Submillimetre source counts: first results from SCUBA

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Abstract. The SCUBA submillimetre camera has opened up new possibilities for tracing the evolution of active star formation in dusty galaxies to high redshift, with profound implications for our understanding of the star formation history of the Universe and the contribution from galaxies to the anisotropy of the microwave sky. We review results from several submillimetre surveys started during SCUBA’s first year of operation, and discuss their future development, together with other projects that will greatly improve our understanding of the extragalactic point source contribution to the submillimetre sky in the era of MAP and Planck.

1. Introduction

Advances in modern observational astronomy are usually led by innovation in detector technology, rather than through inspiration on the part of observers. A good example of this is the recent upsurge of interest in submillimetre astronomy, following the installation of the Submillimetre Common User Bolometer Array (SCUBA\textsuperscript{2}) on the James Clerk Maxwell Telescope on Mauna Kea, Hawaii. The (sub)millimetre is one of the few regions of the electromagnetic spectrum remaining largely unexplored by modern astronomy, and, as we detail below, SCUBA is the first instrument to cross the sensitivity threshold beyond which serious extragalactic astronomy in the submillimetre becomes not only possible, but very powerful. This has led several groups to start survey programmes with SCUBA, and this article reviews their progress to date. These surveys impact on the study of CBR foregrounds in three ways:

1. the central wavelength of the most sensitive SCUBA band (850\(\mu\)m) matches that of one of the channels of the Planck High Frequency Instrument (HFI):

\textsuperscript{1}A.W. Blain (Cambridge), J.S. Dunlop (Edinburgh), A.N. Efstathiou (ICSTM), D.H. Hughes (INAOE), R.J. Ivison (UCL), A. Lawrence (Edinburgh), M.S. Longair (Cambridge), S.J. Oliver (ICSTM), J.A. Peacock (Edinburgh), M. Rowan-Robinson (ICSTM), S.B.G. Serjeant (ICSTM)

\textsuperscript{2}SCUBA Home Page: www.jach.hawaii.edu/JCMT/scuba
Puget et al. 1998), so SCUBA is directly sampling one of the foregrounds
to be seen by Planck, albeit at fainter flux densities than HFI will reach

2. the source counts resulting from the SCUBA surveys will provide important constraints on the models of galaxy evolution required to predict the level of point source contamination in microwave sky maps produced by CBR experiments in less directly studied passbands

3. SCUBA observations may resolve the cosmic infrared/submm background (Puget et al. 1996) detected in COBE maps.

These issues are addressed more directly in the contributions to this volume by Eric Gawiser, Bruno Guiderdoni, Luigi Toffolatti, and collaborators, so we shall concentrate here on observational aspects of SCUBA survey programmes.

2. Why study galaxies in the submillimetre?

IRAS revealed a strongly evolving population of starburst galaxies forming stars at rates of a few hundred solar masses per year in heavily obscured regions, reminiscent of the formation of massive stars in giant molecular clouds in the Galaxy. Typical starbursts emit $\sim 50\%$ of their bolometric luminosity in the rest-frame far–infrared, as the UV radiation from massive young stars heats the dust around them, while this fraction can increase to $\sim 90\%$ in ultraluminous infrared galaxies (ULIRGs: those with $L_{\text{FIR}} > 10^{12}L_\odot$), although some of these are partially powered by active galactic nuclei (Genzel et al. 1998). The absorption of such a large fraction of the UV/optical radiation from massive stars in starburst galaxies necessarily means that studies performed in those bands will underestimates the star formation rates in individual starbursts (as indicated by Cram et al. 1998, from the comparison of estimates of the rates of star formation in a sample of $\sim 700$ local galaxies derived from U band, Hα, far–infrared and decimetric radio continuum luminosity[3]), as well as allowing the possibility of the complete omission of a population of heavily–obscured starbursts from the cosmic star formation census. Since most massive stars are made in starburst galaxies this can have a significant effect on the global star formation rate, and, once extinction corrections (Meurer et al. 1997, Pettini et al. 1998) are applied, the star formation history of the Universe deduced from UV/optical studies can change substantially (e.g. Steidel et al. 1999) from the well–known shape of the much–touted “Madau diagram” (Lilly et al. 1996, Madau et al. 1996).

In Figure 1 we plot the spectral energy distribution (SED) of the prototypical local starburst galaxy M82, which shows the characteristic starburst shape of a peak at $\sim 60 \mu m$, and a steep decline to longer wavelengths, well fitted by a single temperature greybody curve with emissivity $\propto \nu^{1-2}$ and temperature

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[3] While these and most other conventional methods of estimating the star formation rate of a galaxy determine the luminosity from the massive stars it contains, the exact stellar mass range probed by each method is slightly different, and the conversions from luminosity density to star formation density required to put each point on the “Madau diagram” are uncertain to factors of a few (e.g. Rowan–Robinson et al. 1997) due to differing assumptions about the stellar initial mass function.
Figure 1. The SED of the prototypical starburst galaxy M82 (from Efstathiou et al. 1999: ERRS). Observational data points are plotted, together with model SEDs resulting from two bursts of star formation (dotted and dashed lines), whose sum (solid line) provides a good fit to the galaxy’s SED over the range 0.5–850 µm: see ERRS for details.

Figure 2. Starburst submillimetre flux density as a function of $z$. The solid (dotted) line shows the result of taking M82 (the solid line of Fig. 1) and observing it at 850µm at increasingly high redshift in a Universe with $\Omega_0 = 1$ ($\Omega_0 = 0.1$) and $\Lambda = 0$. The dashed (dot–dashed) lines show the results of doing this at 350µm (2mm), while the dot–dot–dot–dashed line shows the effect on the solid line of replacing M82 ($L \sim 10^{10}L_\odot$) with Arp 220, which is about $\sim 60$ times more luminous, and has a slightly different SED (A. Efstathiou, priv. comm.).
\( \sim 50 \) K (although the physics of the dust emission is certain to be more complicated than this simple model might seem to imply). The steepness of this decline means that such galaxies have high negative \( k \)-corrections in the submillimetre – i.e. as they are observed in a fixed passband at increasingly high redshift, the rest–frame wavelength of the observed emission moves towards the peak and so the rest–frame flux increases – which counterbalance the inverse square law effect due to the increasing distance, with the result that the observed submillimetre flux (in a fixed passband) of a starburst galaxy of a given luminosity is almost independent of redshift for \( 1 \leq z \leq 10 \) or so (for \( \Omega_0 = 1 \) – the effect depends on cosmology through the luminosity distance), as shown in Figure 2.

3. The Submillimetre Common User Bolometer Array (SCUBA)

SCUBA consists (Holland et al. 1998) of two arrays of bolometers (37 in the long wave array, 91 in the short wave array) allowing simultaneous imaging in pairs of submillimetre bands (the most sensitive being 850\( \mu \)m and 450\( \mu \)m) over a field of view of \( \sim 2.3 \) arcmin diameter, or photometry at 1.1, 1.3 or 2.0 mm using single detectors in each band. The bolometer feedhorns are close–packed, but finite gaps between them necessitate a series of offset observations (performed by “jiggling” the secondary mirror of the JCMT) to sample the field of view fully. A total of 64 pointings is required to produce fully sampled maps at both 850 and 450 \( \mu \)m, and these have diffraction–limited angular resolutions of 14.7 and 7.5 arcseconds (FWHM), respectively. Each bolometer is \( \sim 100 \) times more sensitive than the previous JCMT single–element broadband photometer (UKT14) which, combined with its large number of pixels, means that SCUBA reaches the plateau in the flux–redshift plot for luminous starbursts in a sufficiently short time and large field of view to make large submillimetre surveys feasible for the first time.

4. Submillimetre surveys with SCUBA

Four groups have reported results from SCUBA surveys, and several others are underway. Two complementary strategies have been adopted: (i) simple mapping of blank fields; and (ii) pointed observations of massive clusters of galaxies, using their gravitational lensing effect to probe deeper than otherwise possible in a given integration time. Harnassing gravitational lensing amplification probes deeper (simplifying follow-up observations in other wavebands, as well as initial source detection with SCUBA) but it can introduce into quantitative results uncertainty resulting from imprecision in the cluster lens model, and, given the large beam size, there is the possibility of misidentifying emission from cold dust around the central galaxy in the cluster core – as seen by IRAS in some clusters (Bregman, McNamara & O’Connell 1990) and as expected in cooling flow models (see Fabian 1994 for a review) – with emission from a gravitationally–lensed background galaxy along the line of sight.

4.1. The SCUBA Lens Survey

The first SCUBA survey results were reported by Smail, Ivison & Blain (1997) who detected six sources in observations of the two clusters A370 and Cl 2244-02
at $z = 0.37$ and 0.33 respectively. They deduced a source density of $(2.4 \pm 1.0) \times 10^3 \text{deg}^{-2}$ at a 50% completeness limit of $\sim 4 \text{mJy}$ at 850 $\mu$m, requiring strong evolution of the starburst population at $z > 1$ (on the basis of the IRAS 60 $\mu$m luminosity function of Saunders et al. 1990, and the galaxy SED models of Blain & Longair 1996). The SCUBA Lens survey is now complete (Smail et al. 1999), with 17 sources detected at 3$\sigma$ or better, from observations of seven clusters over the redshift range $0.19 \leq z \leq 0.41$, covering a total area of 0.01 deg$^2$ to a depth of 2mJy. Notable amongst the follow-up of the sources is the study of the galaxy SMM J02399-0136 (Ivison et al. 1999) detected in the field of A370 and identified with a $z = 2.8$ galaxy. It exhibits a hybrid of features associated with star formation (high molecular gas mass deduced from CO emission, high radio and H$\alpha$ luminosities) at a rate of several thousand solar masses per year, and with the presence of an active nucleus (optical emission line properties and radio morphology): this mix of features is also seen in some hyperluminous infrared galaxies (e.g. F10214+4724: Lawrence et al. 1994).

4.2. The UK Submillimetre Survey

Our own UK Submillimetre Survey comprises two separate blank field programmes – a narrow, deep survey and a wide, shallow survey – which will combine to produce a dataset capable of tracing the form of the evolution of the starburst population to high redshift. We have completed our narrow, deep survey (Hughes et al. 1998) which was undertaken in the Hubble Deep Field (HDF: Williams et al. 1996) during a period of exceptionally good weather conditions. We covered an area of $\sim 5.5 \text{arcmin}^2$ to a 1$\sigma$ noise level of 0.45 mJy at 850 $\mu$m, putting us beyond the classical confusion limit, given the size of the SCUBA beam. This complicated the identification of discrete sources, but, on the basis of simulations (see Hughes et al. 1998 for details), we conservatively accepted as real and discrete a sample of 5 sources with fluxes above 2 mJy.

The principal reason for undertaking our narrow, deep survey in the HDF was the existence of a wealth of data in other wavebands in that field, which would help with the process of identification of our SCUBA sources. For our five sources we found four plausible associations, with galaxies at redshifts (spectroscopic or photometric) $z \simeq 1$, 2, 3 and 3, while the fifth source had two candidate counterparts, one with a photometric redshift of $z \simeq 4$ and the second a faint galaxy lying in the Hubble Flanking Fields and therefore not amenable to photometric redshift estimation. Note that the optical/far–infrared flux ratios typical of starburst galaxies do not preclude our SCUBA sources being high–redshift galaxies too faint to be detected in the optical HDF, despite its unprecedented depth, and also that only our brightest source (with a flux of 7 mJy at 850 $\mu$m) is detectable at 1.3 mm with the IRAM interferometer, which would yield a more accurate source position, simplifying its identification.

4.3. The Hawaii survey

In the same issue of Nature in which we reported on our HDF survey, Barger et al. (1998) presented results of pointings in two blank fields: one in the Lockman Hole, and one in Hawaii deep survey field SSA13. They detected two sources above 3 mJy, the brightest of which they deduce to lie in the range $1.5 \leq z \leq 3.5$. 
Figure 3. Integral source counts from the four 850\,\mu m surveys described in the text: empty circles (Smail et al. 1999); filled circle (Smail et al. 1997); empty triangle (Barger et al. 1998); filled triangle (Eales et al. 1999); and filled squares (Hughes et al. 1998). For clarity, filled symbols are plotted 0.1\,mJy brighter than their true flux limit: the line $N(> S) = 10^4(S/1\,\text{mJy})^{-5/4}[\text{deg}^{-2}]$ – is not a fit to the data.

4.4. The Canada–UK Deep Submillimetre Survey

A second wide–area survey is being undertaken in two of the fields of the Canada–France Redshift Survey (CFRS), which total 200 arcmin$^2$. Results from the first 22 arcmin$^2$ have been presented by Eales et al. (1999), who report detections of 12 sources with $S_{850\mu m} > 2.8$ mJy. Lilly et al. (1999) found within the CFRS associations for six of these sources, while a further two have tentative identifications to the CFRS photometric limit of $I_{AB} = 25$: of these, four have spectroscopic or photometric redshifts below $z = 1$, four lie in the interval $1 \leq z \leq 3$, while the four unidentified sources are assumed to have $z > 3$.

5. Summary

The results reported to date appear to present a fairly consistent picture. Figure 3 shows that the integral source count distribution is already becoming constrained over more than an order of magnitude in flux density, while Lilly et al. (1999) note that the redshift distribution they derive appears broadly consistent (given the small numbers of sources, and the uncertainty in estimating photometric redshifts at $z > 1$) with that of our HDF sources, and that the $I_{AB}$ band magnitude distributions of the galaxies associated with the CFRS and SCUBA Lens Survey sources also appear to agree well. All four groups broadly ascribe their results to a population of luminous starburst galaxies, which resolve most (perhaps nearly all?) of the cosmic far–infrared/submillimetre background, have SEDs broadly similar to that of Arp 220, and are observed to be forming stars at rates of several hundred solar masses per year. Much of this activity is taking
place at redshifts where previous UV/optical studies (Madau et al. 1996) suggested there should be little star formation, although uncertainty over the local template to use for these galaxies means (Eales et al. 1999) that it is not clear whether these two views of the star formation history really are inconsistent. The revision upwards of the UV/optical star formation rates at \( z > 2 \) (Steidel et al. 1999) does, however, make a consistent picture emerge, in which luminous, dusty starbursts at high \( z \) produce a large fraction of the Universe’s stellar mass.

It is tempting to identify these objects as the long-sought precursors of today’s luminous elliptical galaxies, and perhaps this will become clear by the time these surveys are complete. The two wide area surveys described here should detect a few hundred sources in total, sufficient to characterise the nature and evolution of this population well (although optical spectroscopy of most of these objects will not be possible, even with 10m class telescopes). In particular, our UK Submillimetre Survey has been awarded the time needed to complete our shallow (3\( \sigma \) depth of 8 mJy at 850\( \mu \)m) survey of 640 arcmin\(^2\) in three fields with deep ISOPHOT 175 \( \mu \)m data: these sources should be bright enough to follow up at 1.3mm with the IRAM interferometer, to produce more precise positions, making the association procedure easier, while non-detection of any sources in the deep 175\( \mu \)m data robustly indicate that the galaxy lies at \( z > 2 \).

As discussed in other contributions to this volume, the SCUBA results described here are already providing information on the extragalactic point source population that will be important to MAP, while, by the time \textit{Planck} is launched in 2007, there will be several other very powerful facilities available for studying galaxies in the (sub)millimetre. Firstly, SCUBA itself may be upgraded\(^4\), with suggested improvements capable of increasing sensitivity so that the confusion limit at 850\( \mu \)m can be reached in 2–3 hours of good weather, rather than \( \sim 20 \) as at present. The first of the completely new facilities is the Large Millimeter Telescope (LMT\(^5\)), a 50m single dish telescope to be built by a US/Mexican consortium at a site in Mexico at an altitude of 4,600m. The LMT will operate over the range 0.85–3.4mm, and its Bolocam broad band camera should reach a 10\( \sigma \) sensitivity of 0.3 mJy in 1 hour at 1mm (D. Hughes, priv. comm.). Most important is the planned Large Millimetre Array (LMA), which is likely to result from a merger of ESO’s Large Southern Array\(^6\) project and the Millimeter Array\(^7\) planned by NRAO for the same exceptional site at Llano de Chajnantor in Chile. The design of the LMA is still under discussion, but it will provide the possibility of sub-arcsec resolution (sub)millimetre imaging by interferometry to very faint levels, albeit in a small field of view. This would allow detailed follow up of sources found in surveys made with SCUBA, LMT, FIRST\(^8\), etc, and also with the HFI on \textit{Planck} itself. It is clear that the continued rapid development of (sub)millimetre astronomy over the next decade will provide the greatly im-

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\(^4\)see www.jach.hawaii.edu/JCMT/scuba/upgrades/up.html

\(^5\)LMT Home Page: www-lmt.phast.umass.edu/

\(^6\)LSA Home Page: puppis.ls.eso.org/lsa/lsahome.html

\(^7\)MMA Home Page: www.mma.nrao.edu

\(^8\)FIRST Home Page: astro.estec.esa.nl/First/first.html
proved understanding of the extragalactic point source population required for the success of future CBR experiments like MAP and *Planck* as well as facilitating important secondary science with these missions, studying the astrophysics of the point sources they will remove from their maps of the microwave sky.

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