– Dust in Distant Galaxies – Overcoming Confusion Noise with a 5m FIR Facility

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The vast majority of galaxy evolution studies in the past fifty years have focused on deep optical and near-infrared ($\lambda < 5\mu m$) datasets, tracing galaxies direct emission from starlight. Yet half of all energy emanating from these galaxies is emitted in the far-infrared and submillimeter, where dust and gas emit[1,2]. Dust absorbs emission from young, hot stars and re-radiates that energy at long wavelengths, peaking at rest-frame $\approx$100μm. This dust emission provides very important clues to galaxies' evolutionary history, but is virtually unconstrained observationally over the majority of the Universe's evolution and in normal, Milky Way type galaxies.

Previous limitations in far-infrared instrumentation and the atmospheric opacity at these wavelengths has made detailed studies of dust in distant galaxies extremely challenging in the past, with only a handful of missions successfully surveying the sky in the past thirty years. These include the *IRAS*[3] (1983) and *ISO*[4] (1995) missions, and in more recent history *Spitzer*[5] (2003), *AKARI*[6] (2006), and *Herschel*[7,8] (2009). However, these missions were all significantly limited by a combination of limited sensitivity and small apertures, thus large beamsizes and confusion noise. While improving on detector sensitivity has been quite successful in the past few decades, overcoming confusion noise has been difficult.

Here we outline the impact that a 5m space-borne FIR facility would have on the direct detection of dust in distant galaxies at $\approx$50–200μm. With a relatively modest increase in aperture size, the confusion-limited depth is vastly increased over that of the *Herschel Space Observatory*. This is a simple consequence of the fact that at these frequencies, the 5-meter class aperture is reaching below the knee in the luminosity function, and the shallow faint-end slope translates to a rapid increase in depth with decreasing beam size.

Confusion noise arises when the density of sources on the sky is high relative to the beamsize of observations. Overcoming confusion noise is difficult without a large aperture. For example, the *Herschel* PACS and SPIRE instruments (operating at 70–160μm and 250–500μm, respectively) were confusion limited such that integrating for long periods of time would not improve the depth of the instruments surveys because the resolution was not sufficient to distinguish sources from one another. Strictly speaking, the confusion limit for a given facility, $S_{\rm conf}$, is the limiting flux density for which $\Omega_{\rm beam} \times N(> S_{\rm conf}) = 1$, where $\Omega_{\rm beam}$ is the solid angle of one beam (in deg^{-2}) and $N(> S_{\rm conf})$ is the density of sources at or above $S_{\rm conf}$ at the given wavelength. Confusion noise will dominate for sources with fluxes fainter than $S_{\rm conf}$, where there are more than one source per beam. Another commonly used qualification of confusion noise, used to derive confusion noise in existing observational datasets[9], defines $S_{\rm conf}$ as $\int_0^{x_c} x^2\, dn$, where x is the measured flux, $x = S\, f(\theta, \phi)$, S is the source flux convolved with the normalized beam response, $f(\theta, \phi)$, and dn is the differential source distribution. In both cases, it is clear that the beamsize is the primary limitation in conducting very sensitive, deep FIR surveys.

Figure 1 illustrates the best measured differential number counts[10] at 70μm (from *Spitzer* MIPS[11,12] and *Herschel* PACS[13]), 100μm (from ISOPHOT[14,15,16] and *Herschel* PACS[13,17]) and 250μm (from BLAST[18,19] and *Herschel* SPIRE[20,21,22]). The differential number counts represent the number of sources per flux bin per area, plotted here in units of dN/dS [mJy^{-1} deg^{-2}], and is often fit to a parametric double power law or Schechter function, although it should be noted that such parametrizations are physically meaningless, as flux density is a function of luminosity, redshift and SED shape (dust emissivity, opacity, temperature, etc). Here we have overplot some best-fit double power law parametrizations, which extend to very low flux densities well below the limit of past FIR surveys. We have designated uncertainty on the faint end slope, α, of the number counts to mirror the uncertainty in the data in that regime.

The right panels on Figure 1 show the cumulative number counts in units of sources per beam. For each panel, the left y-axis represents the beamsize of a proposed 5m FIR facility, while the right y-axis represents the beamsize of *Herschel*, a 3.5m facility. Solid horizontal lines illustrate the $S_{\rm conf}$ limit of one source per beam, as per the formal definition of confusion noise, while the dotted lines represent a more practical confusion limit of $^1/_4$ source per beam, in line with measured confusion limits from *Herschel* (note this value will depend strongly on the clustering of galaxies, which differs by wavelength). **What this shows us is that a beamsize that is reduced by a factor of ∼2 (due to the increased aperature of a 5m facility) will push the confusion limit at ≈70μm a factor of ∼3× deeper, and a factor of ∼10× deeper at 100μm and 250μm.** For example, the measured confusion limit at 100μm from *Herschel* PACS[17] is ≈0.15 mJy, which from Figure 1, appears to correspond to a cumulative number of sources per beam (right y-axis) of ∼0.13. Assuming the same effective limit with a 5 m facility (left y-axis value of 0.13), we derive a confusion limit at 100μm of ∼11μJy. See Table 1 for our estimates at other wavelengths. The factor of ten improvement in the confusion limit at 100μm is due to the shallow slope of the faint-end of the number counts below 0.1mJy. While a steep slope would result in a less advantageous jump in the confusion limit, we know such slopes are unphysically possible as they would imply the cosmic infrared background (CIB[2]) should be several times larger than it is measured to be.

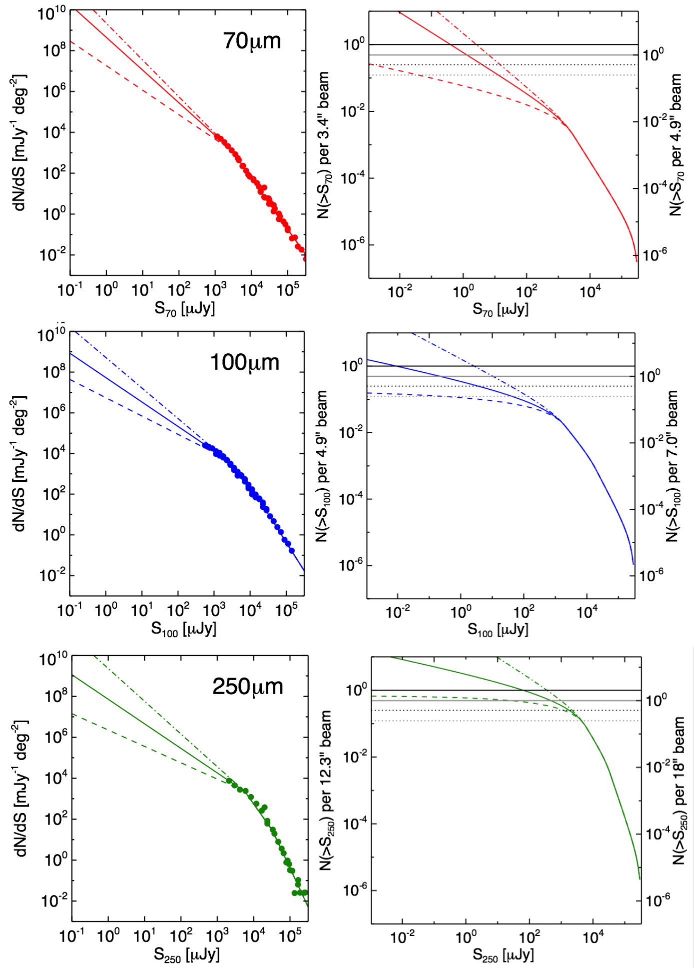

Figure 1: Differential and cumulative number counts at 70–250μm; see text for details.

So what is the scientific value of having a facility with such a low FIR confusion limit? A factor of ten in the confusion limit translates to a factor of ten improvement in the depth of FIR surveys, implying easy detection of Milky Way type galaxies in direct dust emission out to $z \sim 1.5$. The dramatic improvement in depth also implies the number of galaxies with direct detections in the FIR will increase by a factor of ∼100, extrapolating from the underlying shape of the dusty galaxy luminosity function[10]. This will allow very detailed analysis of dust emission, obscuration, and star-formation in distant galaxies on a far larger scale than has previously been possible and resolving the vast majority of individual galaxies contributing to the CIB, well below the knee of the galaxy luminosity function.

Wavelength	*Herschel* conf. lim.	5m conf. lim.	Factor of Improvement
70μm	35 μJy	11 μJy	3.2
100μm	150 μJy	11 μJy	14
250μm	460 μJy	68 μJy	7

Table 1. Estimated confusion limit for a 5m FIR facility in comparison to *Herschel*.

References: [1] Puget et al. 1996, A&A 308, 5 [2] Fixsen et al. 1998, ApJ 508, 123 [3] Neugebauer et al. ApJL 278, 1 [4] Lemke et al. 1996, A&A 315, 64 [5] Rieke et al. 2004, ApJS 154, 25 [6] Murakami et al. 2007, PASJ 59, 369 [7] Poglitsch et al. 2010, A&A 518, 2 [8] Griffin et al. 2010 A&A 518, 3 [9] Condon 1974, ApJ 188, 279 [10] Casey, Narayanan & Cooray 2014, Phys. Rep. 541, 45 [11] Dole et al. 2004, ApJS 154, 87 [12] Béthermin et al. 2010, A&A 516, 43 [13] Berta et al. 2011, A&A 532, 49 [14] Héraudeau et al. 2004, MNRAS 354, 924 [15] Rodighiero et al. 2004, A&A 419, 55 [16] Kawara et al. 2004, A&A 413, 843 [17] Magnelli et al. 2013, arXiv/1311.2956 [18] Patachon et al. 2009, ApJ 707, 1750 [19] Béthermin et al. 2010, A&A 512, 78 [20] Oliver et al. 2010, MNRAS 405, 2279 [21] Clements et al. 2010, MNRAS 403, 274 [22] Béthermin et al. 2012, ApJL, 757, 23