG0690p005    | -0.004| -0.424 | 0.388 | 0.329  |
| MG0700n005    | -0.263| -0.007 | 0.437 | 0.409  |
| MG0700p005    | -0.011| -0.420 | 0.379 | 0.377  |
| MG0710n005    | -0.312| -0.059 | 0.431 | 0.405  |
| MG0710p005    | -0.172| -0.251 | 0.444 | 0.445  |
| MG0720n005    | -0.356| 0.04   | 0.407 | 0.379  |
| MG0720p005    | -0.308| -0.093 | 0.409 | 0.395  |
| MG0730n005    | -0.340| 0.099  | 0.407 | 0.339  |
| MG0730p005    | -0.320| 0.036  | 0.418 | 0.358  |
| MG0740n005    | -0.276| 0.103  | 0.410 | 0.369  |
| MG0740p005    | -0.311| 0.110  | 0.399 | 0.372  |
| MG0750n005    | -0.226| 0.023  | 0.430 | 0.394  |
| MG0750p005    | -0.345| 0.038  | 0.394 | 0.369  |
| MG0760n005    | -0.122| -0.057 | 0.411 | 0.385  |
| MG0760p005    | -0.250| 0.010  | 0.402 | 0.360  |
| MG0780n005    | -0.068| -0.056 | 0.432 | 0.401  |
| MG0780p005    | -0.173| -0.027 | 0.426 | 0.397  |
respectively. Among those two source lists, 39,910 sources found in H09 were used to extract the photometry of red 2MASS and GLIMPSE sources within the common coverage region of H09. Based on this sample, we merged our archive with the MIPS 24 μm photometry of the Galactic center region from Hinz et al. (2009, H09). As with R08, the image data sets are the same as ours, but the image data treatment and source extraction differ. In this case, the image data were processed with the MIPS instrument team’s DAT software (Gordon et al. 2005), and the photometry was extracted via PSF fitting. The benefit of this reference catalog over that of R08 is that it is a complete catalog of 24 μm sources from the region in question, instead of targeted photometry of red 2MASS and GLIMPSE sources across the entire inner Milky Way. As such, it is a good test of our completeness within one of the most challenging parts of the survey. Of the 120,883 sources in Hinz et al. (2009), we have 82,832 and 68,608 coincident sources in our archive and catalog products, respectively. Obviously, this is a substantial miss rate. In Figure 7, we plot the magnitude residuals versus magnitude in the top plot, demonstrating largely consistent photometry among matches. Thus while the photometry appears to agree, the issue of the discrepant sources demands further characterization.

In order to fairly examine the sources within a well-covered region, we first crop both the H09 catalog and our archive to an easily defined common coverage region of $-3 < l < 4$ and $|b| < 0.5$. Within this region, we find 63,129 and 51,937 sources from the H09 catalog and our archive product, respectively. Among those two source lists, 39,910 sources match. The bottom panel of Figure 7 shows the relative detection fraction per 1 mag bin among the matched sources (solid line), those found in our archive but missed by H09 (dotted-dashed line), and those missed in our archive but found in H09 (dashed line) with the common coverage region. In the brightest bin, we see a clear deficit of H09 sources. Generally, those with marginally detectable peak saturation are rejected by the PSF fitting of H09 but are included in our archive. The range $1 < [24] < 6$ mag exhibits consistent behavior: 70% matched sources, 10% H09-only sources, and 20% H09-missed archive sources. At [24] > 6 mag, the

### Table 2 (Continued)

| Tile Name       | ΔR.A. | ΔDecl. | σR.A. | σDecl. | ΔR.A. | ΔDecl. | σR.A. | σDecl. |
|-----------------|-------|--------|-------|--------|-------|--------|-------|--------|
| MG3590n005      | -0.089| -0.091 | 0.303 | 0.341  |       |        |       |        |
| MG3590p015      | -0.219| 0.091  | 0.311 | 0.352  |       |        |       |        |
| MG3590p025      | -0.103| -0.133 | 0.289 | 0.321  |       |        |       |        |
| MG3600n025      | -0.163| 0.066  | 0.298 | 0.320  |       |        |       |        |
| MG3600p025      | -0.089| -0.091 | 0.303 | 0.341  |       |        |       |        |

As a secondary check, we merged our archive with the MIPS 24 μm photometry of the Galactic center region from Hinz et al. (2009, H09). As with R08, the image data sets are the same as ours, but the image data treatment and source extraction differ. In this case, the image data were processed with the MIPS instrument team’s DAT software (Gordon et al. 2005), and the photometry was extracted via PSF fitting. The benefit of this reference catalog over that of R08 is that it is a complete catalog of 24 μm sources from the region in question, instead of targeted photometry of red 2MASS and GLIMPSE sources across the entire inner Milky Way. As such, it is a good test of our completeness within one of the most challenging parts of the survey. Of the 120,883 sources in Hinz et al. (2009), we have 82,832 and 68,608 coincident sources in our archive and catalog products, respectively. Obviously, this is a substantial miss rate. In Figure 7, we plot the magnitude residuals versus magnitude in the top plot, demonstrating largely consistent photometry among matches. Thus while the photometry appears to agree, the issue of the discrepant sources demands further characterization.

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fraction of sources rapidly becomes dominated by the H09 source counts, as our archive loses completeness (characterized in detail in Section 4, below). We visually inspected some of the faint H09 source positions in the MIPSGAL tiles and found that the vast majority of those that we viewed are not apparent

Table 3
MIPSGAL Confusion Conditions

| Region No. | Conditions | No. w/o GLIMPSE | No. w/GLIMPSE | Ratio |
|------------|------------|-----------------|---------------|-------|
| 1          | $d_{NN} < 5''$ or $(d_{NN} < 8''$ and $|\Delta[24]| < 0.2$ mag) | 2083            | 7197          | 0.290 |
| 2          | $8'' < d_{NN} < 11.5$ and $|\Delta[24]| > 0.8$ mag and $\Delta[24] > 0.4(d_{NN} - 11.5) + 1.8$ mag) | 3284            | 10767         | 0.305 |
| 3          | $25'' < d_{NN} < 27.5$ and $|\Delta[24]| > 5.4$ mag | 355             | 600           | 0.591 |
| Ref.       | $13'' < d_{NN} < 25''$ and $|\Delta[24]| < 5.4$ mag | 35,655          | 393,842       | 0.091 |

Table 4
MIPSGAL Catalog Requirements Summary

- $\sigma[24] < 0.2$ mag
- $|\text{FWHM} - 6.25| < 0.5(1 + 0.125 \times [24])$
- Internal Confusion Flag = 0
- Edge Flag = 0

Figure 5. Magnitude vs. uncertainty source density plots and magnitude histograms for the entire survey (top), and two of samples showing the extremes in sensitivity: the Galactic Center (middle), and the off-plane disk (bottom). The grayscale is inverted log scale, where white is $<1$ and black is $>10^4$ sources per bin.

Figure 6. Photometry comparison of our MIPSGAL archive to the MIPSGAL photometry reported in Robitaille et al. (2008). Our calibration offset estimate is plotted as a solid line. The density map is inverted log scale, with white and black levels set to 1 and $10^3$ sources per bin, respectively. Contours are plotted at 0.5, 5, and 50 sources per bin.

Figure 7. Photometry and apparent completeness comparison of our MIPSGAL archive to the MIPSGAL photometry reported in Hinz et al. (2009). The top panel is similar to Figure 6, above, and the source density scaling and contour levels are identical to that plot. Our calibration offset estimate is plotted as a solid line. The bottom plot contains the fraction of sources detected in our MIPSGAL archive only (gray, dotted–dashed), the H09 catalog only (black, dashed), and both data sources (black, solid), as a function of magnitude.
in those data. This effort was sufficient to cement our confidence in our method’s omission of these fainter sources. Further investigation of the veracity of the faint H09 sources is beyond the scope of this paper.

3.3. WISE 22 μm

Finally, the merger of the MIPSGAL archive with the all-sky WISE catalog enables a check for general agreement between our photometry and the WISE 22 μm photometry on a larger sample of objects. We find that 368,956 objects have reported <0.33 mag uncertainties in both the MIPSGAL archive and WISE 22 μm catalogs. We plot the magnitude residuals versus WISE 22 μm magnitude in Figure 8. The median residual for bright sources ([24] < 3 mag) in the “Disk, Off-Plane” field is ~0.07 mag, similar to the offset to the MIPSGAL photometry reported in R08 and discussed above. The bias toward brighter values in the faint source WISE photometry is frequently observed in lower relative resolution data, where structured nebular emission is more likely to contaminate the photometric aperture relative to the surrounding sky in some sources, resulting in background flux underestimation and source flux overestimation (e.g., Gutermuth et al. 2009). In this case, the WISE 22 μm fluxes of some sources are found to be as much as 3 mag brighter than the MIPSGAL photometry.

4. COMPLETENESS CHARACTERIZATION

The general means to test the effective sensitivity of a given photometric survey data set and a given source extraction and analysis algorithm is to add false sources to the data and attempt to recover them. Many papers have acknowledged spatial variations in such completeness tests, but few have presented a detailed characterization. One recent effort to characterize and treat this effect was performed as part of the analysis of the Spitzer survey of the Orion Molecular Clouds (Megeath et al. 2012). That work emphasized probing locations near where objects of interest, YSOs in this case, have already been detected. As with any nearby star-forming region, the 24 μm Galactic plane has many areas of bright and structured nebulosity where point source sensitivity will be reduced. Any catalog produced from these data would only be complete with respect to this spatially varying point source sensitivity, and thus the impact of this effect is important to characterize in some detail (e.g., Gutermuth et al. 2005; Megeath et al. 2012).

Many science goals, such as constructing luminosity functions or analyzing source clustering, demand a spatially unbiased characterization of varying completeness. We have mapped this effect and provide it as a companion to the point source catalog and archive products. To quantify source completeness, we have adopted and updated the method described in Gutermuth et al. (2005) for this purpose, at a grid sampling resolution of 1' × 1'. The local completeness decay as a function of source flux in each grid cell is evaluated by performing successive trials of adding and recovering false sources of varying flux. Fluxes are sampled in 0.5 mag steps over a typical range from 0 < [24] < 10 mag. Each 1'cell is sampled completely by adding sources at each position in a 3'×25 grid within the cell, thereby Nyquist sampling the 625 FWHM beam width of the MIPS 24 μm channel. The resulting total is ~400 sources per flux step per cell. The tally for each flux step and cell is normalized to represent a fractional completeness. For each MIPSGAL tile, a data cube of dimensions 60 × 60 × 20 represents the differential completeness fraction for each cell position within the 1 deg² tile as a function of the ~20 flux steps of 0.5 mag.

In Figure 9, we plot examples of the differential completeness as a function of source flux for two contrasting locations, one with a smooth and low surface brightness background and the other with a structured and high surface brightness background. The low background case demonstrates a clear increase in sensitivity to faint sources relative to the bright, highly structured field. In addition, the rate of decay as a function of source flux varies between these two examples. Using the difference between the 20% and the 90% differential completeness limits as an estimator of this effect, there is a slower completeness decay in the less sensitive area (1.8 versus 1.4 mag in the plotted examples). Despite the potential differences among completeness decay curve shapes, assigning a completeness value to each source in the archive is valuable as a convenient indicator of local source sensitivity. For each

Figure 8. Photometry comparison to those MIPSGAL archive sources with WISE 22 μm counterparts with σ < 0.33 mag, plotted as a source density map. The grayscale is inverted log scale, with white and black levels set to <1 and >10³ sources per bin, respectively. Our estimate of the offset calibration is plotted as a solid line. The approximate local saturation and sensitivity limits on the data space are marked with gray dashed lines.
source, the completeness decay curve is extracted from the spatially nearest position to the source in the completeness cube. A linear interpolation of this curve is used to determine the magnitude at which 90% of the sources are successfully recovered. This 90% differential completeness limit, named “\text{dcomp90}” here, is listed for each archive and catalog source. Since some science objectives may require higher or lower completeness percentages than 90%, the corresponding limiting magnitude can be derived from these differential completeness data cubes.

The correlations of source fluxes in the catalog with their local \text{dcomp90} values are shown in Figure 10 as a two-dimensional histogram. The most obvious feature of this plot is the strong linear feature where moderate to bright sources are correlated with their \text{dcomp90} value such that \([24] \approx \text{dcomp90} - 1\). This correlation is expected as we have sampled the completeness at such high spatial resolution relative to the large MIPS 24 \(\mu\)m PSF. Any region of otherwise dark background will have effectively reduced sensitivity due to the presence of a relatively bright source, and that sensitivity reduction will be correlated with the flux of that source. In addition, Figure 10 also shows that a completeness limit is not the same as a sensitivity limit. Regions of relatively bright \text{dcomp90} are rarely uniform within the sampling area, thus objects considerably fainter than the completeness limit are often detected. In contrast, it is unlikely that a bright source will be found in a region of high \text{dcomp90} magnitude, as the very presence of a moderate to bright source reduces the local completeness, as noted above.

5. SUMMARY

We present the results of a full point source extraction from the entire MIPSGAL 24 \(\mu\)m enhanced mosaics of the Milky Way.

1. Over \(1.3 \times 10^6\) sources have been identified, photometered, and characterized for source quality via FWHM and nearest neighbor distance \((d_{NN})\) measurements in our archive product.

2. The archive source list has been matched with several complementary catalogs from the public archives (2MASS, GLIMPSE, WISE), yielding a substantial new multiple bandpass photometric resource for the community. Over 94% of the MIPSGAL sources have a counterpart in at least one of the external catalogs.

3. We have used comparisons to these large surveys as well as some MIPSGAL photometry in the literature to evaluate the astrometric and photometric veracity of our archive and examine its completeness. Based on this work, constant astrometric offsets were applied to each tile.

4. Ideal ranges of source quality measurements were identified from which a high reliability catalog product was constructed. The catalog is composed of over \(9 \times 10^5\) sources that obey the more stringent constraints.

5. We measured source detection completeness decay as a function of source flux at 1 square arcminute scale for the entire MIPSGAL 24 \(\mu\)m survey. The data cubes (one for each MIPSGAL tile) resulting from this effort are provided as a companion product to aid in subsequent analysis of the catalog.

6. The catalog and non-catalog archive source lists, as well as the completeness decay cubes in FITS format, are hosted and publicly available in the Infrared Science Archive (IRSA) at Caltech’s Infrared Processing and Analysis Center (IPAC).

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Facility: Spitzer

APPENDIX

MIPSGAL 24 µm POINT SOURCE

TABLE COLUMN REFERENCE

Here we provide a reference listing of the columns delivered in the archive and catalog data product tables as they appear in the tables hosted in the IRSA at IPAC.

1. l, b, R.A., decl.: Galactic Longitude, Latitude, R.A. and decl., in degrees, J2000, ICRS reference.
2. Fnu_XX: Flux Density at the noted bandpass, XX, in mJy.
3. sigma_Fnu_XX: Flux Density Uncertainty at the noted bandpass, XX, in mJy.
4. Mag_XX: Vega-standard Magnitude at the noted bandpass, XX.
5. sigma_Mag_XX: Magnitude Uncertainty at the noted bandpass, XX.
6. SURVEY_NAME: Source name from the noted SURVEY (e.g., MIPSGAL, TWOMASS, WISE, or GLIMPSE) point source catalog.
7. SURVEY_COUNT: The number of sources from the noted SURVEY (e.g., TWOMASS, WISE, or GLIMPSE) found within the 6'35 MIPSGAL photometric aperture.
8. d_NN: The angular separation in arcseconds between the source and its nearest neighbor within the MIPSGAL archive product.
9. FWHM: Empirically measured FWHM of the MIPSGAL source, in arcseconds.
10. Sky_24: The background flux density measured in the sky annulus in MJy sr⁻¹.
11. Comp_Lim_Fnu_24: The 90% differential completeness limit, in mJy.
12. Comp_Lim_Mag_24: The 90% differential completeness limit, in Vega-standard magnitudes. Refered to as diffcomp90 in the text.
13. Edge_Flag: A binary flag set to 1 when the aperture overlaps with a masked out area of the MIPSGAL tiles, such as saturated areas or coverage edges.
14. Int_Confuse_Flag: An integer flag set to 0 if unconfused, or 1, 2, or 3 to denote which of the three confusion criteria in Table 3 flagged this source.

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