Cosmological Surveys at Submillimetre Wavelengths

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Abstract. One of the major goals of observational cosmology is to acquire empirical data that has the diagnostic power to develop the theoretical modelling of the high-redshift universe, ultimately leading to an accurate understanding of the processes by which galaxies and clusters form and subsequently evolve. New bolometer arrays operating on the world’s largest submillimetre telescopes now offer a unique view of the high-redshift universe through unbiased surveys with unprecedented sensitivity. For brevity, except when there is a need to be more specific, the FIR to millimetre wavelength regime (100µm < λ < 6000µm) will be referred to as the “submillimetre” (submm). One of the major challenges in this field is to accurately quantify the star-formation history of submm-selected galaxies, particularly those at redshifts > 1, and determine their contribution to the submm extragalactic background. The field of observational cosmology will be revolutionized during the course of the next 10 years due to the variety of powerful new ground-based, airborne and satellite facilities, particularly those operating at FIR to millimetre wavelengths. This review summarises the results from the recent blank-field submm surveys, and describes the future observations that will provide accurate source-counts over wider ranges of wavelength and flux-density, constrain the spectral energy distributions of the submm-selected galaxies and accurately constrain the redshift distribution and submm luminosity function by removing the current ambiguities in the optical, IR and radio counterparts.

1. Evidence for Massive Star-Formation at High-Redshift

In addressing the question ‘what is the main epoch of metal production in the universe?’, or equivalently, ‘when did the cosmic star-formation rate reach its peak value?’, a number of separate lines of evidence suggest that a high-rate of star-formation (\( \gg 100 \, M_\odot \, yr^{-1} \)) must have occurred in massive systems at \( z \approx 3 \). This evidence includes (i) the demonstration by Renzini (1998), using clusters of galaxies as probes of the past star-formation and metal production history, that 30–50% of the present-day baryons are currently locked up in massive structures which appear to have formed at \( z > 3 \); (ii) the peak in the co-moving number density of AGN (radio galaxies and quasars) at \( z \approx 2 \), AGN whose counterparts at low-redshift are hosted in luminous, massive elliptical galaxies (\( > 2L^* \) - Taylor et al. 1996, McClure et al. 1999). At \( z \approx 2 \) the universe is only 3–4 Gyrs
old, which implies that a sustained star-formation rate (SFR) \( > 200 M_\odot yr^{-1} \) is required to build a massive elliptical galaxy by \( z \sim 2 \) (assuming that galaxies hosting high-z AGN have already converted the major fraction of their mass into stars); (iii) the recent discovery of elliptical galaxies at \( z \sim 1.5 \) which contain stellar populations with ages of 3–4 Gyrs (Dunlop et al. 1996, Peacock et al. 1998). Regardless of the cosmological model this requires an extreme formation redshift \( (z > 5) \) for the initial starburst in these galaxies; (iv) the dramatic increase in the number of star-forming galaxies at high-redshift identified in ground-based and HST faint galaxy samples. Using a Lyman-break colour selection technique (Steidel et al. 1996), more than 3000 galaxies now have photometric redshifts with \( \sim 700 \) galaxies already spectroscopically confirmed at \( z \simeq 2 \) (Adelberger priv. comm.), with SFRs \( \sim 1 - 5 h^{-2} M_\odot yr^{-1} \). However the attenuating effects of dust, inevitably associated with star-formation, means that SFRs estimated from these rest-frame UV luminosities must be treated as strict lower-limits. Near-IR observations of rest-frame Balmer-line emission suggest an upward correction factor to the SFRs of \( 2 - 15 \times \) (Pettini et al. 1998), whilst more robust measurements of SFRs, derived from rest-frame FIR luminosities, imply SFRs 600 times greater than that estimated from the UV luminosity (Hughes et al. 1998, Cimatti et al. 1998); (v) similar evolution seen in both the radio-source population and the local starburst population, implying that radio source evolution is a good tracer of the star-formation history of the Universe, suggests that the SFR density derived from Lyman-limit galaxies at \( z \sim 3 - 4 \) is under-estimated by a factor of \( \simeq 5 \) (Dunlop 1998), and therefore that once again the star-formation activity in the Universe peaked at \( z > 2 \); (vi) the small, but increasing number of submm continuum and CO detections of high-z quasars and radio galaxies, indicate that the host galaxies of these powerful AGN contain large quantities of metal-enriched molecular gas \( (1 - 10 \times 10^{10} M_\odot, \text{ after correcting for gravitational amplification}) \) which can fuel massive bursts of star-formation (Omont et al. 1996, Hughes et al. 1997, Combes et al. 1999).

Taken together, the observational evidence suggests that much of the ongoing star-formation in the young Universe may be hidden by dust from optical surveys and possibly also from IR surveys. Hence the transparent view of the Universe provided by submm observations, which now have the instrumental sensitivity to detect high-z dust-enshrouded galaxies forming stars at a rate \( > 100 M_\odot yr^{-1} \), and the preliminary evidence that galaxies (particularly massive spheroidal systems) exhibit strong luminosity evolution at submm wavelengths, demonstrate that comprehensive submm surveys will provide an important alternative measurement of the star-formation history of high-z galaxies unhindered by the effects of dust.

2. Submillimetre Cosmological Surveys

The star-formation history of the high-z starburst galaxy population can be determined from an accurate measure of the integral submm source-counts, the luminosities and redshift distribution of the submm-selected galaxies. The contribution of the submm sources to the total FIR–mm background measured by COBE (Hauser et al. 1998, Fixen et al. 1998) places an additional strong constraint on the possible evolution. By designing a series of cosmological submm
surveys, covering a sufficiently wide range of complementary depths and areas, it is possible to discriminate between competing models of galaxy evolution and the epochs of formation of massive galaxies.

The possibility of conducting cosmological surveys at submm wavelengths has been realised in the last few years with rapid technological advances in semiconductor materials, wafer fabrication, filter design and the temperature stability and performance of cryogenic systems operating at \( \sim 100 - 400 \) mK. This has led to the development and successful commissioning of sensitive bolometer arrays (e.g. SCUBA, SHARC, MAMBO, BOLOCAM), all of which will be upgraded within the next few years. These cameras operate on largest telescopes (10-m CSO, 15-m JCMT, 30-m IRAM) and exploit the best ground-based mm and submm observing conditions.

Despite these recent advances in instrumental sensitivity the primary reason that submm observations of galaxies at cosmological redshifts are at all possible is illustrated in Fig 1. When attempting to observe galaxies out to extreme redshifts, observational cosmologists usually suffer the combined effect of cosmological dimming due to the vast distances, a steeply declining luminosity function and positive K-corrections. However the steep spectral index of the Rayleigh-Jeans emission from dust \( (S_\nu \propto \nu^{2+\beta}, \beta \simeq 1.5) \) heated by young massive stars or AGN, which radiates at 30–70K and dominates the FIR-submm luminosity, produces a negative K-correction at submm and mm wavelengths of sufficient strength to completely compensate for cosmological dimming at redshifts \( z \geq 1 \) with the result that, in an Einstein-de Sitter universe, a dust-enshrouded starburst galaxy of a given luminosity should be as easy to detect at an extreme redshift \( z \simeq 8 \) as at \( z \simeq 1 \). Note that at millimetre wavelengths sources actually become brighter with increasing redshift. The situation is inevitably less favourable (by a factor of 2-3) for low values of \( \Omega \), but nevertheless this relative “ease” of access to the very high-redshift universe remains unique to submm cosmology (Blain & Longair 1993, Blain & Longair 1996, Hughes & Dunlop 1998).

By early 2001, the initial extensive programme of extragalactic SCUBA (850 \( \mu \)m) surveys conducted on the 15-m JCMT will be completed, covering areas of 0.002–0.12 deg\(^2\) with respective 3\(\sigma\) depths in the range 1.5 mJy < \( S_{850\mu m} \) < 8 mJy. To ensure these submm data are fully exploited, the current SCUBA surveys have been restricted to fields extensively studied at other wavelengths and which contain deep X-ray, optical, IR and radio imaging data (e.g. Hubble Deep Field, Hawaii Deep Fields, low-\( z \) lensing clusters, CFRS, Lockman Hole, ELAIS). The results from these first submm surveys (outlined below) confirm that an era of massive dust-enshrouded star-formation exists at early epochs (\( z > 1 \)), with an intensity previously underestimated at optical wavelengths (Smail et al. 1997, Hughes et al. 1998, Eales et al. 1999, Blain et al. 1999, Barger et al. 1999b). However despite the enhancement of observed sub-mm fluxes of high-\( z \) starburst galaxies by factors of 3–10 at 850\( \mu \)m, the deepest SCUBA surveys today are still only sensitive to high-\( z \) galaxies with SFRs comparable to the most luminous local ULIRGs \( (\geq 100M_{\odot} yr^{-1}) \).

The following preliminary results from the on-going SCUBA surveys have already made a significant impact on several cosmological questions.
Figure 1. Flux density vs. redshift for a galaxy with a FIR luminosity similar to Arp220, $L_{\text{FIR}} \sim 2 \times 10^{12} L_{\odot}$. At redshift $z = 0.1$, the order of the individual curves corresponds to the same relative order as the wavelength labels. An $\Omega = 1$ cosmology is assumed.

- The faint submm source-counts at 850 $\mu$m are reasonably well determined between 1–10 mJy (e.g. Barger et al. 1999b) and significantly exceed a no-evolution model, requiring roughly $(1 + z)^3$ luminosity evolution out to $z \sim 1 - 2$, however a variety of models are consistent with the data. The submm background measured by COBE requires that the SCUBA source-counts must converge at $S_{850\mu m} \leq 0.5$ mJy.

- Submm sources generally appear to be associated with $z > 1$ galaxies, although it is not yet clear whether they necessarily have optical, IR and radio counterparts. There is still much debate about the fraction of submm sources at $z \geq 2$, and the fraction of submm-selected galaxies that contain an AGN. Currently the most accurate identifications and spectroscopic redshifts are found in the SCUBA survey of lensing clusters (Frayer et al. 1998, 1999, Ivison et al. 1998, Barger et al. 1999a).

- Approximately 30–50% of the submm background has been resolved into individual high-$z$ galaxies at flux densities $S_{850\mu m} > 2$ mJy, and therefore existing unlensed submm surveys, which are confusion-limited at about this flux level, are only within a factor $\sim 4$ in sensitivity of resolving the entire submm/FIR background. In the SCUBA surveys of highly-lensed clusters it is possible to measure the source-counts down to a reduced confusion limit of $S_{850\mu m} \sim 0.5$ mJy (Blain et al. 1998). It now appears
that the majority of submm background is due to a population of high-
$z$ ultraluminous ($L_{\text{FIR}} > 10^{12}L_{\odot}$) dusty galaxies forming stars at rates
$> 100M_{\odot}\text{yr}^{-1}$, i.e. similar to the local ULIRG galaxies although the
surface density of the high-$z$ submm population is significantly higher.

- At high-redshift ($2 < z < 4$) the submm surveys find $\sim 5$ times the star
formation rate observed in the initial optical surveys (Madau 1997). However
new optical surveys now agree more closely with the earlier submm result,
finding no significant evidence for a decline in the star formation
density between $z = 2$ and $z = 4$, when corrections are applied to the rest-
frame UV luminosities to account for obscuration by dust (Pettini et al.
1998, Steidel et al. 1998).

3. Limitations on an Understanding of High-z Galaxy Evolution

Despite the success of the first SCUBA surveys, a number of deficiencies can be
identified in the submm data which prevent a more accurate understanding of the
star-formation history of high-z galaxies. This review describes these deficiencies
and outlines the future observations which will alleviate the following problems.

3.1. Constraining the evolutionary models

To improve the constraints on the competing evolutionary models provided by
the current submm source-counts, it is necessary to (1) extend the restricted
wavelength range of the surveys, (2) increase the dynamic range of the flux
densities over which accurate source-counts are measured, and (3) increase the
number of sources detected at a given flux level by surveying greater areas.

All these goals can be achieved by conducting future surveys with a combi-
nation of more sensitive, larger format bolometer arrays operating at 200$\mu$m
– 3 mm on larger ground-based and airborne telescopes. Ground-based surveys
at mm wavelengths can take advantage of a more stable and transparent atmo-
sphere which will provide increased available integration time (to gain deeper
survey sensitivity or greater survey area) and increased flux calibration accu-
rracy. Future surveys with more sensitive and larger format arrays (e.g. BOLO-
CAM) will allow significantly greater areas to be covered (hence more sources
detected) and will increase the range of the flux densities over which sources
are detected. Furthermore conducting surveys with larger diameter telescopes
(e.g. 50-m Large Millimetre Telescope (LMT/GTM), 100-m Green Bank Tele-
scope) will reduce the beam-size, hence decrease the depth of the confusion limit
(allowing deeper surveys) and improve the positional accuracy.

3.2. Future millimetre cosmological surveys

The SCUBA 850$\mu$m surveys have indicated that the extragalactic submillimetre
background is dominated by a high-$z$ population of sources with $S_{850\mu m}$ $\leq$ 1 mJy.
At $z \sim 1 – 8$ the same population of sources will have 1.1mm flux densities in the
range 0.3 – 0.6 mJy respectively. The extragalactic confusion limit at 850$\mu$m,
estimated from the deepest SCUBA surveys, occurs at a depth of $3\sigma < 2\text{mJy}$
and corresponds to a source density $N(S) \sim 4000 \pm 1500$ deg$^{-2}$ at a resolution of
15 arcsecs. The ratio of 850$\mu$m (JCMT) and 1.1mm (LMT) beam-areas ($\sim 6''$)
Table 1. Number of $5\sigma$ galaxies detected in alternative 50-hour BOLOCAM 1.1mm surveys during the initial commissioning phase (with a 100$\mu$m r.m.s. surface) of the LMT, and later during routine operation with an improved surface accuracy (70$\mu$m) and sensitivity. BOLOCAM sensitivities allow for overheads.

| $S^a$ | Area$^c$ | N (5$\sigma$ galaxies) | Area$^c$ | N (5$\sigma$ galaxies) |
|-------|-----------|-------------------------|-----------|-------------------------|
| 0.05 mJy | 0.01 | 6 | 0.06 | 40 |
| 0.1 mJy | 0.04 | 15 | 0.25 | 100 |
| 0.5 mJy | 1 | 140 | 6 | 860 |
| 2.0 mJy | 16 | 400 | 100 | 2460 |
| 10.0 mJy | 400 | 660 | 2500 | 4120 |

$^a$S – Conservative BOLOCAM Noise Equivalent Flux Density (NEFD) at 1.1 mm

$^b\eta$ – Primary aperture r.m.s. surface accuracy ($\mu$m)

$^c$Survey area ( ×100 sq. arcmins.)

implies that confusion at 1.1 mm on the LMT will begin to become significant at a source density of $\sim 24000$ deg$^{-2}$. Extrapolating models that adequately describe the measured 850$\mu$m source-counts to longer wavelengths suggests that at 1.1 mm confusion occurs at $\sim 0.05 – 0.1$ mJy. Consequently a deep 1.1 mm BOLOCAM/LMT survey has sufficient sensitivity and resolution to detect the entire submm-mm extragalactic background at a level above the confusion limit.

The current submm source-counts are measured with varying degrees of precision at 850$\mu$m between 1–10 mJy (Fig. 2), whilst the future combination of BOLOCAM on the 10-m CSO (2000) and later ($\sim 2002$) on the 50-m LMT will provide accurate source counts at 1.1 mm between 0.1 and 100 mJy. Table 1 illustrates the predicted number of galaxies detected in a series of future 50-hour LMT surveys at 1.1 mm with BOLOCAM covering areas of 0.001–70 sq. degrees during the commissioning phase of the telescope and later, with an improved surface ($\eta \sim 70\mu$m) during routine operation. For example in a similar duration to the original SCUBA HDF survey, a 50-hour LMT survey at 1.1 mm (with a $3\sigma$ detection limit of 2 mJy) will detect $\sim 2000$ galaxies equivalent to HDF850.1, the brightest submm source in the HDF ($S_{850\mu m} \sim 7$ mJy).

3.3. Ambiguity in the counterparts & redshifts of submm galaxies

The current SCUBA surveys (with 15$''$ resolution at 850$\mu$m) are struggling to unambiguously identify the submm sources with their optical/IR/radio counterparts. Hence the redshift distribution and luminosities of the submm sources are still uncertain. This results directly from the submm positional errors of $\sim 2–3''$ that are typical for even the highest S/N submm detections, and from the lack of submm data measuring the redshifted FIR spectral peak at 200–450 $\mu$m.

The positions of the brightest SCUBA sources ($S_{850\mu m} > 8$ mJy) can be improved with mm-interferometric observations. However an IRAM Plateau de Bure follow-up of the brightest source in the Hubble Deep Field has demonstrated that even with $\leq 2''$ resolution and sub-arcsec positional errors, an am-
Figure 2. The integral number-counts vs. flux density. The data represent the 850\,µm source-counts from the SCUBA surveys (§2). A representative model at 850\,µm is extrapolated to derive the expected number counts at 300–2000\,µm. The range of flux densities represents the extended range that can be surveyed with sufficient accuracy to fully constrain the competing models.

Figure 3. The 300/850\,µm flux ratio, appropriate for the combination of BLAST and SCUBA surveys (§2.1.2), is a powerful discriminant of redshift. The example of a 5σ 850\,µm detection (13 mJy), from the medium-depth UK SCUBA survey, with no BLAST 300\,µm counterpart (< 50 mJy) is indicated by the horizontal line. The upper limit to the 300/850\,µm ratio implies a redshift > 3 assuming the SED of the high-z source is similar to empirical range of starburst and AGN SEDs represented by the solid (Arp220), dashed (M82) and dashed-dotted (Mkn231) curves.

Biguous optical identification, and hence ambiguous redshift remains (Downes et al. 1999). It should be no surprise that submm selected galaxies, including those with mm-interferometric detections, do not always have optical counterparts, since high-z galaxies observed in the earliest stages of formation may be heavily obscured by dust. Indeed this is the most compelling reason for conducting the submm surveys in the first instance and therefore searches for the counterparts may be more successful at near-infrared wavelengths. This was recently demonstrated by Smail et al. (1999) who took deep near-IR (2\,µm) images of two lensed clusters, previously observed by SCUBA (Smail et al. 1997). The original counterparts were identified as two bright low-redshift (z ~ 0.4) galaxies 5–10 arcsecs distant from the submm sources. However the new IR images revealed two high-z (z > 2) IR galaxies, with no optical counterparts, within 2–3 arcsecs of the SCUBA sources. The consequence of these mis-identifications is an inaccurate determination of star-formation history of high-z galaxies.

The uncertainty in the redshift distribution of the submm-selected galaxies can be significantly reduced by measuring the mid-IR to radio SEDs of the individual sources. The power of using mid-IR to radio flux ratios (e.g. 15/850\,µm, 450/850\,µm, 850/1300\,µm, 850\,µm/1.4 GHz) as a crude measure of the redshift of submm-selected galaxies was demonstrated by Hughes et al. (1998) during the SCUBA survey of the Hubble Deep Field and has since been described elsewhere.
Figure 4. Radio to IR SEDs of low-z starbursts, quasars, ULIRGS, Seyferts normalised at 850 µm (Hughes et al. 2000, in prep.). The curves represent fits to the SEDs of Arp220 (solid), M82 (dashed) and Mkn231 (dashed-dotted). These 3 template SEDs are used to calculate the range of 300/850 µm colours as a function of redshift in Fig 3.

(e.g. Carilli & Yun 1999, Blain 1999). The overall similarity of the IR-radio SEDs of starburst galaxies, ULIRGS and radio-quiet AGN in the low-z universe provides a useful template with which to compare the colours of high-z submm population (particularly in the absence of information regarding the relative starburst/AGN contributions). Hence given sufficient instrumental sensitivity, the FIR–submm–radio colours of a submm source can discriminate between optical/IR counterparts which are equally probable on positional grounds alone, but which have significantly different redshifts, \( \delta z \geq 1.5 \) (Fig. 3).

This important technique, and the necessity for sensitive short submm data (200–500 µm) measuring the rest-frame FIR SEDs of the individual high-z submm galaxies, without which it remains impossible to constrain their bolometric luminosities and SFRs, provide the major scientific justifications behind BLAST, a future (~2003) NASA long-duration balloon-borne large-aperture submm telescope (P.I. M. Devlin, UPenn) operating at an altitude of 140,000 ft. Table 2 describes a series of possible BLAST surveys which demonstrate that even a single 50-hour survey will be able to follow-up all the wide-area shallow SCUBA surveys observed to date. For example if there are 5σ SCUBA sources \( S_{850\mu m} > 13 \) mJy with no BLAST 5σ counterparts at 300µm, i.e. \( S_{300\mu m} < 50 \) mJy, then the 300/850µm flux ratio must be \( \leq 4 \). This implies that the SCUBA source is most likely a galaxy at \( z \geq 3 \) for all typical starburst SEDs (Fig. 4). BLAST will also be an ideal complement to the future
Table 2. Predicted number of galaxies detected in possible 50-hour BLAST surveys. Illustrative redshift distributions are given for galaxies detected with a S/N > 5. A single long-duration balloon flight will be ∼ 250 hours duration and will allow several complementary surveys. The extragalactic confusion limit at 300 µm will be 20–30 mJy.

| survey area (sq. degrees) | 1σ depth (mJy) | no. of galaxies > 5σ | no. of > 10σ galaxies | no. of > 5σ galaxies | no. of galaxies > z > 1 | no. of galaxies > z > 3 |
|---------------------------|----------------|----------------------|-----------------------|----------------------|-----------------------|-----------------------|
| 0.6                       | 5 mJy          | 510                  | 160                   | 470                  | 90                    |                       |
| 1.2                       | 7 mJy          | 600                  | 170                   | 550                  | 90                    |                       |
| 2.5                       | 10 mJy         | 670                  | 180                   | 600                  | 90                    |                       |
| 5.5                       | 15 mJy         | 680                  | 150                   | 630                  | 90                    |                       |
| 22.2                      | 30 mJy         | 600                  | 150                   | 550                  | 65                    |                       |

BOLOCAM bright mm-surveys (S_{1.1mm} > 4mJy) on the CSO and LMT. A measurement of the confusion noise due to extragalactic sources at 200–500 µm with a ∼ 2-m class telescope is an important secondary goal since the result will influence future FIRST survey strategies beyond 2007.

3.4. Millimetre CO-line spectroscopic redshifts

An accurate determination of the redshift distribution of submm-selected galaxies can ultimately be achieved through the measurement of mm-wavelength CO spectral-line redshifts, without recourse to having first identified the correct optical or IR counterparts. In the high-z Universe the frequency separation of adjacent mm-wavelength CO transitions is δν_{J,J-1} ∼ 115/(1+z) GHz. Hence at redshifts > 2, any adjacent pair of CO transitions are separated by < 40 GHz, similar to the width of the 3 mm (75–110 GHz) atmospheric window. At these frequencies one can expect to detect the most luminous redshifted CO transitions from starbursts (J=6–5 → J=3–2). Therefore, provided one can first pre-select from submm surveys those galaxies with sufficiently high (but still unknown) redshifts, using their FIR–mm colours, the availability of a “CO redshift machine” with a large instantaneous bandwidth (Δν ~ 35 GHz), operating on large single-dish mm-wavelength telescopes (e.g. 50-m LMT, 100-m GBT), will offer an incredibly powerful and more efficient alternative method to determine the accurate redshift distribution of the submm population.

Whilst future submm surveys will undoubtedly detect increasing numbers of high-z galaxies, an accurate description of their evolutionary history will not be possible without accurate redshifts and constraints on their bolometric luminosities (and star-formation rates). The overall strategy requires the follow-up of submm surveys with sensitive FIR–submm airborne (SOFIA), balloon-borne (BLAST) and satellite observations (SIRTF, FIRST), together with wide-band mm-wavelength spectroscopic measurements.
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