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CONFUSION OF EXTRAGALACTIC SOURCES IN THE MID- AND FAR-INFRARED: *SPITZER* AND BEYOND

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ABSTRACT

We use the source counts measured with the Multiband Imaging Photometer for *Spitzer* at 24, 70, and 160 μm to determine the 5 σ confusion limits due to extragalactic sources: 56 μJy, 3.2 mJy, and 40 mJy at 24, 70, and 160 μm, respectively. We also make predictions for confusion limits for a number of proposed far-infrared missions of larger aperture (3.5–10 m diameter).

Subject headings: galaxies: evolution — galaxies: statistics — infrared: galaxies

1. INTRODUCTION

In addition to detector/photon noise, cosmological surveys in the far-infrared (FIR) spectral range are limited in depth by (1) structure in the infrared cirrus emission and (2) confusion due to extragalactic sources. The first of these limitations can be avoided for some programs by observing in particular low-background regions on the sky. The second limitation arises because the high density of faint (resolved or unresolved) distant galaxies creates signal fluctuations in the telescope beam (e.g., Condon 1974; Franceschini et al. 1989; Helou & Beichman 1990; Rieke et al. 1995; Dole et al. 2003; Takeuchi & Ishii 2004). Because distant galaxies are distributed roughly isotropically and with a high density compared to the beam size, this noise is unavoidable.

Extragalactic confusion noise can be robustly estimated by measurements of source counts combined with modeling to extend the counts to faint levels. We use new determinations of number counts in the three Multiband Imaging Photometer for *Spitzer* (MIPS; Rieke et al. 2004) bands, 24, 70, and 160 μm (Dole et al. 2004; Papovich et al. 2004), and a model fitting all those observables (Lagache et al. 2004) to determine more accurate limits for extragalactic confusion than have been available previously. Extragalactic confusion noise does not strictly follow Gaussian statistics. Therefore, we discuss confusion limits in four different ways that are appropriate to various measurement situations: the photometric criterion, the source density criterion (SDC; Dole et al. 2003), and the levels deduced from the source densities of one source per 20 and 40 independent beams. We parameterize the noise as a "5 σ" limit calculated as if it were Gaussian, because it is difficult to derive any other simple metric. All the definitions and values relative to MIPS beams are summarized in Table 1 of Dole et al. (2003).

We summarize the confusion limits for *Spitzer* in its three far-infrared bands in Table 1. The situation is different at 24 and 70 μm from that at 160 μm. In the two first bands, where the background is resolved to a significant extent, the confusion mainly results from the high density of resolved sources and their interference with the extraction of fainter ones, and the SDC is the appropriate measure (and the classical photometric criterion underestimates the confusion level). In the third band, where the background is not well resolved, the confusion results from a population fainter than the sensitivity limit. In the latter case, confusion (and cosmic infrared background [CIB] fluctuation) properties are directly linked to galaxy populations that are not directly detectable but that modulate the background level, and the photometric criterion is appropriate.

2. CONFUSION IN THE MID- AND FAR-INFRARED

2.1. *Confusion of Extragalactic Sources at* 24 μm

The available measurements extend well into the extragalactic confusion regime at 24 μm, and the detector performance is also well understood even for long integrations. Therefore, we use this band to develop the general principles applicable to determining the confusion limits in *Spitzer* mid- and far-infrared imaging data.

2.1.1. *Confusion Limit Calculation*

Our confusion estimates are based on the methodology described by Dole et al. (2003). We have used the number counts determined by Papovich et al. (2004), extrapolated to fainter flux limits according to the model of Lagache et al. (2004). Because these counts indicate that the background will be largely resolved into individual sources, the appropriate measure of the confusion is the SDC. We obtain 56 μJy for the 5 σ confusion level, corresponding to 12 beams per source. It appears that this confusion level is in perfect agreement with the 5 σ prelaunch predictions of Xu et al. (2001), even if it was derived differently. If it were limited by photon noise only, the instrument would reach a detection limit of 56 μJy for 5 σ in 1900 s of integration (Rieke et al. 2004), so the model predicts that the gain in signal-to-noise ratio (S/N) will have leveled out significantly for integrations of this length.

There is excellent agreement between the observed 80% completeness level and source density of Papovich et al.

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TABLE 1
MIPS Confusion Levels[a]

Criterion/Flux	24 μm (μJy)	70 μm (mJy)	160 μm (mJy)
SDC[b]	56	3.2	40
20 beams[c]	71	3.5	45
40 beams[d]	141	6.3	63
Photometric[e]	8	0.7	45

[a] With the Lagache et al. (2004) model.
[b] From Dole et al. (2003).
[c] Using the flux corresponding to one source per 20 beams.
[d] Using the flux corresponding to one source per 40 beams.
[e] Using the standard photometric criterion and $q = 4$, for illustration.

(2004) and our SDC confusion level. However, it should be possible in principle to integrate below the 56 μJy level, on a *selected field* of very low source density. In the "GOODS Test Field" in the European Large-Area *ISO* Survey North-1 (ELAIS N1) field (described in Papovich et al. 2004), we estimate the area suitable for a deeper integration to be about 5% of the field area.

2.1.2. *Noise Analysis*

We desired a test of these predictions that, as much as possible, was independent of assumptions about the infrared galaxy population. For this purpose, we have characterized the noise in the 24 μm data from the ELAIS N1 field as the deepest observation obtained to date at this wavelength. We selected a very cleanly reduced region in the field, about $2' \times 4'$ in size. We prepared two versions of the image in this region, both reduced identically, but one with an integration of 630 s and the other with an integration of 3800 s. We determined the pixel signal histogram in two ways. (1) On a small region that also appeared to be free of detected sources, we verified that the standard deviation as measured in these histograms scaled inversely with the square root of the integration time. (2) On the entire $2' \times 4'$ region, we fitted a Gaussian with a width that was fixed to the expectation for detector/photon noise. We required this Gaussian to fit the negative side of the histogram only, on the assumption that there were no negative sources. We took the departure of the measured histogram from this fit toward positive fluctuations to be the influence of (at least) sources in the field. We measured the extension of the distribution toward positive values at half-maximum. We found that the width of the positive side of the distribution was larger than the pure detector/photon noise expectation by a factor of 1.7, in qualitative agreement with the effects of confusion. These excess fluctuations likely result from a combined effect of extragalactic sources, a faint cirrus, and a zodiacal light gradient. It is not clear at this stage which component dominates the fluctuations.

2.1.3. *Monte Carlo Simulation*

To empirically quantify the effect of confusion, we carried out a Monte Carlo simulation of source extraction under the conditions appropriate for the *Spitzer* deep 24 μm exposures. The approach is described in detail by Rieke et al. (1995). We built up a test field by distributing confusing sources randomly according to a power-law distribution matching the faint *Spitzer* number counts. Each source was entered as an Airy pattern. A test source of known amplitude was added to the center of the array, along with Gaussian noise. The sources were then identified using a modified CLEAN algorithm, and finally the S/N was measured in a master array built up from the results of the CLEAN process and in extraction apertures of various sizes. An important aspect of this simulation is that it combines the effects of neighboring bright sources and of the underlying, unresolved distribution of faint ones, in a consistent manner. It should give a good measure of the confusion noise independent of the division between source density and photometric criteria.

In the simulation, we excluded all objects brighter than 400 μJy to avoid undue noise from bright-source artifacts. The first set of runs tested the extraction of a 56 μJy source in an $0.8\lambda/D$ beam, the beam size previously indicated to provide optimum performance in a heavily confusion-limited situation (Rieke et al. 1995; this result was confirmed by the new calculations). We made 1200 runs for an integration time that was long enough to drive detector/photon noise down to 12.5 μJy, 5 σ. They yielded a net 5 σ limit of 60 μJy; removing the detector/photon noise leaves 59 μJy of confusion noise. That is, this approach agrees well with the SDC-determined limit of 56 μJy.

We also simulated the results to be expected from shorter integration times. For example, if the 5 σ detector/photon noise limit was set to 65 μJy, then the indicated 5 σ level of confusion noise was 76 μJy, significantly poorer than that from the simulation of very long integrations. This effect probably results from the increased uncertainty in source centroiding and the resulting lower accuracy in extracting accurate source measurements from a confused field. To test this hypothesis further, we simulated extraction of a 36 μJy source in the high S/N integration case and found that the indicated 5 σ confusion limit rose to 64 μJy, confirming the effect.

2.2. *Confusion by Extragalactic Sources at* 70 μm

At 70 μm, we again use the number counts (Dole et al. 2004) as the basic input for determining the confusion level. The updated model of Lagache et al. (2004) was used to extrapolate the counts and to derive updated confusion limits. The use of a model is critical in this case because the contribution of unresolved sources is not negligible. We derive a confusion level at 70 μm of 3.2 mJy using the SDC (Table 1). The differential source counts are almost flat (when divided by the Euclidean component), and the contribution from unresolved sources is much smaller than that of the resolved sources. These results demonstrate that the SDC estimate is the appropriate one; that is, the confusion is dominated by faint resolved sources rather than by the unresolved background due to even fainter objects. Further details are given in Table 1. From the instrument radiometric model, we estimate that about 1800 se of integration would be required to reach this limit.

Again, we sought to check these results by a pure fluctuation analysis on the data without referring to galaxy population models. We used the data described by Dole et al. (2004) for the Chandra Deep Field–South. We determined the evolution of σ_{tot}, the standard deviation of a Gaussian fitted to the surface brightness distribution as a check of the results from extrapolating number counts downward. Data were combined into six mosaics corresponding to 100–600 s integration time per sky pixel with 100 s steps. Figure 1*a* shows the evolution of σ_{tot70} with time. We do not observe substantial flattening in the σ_{tot70} time evolution. We conclude that MIPS 70 μm surveys do not yet reach the confusion limit after 600 s of

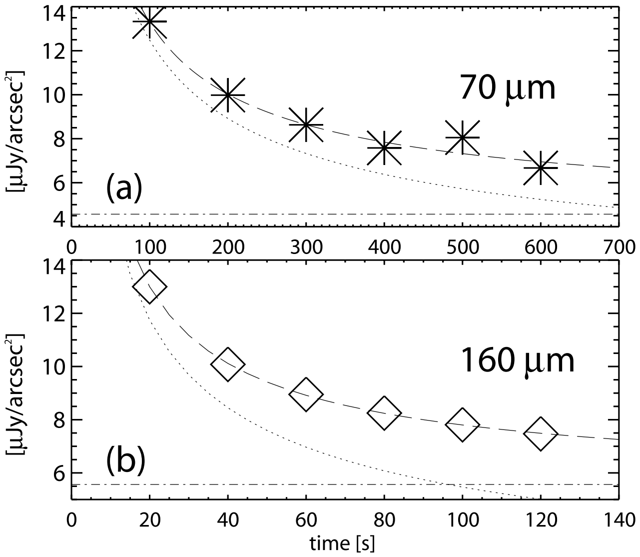

FIG. 1.—Evolution of $\sigma_{\rm tot}$ (resulting contribution from the confusion noise and instrument noise, derived from the Gaussian fit in the brightness map pixel histogram) as a function of integration time, with a fit (*dashed line*) of the form $\sigma^2_{\rm tot} = \sigma^2_{\rm inst} + \sigma^2_{\rm conf.\ brightness} = At^{-1} + C^2$. *Dot-dashed line*: Constant term *C*. *Dotted line*: $(A/t)^{1/2}$ term. (*a*) 70 μm and (*b*) 160 μm. Notice the different scales in time (seconds) and $\sigma_{\rm tot}$ (in brightness μJy arcsec^{-2}).

integration. An estimate of the confusion level is given by fitting the time evolution of $\sigma_{\rm tot70}$. We find that the detector/photon noise will be roughly equal to the confusion noise at $\geq$800 s of integration, with large uncertainties, because the fluctuation curve is still dropping almost like the inverse square root of the integration time at the longest integration available. As at 24 μm, this result is in satisfactory agreement with the integration time predicted by the SDC modeling.

2.3. *Confusion by Extragalactic Sources at* 160 μm

The data used at 160 μm are also described by Dole et al. (2004). The Lagache et al. (2004) model predicts a confusion level of 40 mJy (Table 1). From the instrument radiometric model, we estimate that about 70 s of integration would be required to reduce the instrument and photon noise to the level of the confusion noise.

A fluctuation analysis similar to the one at 70 μm was conducted at 160 μm, where six mosaics corresponding to integration times of 20–120 s (with 20 s steps) were studied. Analyzing the fluctuations is more difficult in this case because bright sources in the Euclidean regime contaminate the statistics and because the map's S/N is not uniform. Nevertheless, we estimate from Figure 1*b* that the confusion noise and the detector/photon noise should be equal at about 95 s of integration, in good agreement with the result from the SDC analysis.

2.4. *Confusion by Galactic Cirrus*

Another sensitivity limitation arises as a result of the structure of the IR cirrus. To estimate how this cirrus emission may affect the source detectability, we compared the 80% completeness limits in sky regions characterized by different cirrus background levels, using simulations as described in Papovich et al. (2004). We used a dedicated engineering observation of a *bright cirrus* in Draco, with an H I column density $n_{\rm H\,I}$ varying between 4 and 14×10^{20} cm^{-2}. At 24 μm, we find a relatively weak effect and derive a completeness degradation of 15% ($\sim$50 μJy increase from 340 μJy) between the dark and bright parts of the cirrus field. The effects of the cirrus are more conspicuous at 70 μm. We reach 80% completeness limits in Draco of $\sim$17 and $\sim$27 mJy. In a low-cirrus field (e.g., Marano) and for a similar integration time (100 s), this level drops to $\sim$12 mJy. We compared the estimates in Draco with those provided by the performance estimation tool of the *Spitzer* Science Center and found that the measured value variations as a function of the cirrus strength are in general agreement (within 30%) with those estimated by the tool from low to medium background. This comparison will be refined as we continue to acquire far-infrared data.

3. IMPLICATIONS FOR FUTURE OBSERVATORIES

A number of cryogenically cooled space telescopes have been proposed for the mid-infrared (MIR), the FIR, and the submillimeter spectral ranges. Table 2 summarizes the main characteristics of some of these observatories. *Herschel* (Pilbratt 2001), the *James Webb Space Telescope* (*JWST*; Gardner 2003), the *Space Infrared telescope for Cosmology and Astrophysics* (*SPICA*; Matsumoto 2003), and the *Single Aperture Far-Infrared Observatory* (*SAFIR*; Yorke et al. 2002) have at least one photometric channel in common with MIPS. As examples, we focus on the *Herschel* Photodector Array Camera and Spectrometer (PACS) at 75 and 170 μm, on the *JWST* Mid-InfraRed Instrument (MIRI) at 24 μm, and on *SPICA* and *SAFIR* at 24, 70, and 160 μm, assuming in each case that the MIPS filters will be used.

For each of these observatories, we compute predictions for the confusion level for unbiased surveys using the Lagache et al. (2004) model of source counts. We assume a Gaussian beam profile for these future observatories, with an FWHM of $1.22\lambda/D$, λ being the wavelength and D the diameter of the primary telescope mirror, given in Table 2. The underlying assumption to be made by these planned facilities for the deepest surveys is that they will be confusion-limited. This means that we did not take into account other sources of noise, for instance photon noise due to insufficient integration times or thermal background due to the warm telescope—by design, *Herschel* and *JWST* might be in the latter case. Normally background-limited photon noise observations would give a sensitivity limit scaling as the aperture squared for a diffraction-limited system. Figure 2 shows that confusion noise at 24 and 70 μm drops much faster than the size of the aperture squared (*dashed line*) because source counts are shallower below fluxes where most of the CIB has been resolved into sources. That is why the next generation of large far-infrared telescopes will be much less confusion-limited than *Spitzer*.

TABLE 2

TELESCOPES AND PREDICTED CONFUSION LEVELS

Parameter	*Herschel*[a]/*SPICA*	*JWST*[b]	*SAFIR*
Diameter (m).........................	3.5	6.0	10.0
24 μm SDC[c] (μJy)	2	0.18	<0.01[d]
70 μm SDC[c] (mJy)..............	0.16	. . .	0.004
160 μm SDC (mJy).............	10	. . .	0.6

[a] With PACS.
[b] With MIRI.
[c] With the Lagache et al. (2004) model and using the SDC from Dole et al. (2003).
[d] Outside the range of the current model flux grid.

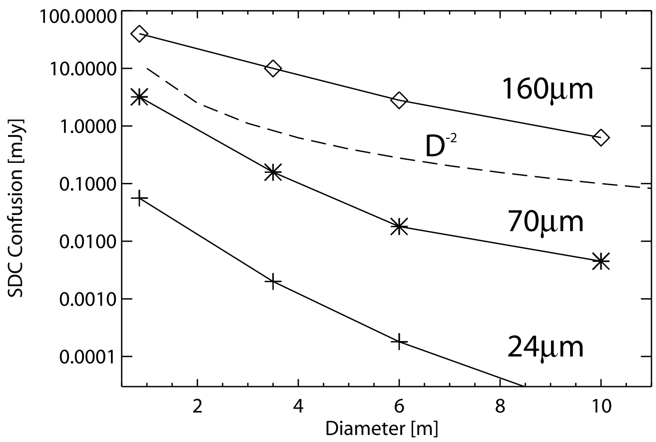

FIG. 2.—Confusion level vs. telescope diameter, predicted by the SDC (Dole et al. 2003) with the updated model of Lagache et al. (2004), at 24 μm (*plus signs*), 70 μm (*asterisks*), and 160 μm (*diamonds*). Diameters refer to *Spitzer*, *Herschel*/*SPICA*, *JWST*, and *SAFIR*. *Dashed line*: Inverse square diameter law shown for illustration.

In Table 3, we use the confusion level given by the SDC and compute the fraction of the CIB potentially resolved into sources. In the MIR, a significant step will be made with the 4 m class space telescope; as an example, *SPICA* would potentially resolve 98% of the CIB at 24 μm. All (>99%) of the CIB would be resolved with *JWST* or *SAFIR* (although doing so with *JWST* would require extremely long integrations). In the FIR, *Herschel* would resolve a significant fraction of the CIB at 70 and 160 μm (93% and 58%, respectively, again with extremely long integrations). *SAFIR* will ultimately nearly resolve all of it (>94%).

TABLE 3

POTENTIAL RESOLUTION OF THE CIB

Observatory	24 μm (%)	70 μm (%)	160 μm (%)
Spitzer	74	59	18
Herschel/*SPICA*	98	93	58
JWST	99	...	...
SAFIR	100	99	94

NOTE.—The CIB value is from Lagache et al. (2004), and we use the limiting flux with the SDC limit and assume confusion-limited surveys. This hypothesis might not be valid for *Herschel* and *JWST*.

4. CONCLUSIONS

Using MIPS data at 24, 70, and 160 μm, the source density measured by Papovich et al. (2004) and Dole et al. (2004) together with the modeling of Lagache et al. (2004) have allowed us to derive the confusion limits for *Spitzer* in the mid- to far-infrared. We tested the model results with a Monte Carlo simulation at 24 μm and with a fluctuations analysis at all three wavelengths. The agreement is uniformly very good.

At 24 and 70 μm, confusion is mostly due to the high density of resolved sources, and at 160 μm, confusion is mainly due to faint unresolved sources. Studying the FIR fluctuations at this wavelength is thus a tool to constrain the nature of the faint galaxies, beyond the confusion limit.

We also derive confusion limits for future space IR observatories. We show that future large-aperture missions will gain in confusion-limited sensitivity substantially faster than the size of the aperture squared for wavelengths ≤ 100 μm, allowing them to reach very deep detection limits. For example, the CIB should be fully resolved into sources in the MIR and FIR with *SAFIR* observations.

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