THE 24 MICRON SOURCE COUNTS IN DEEP SPITZER SPACE TELESCOPE SURVEYS1

C. Papovich, 2 H. Dole, 3 E. Egami, 2 E. Le Floc’h, 2 P. G. Pérez-González, 2 A. Alonso-Herrero, 2, 4 L. Bai, 2 C. A. Beichman, 3 M. Blaylock, 3 C. W. Engelbracht, 2 K. D. Gordon, 2 D. C. Hines, 2, 6 K. A. Misselt, 2 J. E. Morrison, 5 J. Moulu, 7 J. Muzerolle, 2 G. Neugebauer, 2 P. L. Richards, 1 G. H. Rieke, 2 M. J. Rieke, 2 J. R. Rigby, 2 K. Y. L. Su, 2 and E. T. Young 2

Received 2004 March 25; accepted 2004 May 17

ABSTRACT

Galaxy source counts in the infrared provide strong constraints on the evolution of the bolometric energy output from distant galaxy populations. We present the results from deep 24 μm imaging from Spitzer surveys, which include ≈5×10^4 sources to an 80% completeness of ≈60 μJy. The 24 μm counts rapidly rise at near-Euclidean rates down to 5 mJy, increase with a super-Euclidean rate between 0.4 and 4 mJy, and converge below ~0.3 mJy. The 24 μm counts exceed expectations from nonevolving models by a factor of ≈10 at S_24 ~ 0.1 mJy. The peak in the differential number counts corresponds to a population of faint sources that is not expected from predictions based on 15 μm counts from the Infrared Space Observatory. We argue that this implies the existence of a previously undetected population of infrared-luminous galaxies at z ~ 1–3. Integrating the counts to 60 μJy, we derive a lower limit on the 24 μm background intensity of 1.9 ± 0.6 nW m⁻² sr⁻¹ of which the majority (~60%) stems from sources fainter than 0.4 mJy. Extrapolating to fainter flux densities, sources below 60 μJy contribute 0.8+0.2/−0.4 nW m⁻² sr⁻¹ to the background, which provides an estimate of the total 24 μm background of 2.7+1.1/−0.7 nW m⁻² sr⁻¹. The detection of the cosmic background by the Cosmic Background Explorer (COBE) at IR wavelengths shows that the total far-IR emission of galaxies in the early universe is greater than that at optical and UV wavelengths (Fixsen et al. 1998; Hauser & Dwek 2001). The spectral energy distributions (SEDs) of IR-luminous galaxies (L_24 ~ 10^{11}–10^{12} L_☉) peak between 50 and 80 μm (Dale et al. 2001). If these objects constitute a major component of the cosmic IR background, then they follow there is a significant population of IR-luminous galaxies at z ~ 1.5–3, distances largely unexplored by ISO. The mid-IR 24 μm band on the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) is particularly well suited to studying distant IR-luminous galaxies. Locally, the mid-IR emission from galaxies relates almost linearly with the total IR luminosity over a range of galaxy types (e.g., Spinoglio et al. 1995; Chary & Elbaz 2001; Roussel et al. 2001; Papovich & Bell 2002), and there are indications this holds at higher redshifts (e.g., Elbaz et al. 2002). Because the angular resolution of Spitzer is significantly higher for the 24 μm band relative to 70 and 160 μm, the 24 μm confusion limit lies at fainter flux densities. This allows us to probe the IR emission from many more sources and at higher redshifts than with the MIPS longer wavelength bands (e.g., Papovich & Bell 2002; Dale et al. 2003). Here we present the number counts of ≈5×10^4 sources detected at 24 μm in deep Spitzer surveys, and we suggest that the faint Spitzer detections probe a previously undetected population of very luminous galaxies at high redshifts. Where applicable, we assume Ω_m = 0.3, Ω_Λ = 0.7, and H_0 = 70 km s⁻¹ Mpc⁻¹.

1 This work is based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract 1407.
2 Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721; papovich@as.arizona.edu.
3 Institut d’Astrophysique Spatiale, bat 121, Université Paris Sud, F-91405 Orsay Cedex, France.
4 Departamento de Astrofísica Molecular e Infrarrojo, IEM, CSIC, Serrano 113b, 28006 Madrid, Spain.
5 Michelson Science Center, California Institute of Technology, Pasadena, CA 91109.
6 Space Science Institute, 4750 Walnut, Suite 205, Boulder, CO 80301.
7 National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ 85719.
8 Department of Physics, University of California, Berkeley, CA 94720.

1. INTRODUCTION

From the first detections of infrared (IR) luminous galaxies, it was clear that they represent phenomena not prominent in optically selected galaxy surveys (e.g., Rieke & Low 1972; Soifer et al. 1987). Locally, galaxies radiate most of their emission at UV and optical wavelengths, and only about one-third at IR wavelengths (5–1000 μm; Soifer & Neugebauer 1991). IR number counts from the Infrared Space Observatory (ISO) indicate that the IR-luminous sources have evolved rapidly, significantly faster than has been deduced from optical surveys, which implies that IR-luminous galaxies make a substantial contribution to the cosmic star formation rate density (e.g., Elbaz et al. 1999; Franceschini et al. 2001). The detection of the cosmic background by the Cosmic Background Explorer (COBE) at IR wavelengths shows that the total far-IR emission of galaxies in the early universe is greater than that at optical and UV wavelengths (Fixsen et al. 1998; Hauser & Dwek 2001). The spectral energy distributions (SEDs) of IR-luminous galaxies (L_24 ~ 10^{11}–10^{12} L_☉) peak between 50 and 80 μm (Dale et al. 2001). If these objects constitute a major component of the cosmic IR background, then they follow there is a significant population of IR-luminous galaxies at z ~ 1.5–3, distances largely unexplored by ISO. The mid-IR 24 μm band on the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) is particularly well suited to studying distant IR-luminous galaxies. Locally, the mid-IR emission from galaxies relates almost linearly with the total IR luminosity over a range of galaxy types (e.g., Spinoglio et al. 1995; Chary & Elbaz 2001; Roussel et al. 2001; Papovich & Bell 2002), and there are indications this holds at higher redshifts (e.g., Elbaz et al. 2002). Because the angular resolution of Spitzer is significantly higher for the 24 μm band relative to 70 and 160 μm, the 24 μm confusion limit lies at fainter flux densities. This allows us to probe the IR emission from many more sources and at higher redshifts than with the MIPS longer wavelength bands (e.g., Papovich & Bell 2002; Dale et al. 2003). Here we present the number counts of ≈5×10^4 sources detected at 24 μm in deep Spitzer surveys, and we suggest that the faint Spitzer detections probe a previously undetected population of very luminous galaxies at high redshifts. Where applicable, we assume Ω_m = 0.3, Ω_Λ = 0.7, and H_0 = 70 km s⁻¹ Mpc⁻¹.

2. THE DATA AND SOURCE SAMPLES

The data used in this work stem from early Spitzer characterization observations and from time allocated to the MIPS.
Guaranteed Time Observers (GTOs). The images were obtained in five individual fields with large angular separation on the sky in order to minimize cosmic-variance biases from large-scale structure, and with high-quality ancillary data at other wavelengths. The area and depth of each field vary substantially to adequately sample source densities at all flux levels with high statistical significance. Table 1 lists their properties and 24 μm source densities. The MIPS fields used here subtend the largest areas (∼10.5 deg²) and widest range in flux density (50–0.06 mJy) available to date from the Spitzer mission and therefore are the premier data set for studying the mid-IR source counts.

The MIPS 24 μm images were processed with a custom data analysis tool, developed by the MIPS GTOs (Gordon et al. 2004). The measured count rates are corrected for dark current, cosmic rays, and flux nonlinearities, and then divided by flat fields for each unique MIPS scan-mirror position. Images are then corrected for geometric distortion, co-added, and mosaicked. The final mosaics have a pixel scale of 6′′, corresponding to the flux of these PSF apertures within a diameter of 25 pixel⁻¹, with a point-spread function (PSF) FWHM of ∼6′′.

We performed source detection and photometry using a set of tools and simulations. Briefly, we first subtract the image background using a median filter roughly 4 times the size of source apertures (see below) and use a version of the DAOPHOT software (Stetson 1987) to detect point sources. We filter each image with a Gaussian with an FWHM that is equal to that of the MIPS 24 μm PSF and identify positive features in 10′′ diameter apertures above some noise threshold. We then construct empirical PSFs using 20–30 bright sources in each image, and we optimally measure photometry by simultaneously fitting the empirical PSFs to all sources within ∼20′′ of nearby object centroids. The source photometry corresponds to the flux of these PSF apertures within a diameter of 37′′, and we apply a multiplicative correction of 1.14 to account for lost light outside these apertures.

To estimate completeness and photometric reliability in the 24 μm source catalogs, we repeatedly inserted artificial sources into each image with a flux distribution approximately matching the measured number counts. We then repeated the source detection and photometry process and compared the resulting photometry to the input values. In Figure 1, we show for the Chandra Deep Field–South (CDF-S, one of the deep Spitzer fields) the relative fraction of sources within r ≤ 2″3 (half the FWHM) and with a flux difference less than 50% compared to their input values. From these simulations, we estimated the flux-density limit where 80% of the input sources are recovered with this photometric accuracy; these are listed in Table 1. Simultaneously, we estimate that down to the 80% completeness limit the number of sources that result from fainter sources either by photometric errors or the merging of real sources is <10%.

We also repeated the source detection and photometry process on the negative of each MIPS 24 μm image. This test provides an estimate for the number of spurious sources arising from the noise properties of the image, as shown in Figure 1. For all of our fields, the spurious-source fraction for flux densities greater than the 80% completeness limit is less than 10%.

### Table 1

**Properties of Deep Spitzer Fields**

| Field       | R.A. (J2000.0) | Decl. (J2000.0) | (L) (MJy sr⁻¹) | Area (arcmin²) | (l exp) (μJy) | C (50%) (μJy) | N(>C50%) (arcmin⁻²) | N(>300 μJy) (arcmin⁻²) |
|-------------|----------------|----------------|----------------|----------------|---------------|---------------|----------------------|------------------------|
| Marano      | 03 13 52       | −55 15 23      | 19.7           | 1296           | 236           | 170           | 2.0                  | 0.9                    |
| CDF-S       | 03 32 28       | −27 48 30      | 22.5           | 2092           | 1378          | 83            | 4.5                  | 0.7                    |
| EGS         | 14 16 00       | +52 48 50      | 19.5           | 1466           | 450           | 110           | 3.4                  | 0.7                    |
| Boötes      | 14 32 06       | +34 16 48      | 22.7           | 32457          | 87            | 270           | 1.0                  | 0.8                    |
| ELAIS       | 16 09 52       | +54 55 00      | 18.2           | 130            | 3232          | 61            | 5.7                  | 0.6                    |

Notes.—Col. (1): Field name. Col. (2): Right ascension, in units of hours, minutes, and seconds. Col. (3): Declination, in units of degrees, arcminutes, and arcseconds. Col. (4): Mean 24 μm background. Col. (5): Areal coverage. Col. (6): Mean exposure time. Col. (7): 80% completeness limit. Col. (8): Source density with Sₜ > C₅₀%. Col. (9): Source density with Sₜ > 300 μJy.

3. THE 24 μm SOURCE COUNTS

Figure 2 shows the 24 μm cumulative and differential number counts that have been averaged over the fields listed in Table 1. The differential and cumulative counts (corrected and uncorrected) are listed in Table 2. The faintest datum (denoted by the open symbol in Fig. 2) is derived to the 50% completeness limit for the European Large-Area ISO Survey (ELAIS) field (C₅₀% = 35 μJy). The remaining (less deep)
fields are used after correcting for completeness to the 80% level only. Error bars in the figure correspond to Poissonian uncertainties and an estimate for cosmic variance using the standard deviation of counts between the fields. For $S_s \leq 83 \mu Jy$, where the counts are derived solely from the smaller ELAIS field, we estimate the uncertainty (18%) using the standard deviation of counts at faint flux densities in cells of 130 arcmin$^2$ from the CDF-S (see below). We have ignored the contribution to the number counts from stars at 24 $\mu m$ differential source counts (Elbaz et al. 1999), but the peak in the 24 $\mu m$ differential source counts occurs at fluxes fainter by a factor of $\approx 2.0$. The peak lies above the 80% completeness limit for nearly all fields and is seen in the counts of the fields individually. Thus, the observed turnover is quite robust. The counts converge rapidly with a sub-Euclidean rate at $\leq 0.2$ mJy. We broadly fit the faint end ($S_s \approx 35–130 \mu Jy$) of the differential number counts using a power law, $dN/dS_s = C(S_s/1 mJy)^{-\alpha}$, with $\alpha = -1.5 \pm 0.1$. This result is consistent with a separate analysis based solely on the ELAIS field (Chary et al. 2004).

The observed counts are strongly inconsistent with expectations from nonevolving models of the local IR-luminous population. In Figure 2, we show the 24 $\mu m$ counts derived from the local luminosity function at ISO 15 $\mu m$ (Xu 2000) and assuming local galaxy SEDs (Dale et al. 2001). We have used the local ISO 15 $\mu m$ luminosity function, because the $k$-correction between rest-frame ISO 15 $\mu m$ and observed MIPS 24 $\mu m$ bands is minimized at higher redshifts ($z \sim 0.6$), which is more appropriate for the counts at fainter flux densities. However, using the local IRAS 25 $\mu m$ luminosity function (Shupe et al. 1998) yields essentially identical results.

![Figure 2](image)

**Figure 2.** Cumulative (left) and differential (right) 24 $\mu m$ number counts. The differential counts have been normalized to a Euclidean slope, $dN/dS_s \sim S_s^{-2.5}$. The solid stars show the average counts from all the Spitzer fields (see Table 1) and corrected for completeness to their respective 80% limits. The open star corresponds to counts brighter than the 50% completeness limit from the ELAIS field. The error bars correspond to counting uncertainties and a cosmic-variance estimate based on the standard deviation of the field-to-field counts from the different fields. Each flux bin is $\Delta \log S_s = 0.15$ dex. The shaded diamonds correspond to IRAS 25 $\mu m$ number counts from Hacking & Soifer (1991) and adjusted assuming $\nu \lambda S_\nu (24 \mu m) = \nu \lambda S_\nu (25 \mu m)$. The curves show the predictions from various contemporary models from the literature (see figure inset; and adjusted slightly to match the observed IRAS counts) and a model based on the local ISO 15 $\mu m$ luminosity function and assuming nonevolving galaxy SEDs.

---

**Table 2: Measured Spitzer 24 $\mu m$ Number Counts**

| $\log S_s$ (mJy) | $dN/dS_s$ (mJy$^{-1}$ sr$^{-1}$) | $\delta(dN/dS_s)$ (mJy$^{-1}$ sr$^{-1}$) | $\log S_s$ (mJy) | $N(S_s)$ (sr$^{-1}$) | $\delta(N(S_s))$ (sr$^{-1}$) |
|-----------------|--------------------------|--------------------------|-----------------|------------------|--------------------------|
| $-1.475$        | $2.5 (1.4) \times 10^0$  | $4.7 (1.5) \times 10^8$  | $-1.550$        | $2.1 (1.1) \times 10^8$ | $1.2 (0.60) \times 10^7$ |
| $-1.325$        | $1.5 (1.2) \times 10^0$  | $2.7 (0.97) \times 10^8$ | $-1.400$        | $1.2 (0.92) \times 10^8$ | $7.6 (4.9) \times 10^6$  |
| $-1.175$        | $8.7 (6.9) \times 10^0$  | $1.4 (1.4) \times 10^8$  | $-1.250$        | $9.6 (7.2) \times 10^7$  | $3.7 (0.68) \times 10^6$  |

**Notes.**—Col. (1): Flux density for differential number counts. Cols. (2) and (3): Corrected differential counts and uncertainty. Col. (4): Flux density for cumulative number counts. Cols. (5) and (6): Corrected cumulative counts and uncertainty. Numbers in parentheses give the uncorrected values. Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal Supplement*. A portion is shown here for guidance regarding its form and content.
nological models based on the ISO results. This may suggest possibilities such as a steepening in the slope of the IR luminosity function with redshift or evolution in the relation between the mid- and total IR. Phenomenological models that reproduce the IR background predict a faint-end slope of the IR luminosity function that should be quite shallow at high redshifts, with “L*” luminosities that correspond to $L_{IR} > 10^{11}$ $L_{\odot}$ for $z \gtrsim 1$ (see Hauser & Dwek 2001). For most plausible IR luminosity functions, galaxies with $L^*$ luminosities dominate the integrated luminosity density. Elbaz et al. (2002) observed that the redshift distribution of objects with these luminosities in deep ISO surveys spans $z \sim 0.8-1.2$, and that these objects constitute a large fraction of the total cosmic IR background. Therefore, it seems logical that objects with these luminosities dominate 24 $\mu$m number counts at 0.1–0.4 mJy, and it follows that their redshift distribution must lie at $z \sim 1 -3$ (i.e., where this flux density corresponds to $\sim 10^{11-12}$ $L_{\odot}$, using empirical relations from Papovich & Bell 2002). Indeed, a similar conclusion is inferred on the basis of a revised phenomenological model using the 24 $\mu$m number counts presented here (Lagache et al. 2004) and allowing for small changes in the mid-IR SEDs of IR-luminous galaxies. Examples of MIPS 24 $\mu$m sources at these redshifts and luminosities have been readily identified in optical ancillary data (Le Floc’h et al. 2004). We therefore attribute the peak in the 24 $\mu$m differential number counts at fainter flux densities to a population of luminous IR galaxies at redshifts higher than explored by ISO.

Integrating the differential source-count distribution provides an estimate for their contribution to the cosmic IR background at 24 $\mu$m, i.e., $I_\nu = \int dN/dS \nu dS$. For sources brighter than 60 $\mu$Jy, we derive a lower limit on the total background of $\nu I_\nu (24 \mu m) = 1.9 \pm 0.6$ nW m$^{-2}$ sr$^{-1}$. Because of the steep nature of the source counts, most of this background emission results from galaxies with fainter apparent flux densities. We find that $\sim 60\%$ of the 24 $\mu$m background originates in galaxies with $S_\nu \lesssim 0.4$ mJy, and therefore the galaxies responsible for the peak in the differential source counts also dominate the total background emission. Our result is consistent with the COBE DIRBE upper limit $\nu I_\nu (25 \mu m) < 7$ nW m$^{-2}$ sr$^{-1}$ inferred from fluctuations in the IR background (Kashlinsky & Odenwald 2000; Hauser & Dwek 2001).

As a further estimate on the total 24 $\mu$m background intensity, we have extrapolated the number counts for $S_\nu < 60$ $\mu$Jy using the fit to the faint-end slope of the 24 $\mu$m number counts in §3. Under this assumption, we find that sources with $S_\nu < 60$ $\mu$Jy would contribute $0.8\pm 0.9$ nW m$^{-2}$ sr$^{-1}$ to the 24 $\mu$m background, which when summed with the above measurement yields an estimate of the total background of $\nu I_\nu (\nu) (24 \mu m) = 2.7^{+1.1}_{-0.8}$ nW m$^{-2}$ sr$^{-1}$. For this value, the sources detected in the deep Spitzer 24 $\mu$m surveys produce $\sim 70\%$ of the total 24 $\mu$m background.

We acknowledge our colleagues for stimulating discussions, the Spitzer Science Center staff for efficient data processing, Thomas Soifer and the IRS team for executing the Bootes-field observations, Daniel Eisenstein for cosmology discussions, Jim Cadieu for his assistance with the data reduction, and the entire Spitzer team for their concerted effort. We also thank the referee, Matthew Malkan, for a thorough and insightful report. Support for this work was provided by NASA through contract 960785 issued by JPL/Caltech.
REFERENCES

Balland, C., Devriendt, J. E. G., & Silk, J. 2003, MNRAS, 343, 107
Chary, R. R., & Elbaz, D. 2001, ApJ, 556, 562
Chary, R. R., et al. 2004, ApJS, 154, 80
Dale, D. A., Helou, G., Contursi, A., Silbermann, N. A., & Kolhatkar, S. 2001, ApJ, 549, 215
Dole, H., Lagache, G., & Puget, J.-P. 2003, ApJ, 585, 617
Dole, H., et al. 2001, A&A, 372, 364
Elbaz, D., Cesarsky, C. J., Chanial, P., Aussel, H., Franceschini, A., Fadda, D., & Chary, R. R. 2002, A&A, 384, 848
Elbaz, D., et al. 1999, A&A, 351, L37
Fixsen, D. J., Dwek, E., Bennett, C. L., & Shafer, R. A. 1998, ApJ, 508, 123
Franceschini, A., Aussel, H., Cesarsky, C. J., Elbaz, D., & Fadda, D. 2001, A&A, 378, 1
Gordon, K., et al. 2004, PASP, submitted
Hacking, P., & Soifer, B. T. 1991, ApJ, 367, L49
Hauser, M. G. & Dwek, E. 2001, ARA&A, 39, 249
Hauser, M. G., et al. 1998, ApJ, 508, 25
Kashlinsky, A. & Odenwald, S. 2000, ApJ, 528, 74

King, A. J., & Rowan-Robinson, M. 2003, MNRAS, 339, 260
Lagache, G., Dole, H., & Puget, J.-L. 2003, MNRAS, 338, 555
Lagache, G., et al. 2004, ApJS, 154, 112
Le Floc'h, E., et al. 2004, ApJS, 154, 170
Madau, P. & Pozzetti, L. 2000, MNRAS, 312, L9
Papovich, C. & Bell, E. F. 2002, ApJ, 579, L1
Rieke, G. & Low, F. 1972, ApJ, 176, L95
Rieke, G., et al. 2004, ApJS, 154, 25
Roussel, H., Sauvage, M., Vigroux, L., & Bosma, A. 2001, A&A, 372, 427
Shupe, D. L., Fang, F., Hacking, P. B., & Huchra, J. P. 1998, ApJ, 501, 597
Soifer, B. T., & Neugebauer, G. 1991, AJ, 101, 354
Soifer, B. T., Neugebauer, G., & Houck, J. R. 1987, ARA&A, 25, 187
Spinoglio, L., Malkan, M. A., Rush, B., Carrasco, L., & Recillas-Cruz, E. 1995, ApJ, 453, 616
Stern, P. B. 1987, PASP, 99, 191
Xu, C. 2000, ApJ, 541, 134
Xu, C., Lonsdale, C. J., Shape, D. L., Franceschini, A., Martin, C., & Schiminovich, D. 2003, ApJ, 587, 90