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David H. Hughes / Itziar Aretxaga
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UNDERSTANDING THE HISTORY OF OBSCURED STAR FORMATION IN THE HIGH-REDSHIFT WITH COORDINATED GTC[1] AND LMT[2] SURVEYS

David H. Hughes[3] and Itziar Aretxaga[3]

RESUMEN

Los adelantos en los últimos 15 años en la tecnología de detectores bolométricos han permitido que las mediciones de longitudes de onda (sub)milimétricas contribuyan con importantes datos a algunos de los problemas más desafiantes de la cosmología observacional. La disponibilidad de cámaras de gran formato en la siguiente década promete, sin embargo, proporcionar observaciones desde el infrarrojo lejano a milimétricas con fidelidad de imagen sin precedente. El incremento simultáneo del área de recolección de las nuevas instalaciones también proporcionará datos observacionales de mayor sensibilidad y resolución. En esta reseña subrayamos los resultados más importantes de los primeros 6 años de exploraciones extragalácticas (sub)milimétricas, particularmente aquellos que han proporcionado restricciones sobre la historia evolutiva de AGNs de alto corrimiento al rojo y de galaxias oscurecidas ópticamente por polvo y con brotes de formación estelar. También ilustro algunas de las dificultades y ambigüedades que surgen al interpretar los datos submilimétricos existentes y las subsecuentes observaciones en múltiples longitudes de onda. Finalmente describo porqué en breve podremos esperar resolver los problemas más sobresalientes respecto a la naturaleza, distribución del corrimiento al rojo, la función de luminosidad y la distribución a gran escala de la población (sub)milimétrica de galaxias identificadas en exploraciones de campos vacíos mediante las capacidades IR y ópticas combinadas del GTC y los futuros experimentos en longitudes de onda desde el infrarrojo lejano a ondas milimétricas (BLAST y el LMT). La coordinación cuidadosa de exploraciones del GTC y del LMT (en un proyecto clave) contribuirá de manera significativa al aprovechamiento científico de ambas instalaciones.

ABSTRACT

The advances in bolometric detector technology during the last 15 years have allowed (sub)millimetre wavelength measurements to contribute important data to some of the most challenging questions in observational cosmology. The availability of large-format filled-array cameras during the next decade, however, promises to provide FIR to millimetre observations with unprecedented imaging fidelity. The simultaneous increase in the telescope collecting-area of new facilities will also provide the observational data with greater sensitivity and resolution. In this brief review I highlight the major results from the first 6 years of (sub)millimetre extragalactic surveys, in particular those that have offered constraints on the evolutionary history of high-redshift AGN and optically-obscured dusty starburst galaxies. I also illustrate some of the difficulties and ambiguities that arise in the interpretation of the existing submillimetre data and their follow-up multi-wavelength observations. Finally I describe why, with the combined optical and IR capabilities of the GTC and the future FIR to millimetre wavelength experiments (BLAST and the LMT), we can shortly expect to answer the outstanding questions regarding the nature, redshift distribution, luminosity function and large-scale distribution of the (sub)millimetre population of galaxies identified in blank-field surveys. The careful coordination of GTC and LMT surveys (via a *key project*) will significantly contribute to the scientific return of both facilties.

Key Words: **COSMOLOGY: EARLY UNIVERSE — COSMOLOGY: OBSERVATIONS — SURVEYS**

1. INTRODUCTION

Rest-frame far-infrared (FIR) to millimetre wavelength observations have the ability to detect violent star formation in heavily-obscured galaxies which can be "missed" in rest-frame optical-UV searches. Due to a strong negative k-correction, submillimetre and millimetre wavelength observations, in particular, are able to trace the evolution of star formation in dusty galaxies throughout a large volume of the high-redshift Universe (in principle with as much ease at $z \sim 8$ as at $z \sim 1$), and back to extremely early epochs. Hereafter, except when it is necessary to be more explicit, I refer to the submillimetre and

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[1] Gran Telescopio de Canarias.

[2] Large Millimetre Telescope, or Gran Telescopio Milimétrico.

[3] Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), Tonantzintla, Puebla, México.

millimetre wavelength regime ($200\mu\mathrm{m} < \lambda < 3\,\mathrm{mm}$) as *sub-mm*. Given the large accessible volume of sub-mm surveys it is possible to test whether sub-mm galaxies represent the rapid formation of massive (elliptical) systems in a single violent collapse of the material in the highest-density peaks of the underlying large-scale matter distribution, or whether they are built over a longer period from the continuous merging of lower-mass systems with much more modest rates of star formation. Eventually, sensitive and high-resolution interferometric imaging surveys with instruments like ALMA will provide a dramatic description of the manner in which massive galaxies form (i.e. single or multiple sources associated with the sub-mm emission?). In the meantime, however, the source-counts, redshift distribution and clustering information obtained from the current generation of sub-mm surveys can still provide useful, albeit crude, initial tests of competing galaxy formation models (e.g. van Kampen 2003).

I will concentrate my discussion of the high-redshift sub-mm universe to include some of the essential follow-up X-ray, optical, IR and radio observations that have influenced our view of these dust-enshrouded starburst galaxies. I therefore limit myself, in this brief review, to some introductory comments regarding the need to extend the range of the sub-mm wavelength surveys, and summarise the capabilities of new (interferometric and single-dish) telescopes that will contribute sensitive (spectroscopic and continuum) data that can challenge our current understanding of the nature of the sub-mm galaxy population. Two comprehensive descriptions of the properties of the starburst galaxies and AGN identified in sub-mm wavelength surveys by Smail et al. (2002) and Blain et al. (2002) provide useful introductions to this paper.

2. SUB-MM SURVEYS WITH SMALL TELESCOPES AND SMALL CAMERAS

The first generation of cosmological surveys at sub-mm wavelengths have been conducted primarily with the SCUBA (Holland et al. 1999) and MAMBO cameras, which both use modest-sized bolometer arrays (~ 100 pixels), on the 15-m JCMT and 30-m IRAM telescopes respectively. These various sub-mm surveys, which covered areas ranging from 0.002 – 0.2 deg^2 (Smail et al. 1997; Hughes et al. 1998; Barger et al. 1999a; Eales et al. 1999, 2000; Lilly et al. 1999; Scott et al. 2002; Fox et al 2002; Cowie et al. 2002; Smail et al. 2002; Borys et al. 2003; Webb et al. 2003, Greve et al. 2004), have contributed significantly to the first efforts to understand the history of obscured star formation at high-redshift. Using sub-mm observations alone, however, these data remain limited in their ability to accurately measure the evolutionary model and large-scale distribution of the sub-mm galaxy population. Fig.1 illustrates the two fundamental reasons why this is the case: first, the measured sub-mm source-counts from the combined extragalactic surveys cover a dynamic-range of only 15–20; second, the errors on the binned-data reflect the fact that < 100 sub-mm galaxies have been detected in all blank-field surveys at a significance greater than 4σ. Thus, with these restricted statistics it is difficult to measure the flux-density at which the faint-end source-counts converge, and therefore determine the contribution of this sub-mm population to the extragalactic background emission. The combined effect of clustering and small survey-areas also has a strong impact on these faint source-count measurements (Hughes & Gaztañaga 2000). Furthermore, the poor source-count statistics leave enough uncertainty in the steepness of the bright-end counts which makes it difficult to ascertain whether this reflects a cut-off in the evolving luminosity function and redshift distribution of the sub-mm population. Given this, it is remarkable to think that, within the next decade, we can expect the entire shaded region in Fig.1 to be populated with accurate source-counts from the next generation of experiments at 170μm – 3 mm.

The practical reasons for the above limitations have been described elsewhere (Hughes 2000; Hughes & Gaztañaga 2000) and can be summarised as follows: restricted wavelength coverage (enforced by the few FIR–mm atmospheric windows available to ground-based observatories); low spatial resolution (resulting in both a high extragalactic confusion limit and poor positional accuracy); restricted field-of-view with the current sub-mm and mm bolometer arrays (typically 5 arcmin^2); and low system sensitivity (a combination of instrument noise, size of telescope aperture and telescope surface accuracy, sky transmission and sky noise) which restrict even the widest and shallowest sub-mm surveys to areas $<$ 0.2 deg^2. Hence, in the effort to obtain these blank-field surveys, the existing sub-mm observations are necessarily only sensitive to the most luminous and massive star-forming galaxies ($L_{\mathrm{FIR}} \sim 3 > 10^{12} L_{\odot}$, or SFR $> 300 M_{\odot}\mathrm{yr}^{-1}$). Given the shape of the sub-mm k-correction, the errors in the calculated luminosities and star forming rates (considering only the uncertainty in redshift) are factors of a few, provided that the population is dominated by galaxies at red-

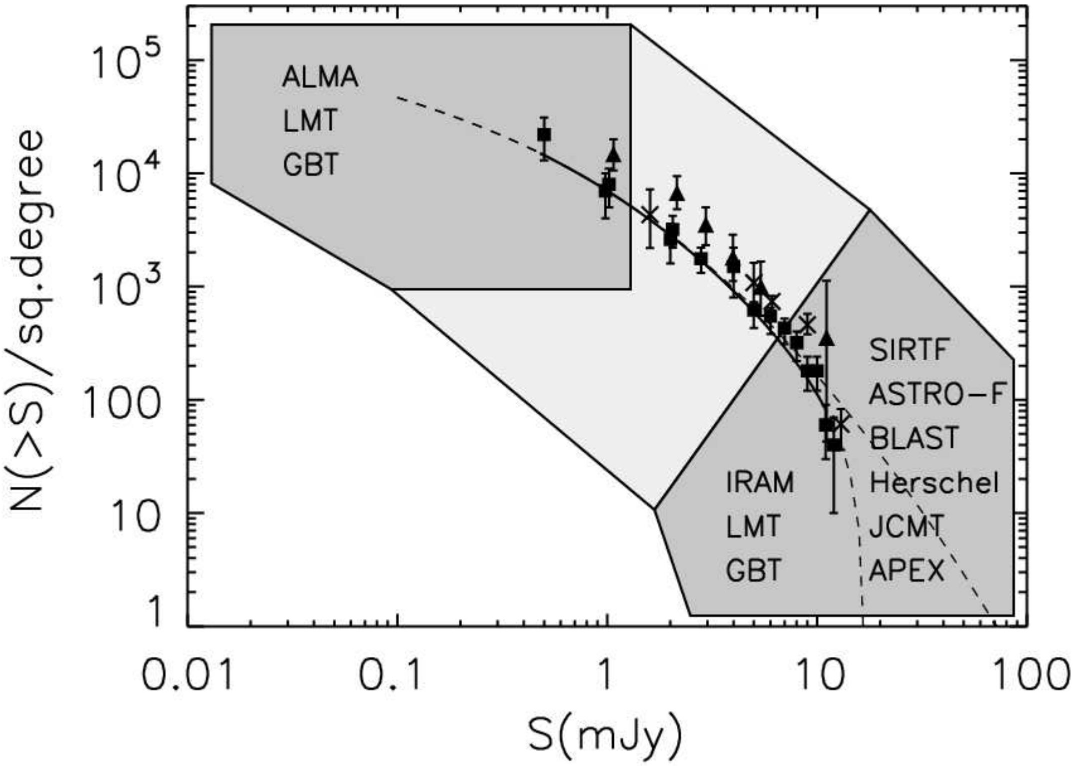

Fig. 1. Extragalactic 850μm source-counts measured from the SCUBA surveys summarised in §2. The solid-line represents one of many possible strongly-evolving models that fit the 850μm data. The measured source-counts cover a narrow range of flux densities ($\sim 0.5 - 12$ mJy) and therefore leave two unexplored regions (shown as dark-grey shaded polygons) populated by the numerous, faint galaxies below the existing observational confusion limits, and the brightest, but rarer galaxies that can only be detected in the widest-area surveys. The combination of both larger single-aperture and interferometric telescopes (e.g. LMT, GBT, ALMA), as well as larger-format cameras on smaller ground-based (JCMT, APEX, IRAM), balloon-borne (BLAST) and satellite telescopes (SIRTF, ASTRO-F, Herschel) are required to provide the necessary increase in resolution, sensitivity and mapping speed to constrain the evolutionary model for the sub-mm population. The shaded-area of the source-count parameter-space will be populated with accurate measurements at 170μm – 3 mm from these new experiments (and existing telescopes with upgraded instrumentation).

shifts > 1 (an assumption that is consistent with the spectroscopic and photometric redshifts, §3.3).

Future observations at sub-mm wavelengths with the next generation of larger telescopes will simultaneously increase the resolution, and provide sufficient sensitivity to detect the fainter population of galaxies that will be accessible with the corresponding reduced confusion-limit. For example, observations at 1.1 mm with the Large Millimeter Telescope (LMT, §4.4), with a primary aperture of 50-m, are expected to reduce the extragalactic confusion limit by a factor of > 20, compared to the measured 850μm limit determined from SCUBA observations with the JCMT. We can expect, therefore, that in the near future mm-wavelength surveys will search for (and find) optically-obscured galaxies with far more modest FIR luminosities ($L_{\rm FIR} \sim 10^{11} L_\odot$) and SFRs ($\sim 10-50 M_\odot {\rm yr}^{-1}$). We must wait for observations with ALMA, however, before fainter and more quiescent galaxies (similar to the Milky Way), can be detected at the highest redshifts (if they exist).

In other words, the current cosmological studies at sub-mm wavelengths trace the distribution of dusty galaxies forming stars at rates similar to the local ULIRG population. Whilst the comparison of sub-mm galaxies with the phenomena observed in ULIRGs is appealing, we have no direct evidence (morphological or kinematical) to support the suggestion that the "sub-mm phase" is associated with intense star forming activity induced during a major merger (that also can fuel, or re-fuel, an AGN).

The construction of larger telescopes alone, however, is not sufficient if the goal is to detect (at the confusion-limit) the faintest and most numerous sub-mm galaxies, as well as the brightest and rarest sub-mm sources in the high-redshift Universe. For example, a search for the most extreme star-forming galaxies (SFR $\gg 5000 M_\odot \mathrm{yr}^{-1}$), associated perhaps with the rapid formation of a massive elliptical in less than a few Gyrs, would require a sub-mm survey covering > 100 sq. degrees before a statistically-significant result could be achieved. Such a survey is well beyond the capability of current instrumentation.

Although the increased sensitivity (using larger telescopes) certainly provides a faster mapping-speed for the current bolometer cameras, the greatest gains will be achieved through the development of the large-format (> 5000 pixel) cameras that can fill the focal-plane of the future large ground-based telescopes (e.g. 100-m GBT, 50-m LMT). The recognition of this fact is prompting the intense activity to build the next-generation of sub-mm and mm cameras, many of which will exploit (i) the speed and sensitivity of superconducting transition-edged sensors (TES), (ii) their multiplexing capability, when combined with a read-out array of SQUIDs, and (iii) new micro-machining techniques that enable these large, fully-sampled monolithic wafers to be fabricated.

3. MULTI-WAVELENGTH FOLLOW-UP OF SUB-MM SURVEYS

To fully understand the nature and physical properties of the sub-mm galaxy population, there is a need for multi-frequency follow-up data (at X-ray, optical, IR, FIR and radio wavelengths) providing valuable information about the galaxy morphology, age, kinematics, dynamics, stellar and gas content, and possible presence of a buried (or heavily-obscured) AGN in the host galaxy.

3.1. *Optical and IR imaging*

Unfortunately, due to the dust-obscured nature of the sub-mm galaxies there will always be a level of ambiguity in associating a sub-mm source with its optical and IR counterpart. The searches for optical and IR counterparts to sub-mm galaxies detected towards lensing clusters and blank-fields have had different levels of success which reflects the diversity of their properties (Ivison et al. 2000). This diversity led Smail et al. (2002) to propose a broad classification scheme (class 0, I, II). In some cases (e.g. Ledlow et al. 2002; Smail et al. 2003a) bright class II (typically red) host galaxies have been found at both optical and IR wavelengths ($I < 25$, $K \sim 18.5 - 21$), whilst other searches have only yielded positive results when deeper optical and/or IR follow-up observations have been made, detecting class I (Lutz et al. 2001) or intermediate class I-II counterparts (Frayer et al. 2003). One of the most extreme examples is the counterpart to HDF850.1 (Hughes et al. 1998), the brightest sub-mm source in the northern Hubble Deep Field, which avoided detection for many years despite the wealth of multi-wavelength data. Dunlop et al. (2002) finally identified and associated an extremely faint red and optically invisible (class 0) host galaxy ($I > 28.7, K = 23.5$) with HDF850.1. Not only is this counterpart inaccessible to spectroscopic observations at optical and IR wavelengths, but follow-up imaging observations to these depths can only be conducted over limited areas ($< 1\,\mathrm{deg}^2$). A K-band study by Frayer et al. (2003) finds a median magnitude $K = 22 \pm 1$ for the sub-mm population identified in the SCUBA Cluster Lens Survey. Only 3/15 sub-mm sources do not have an IR counterpart ($K > 23$). Frayer et al. argue therefore, that, in the absence of radio detection, IR colour selection ($J - K > 3$) can also help identify the counterparts to sub-mm galaxies.

3.2. *Radio and millimetre interferometric imaging*

Quantifying the usefulness of the association of radio sources with sub-mm galaxies continues to provide debate in the literature (Ivison et al. 2002; Dunlop et al. 2003; Aretxaga et al. 2003; Smail et al. 2003b). In essence, the discussion revolves around the question of whether it is the radio position, or the radio flux that is the more relevant. I consider these alternatives in turn.

The high-resolution and sub-arcsec positional accuracy of radio and mm-wavelength interferometric observations have certainly assisted the majority of the identifications of the optical and/or IR counterparts (e.g. Frayer et al. 2000). For example, the radio follow-up observations of the sub-mm surveys in the ELAIS N2 and Lockman Hole fields (Scott et al. 2002; Fox et al. 2002) detected 60 and 70%, respectively, of the sub-mm sources with 1.4 GHz fluxes (5σ) $> 45\mu$Jy and $> 25\mu$Jy (Ivison et al. 2002). At these depths, given the low surface-density of radio-sources, the detection of a 5σ radio-peak within a few arsecs of a sub-mm source makes a convincing case for a genuine association, and can lead to an attempt to gain an optical spectroscopic redshift (e.g. Chapman et al. 2003). SMM04431+0210 provides a counter-example of a sub-mm source without a radio detection ($3\sigma < 70\mu$Jy at 1.4 GHz), whilst in this instance the strong IR counterpart ($K = 19.4$)

provided the key to measuring the rest-frame optical redshift (Frayer et al. 2003).

If, however, the value of the radio detection is not only to provide an accurate position, but also to help constrain the photometric redshift (§4.1), then the accuracy and calibration of the extracted radio fluxes must also be considered. Using the same example, the fraction of sub-mm sources with significant ($S/N > 3$) 1.4 GHz radio-fluxes in the ELAIS N2 and Lockman Hole surveys reduces to 40-50%.

Since the above 1.4 GHz surveys already represent some of the deepest radio observations it will not be easy (until the completion of the e-VLA and e-Merlin) for future radio observations to keep pace with the rapid increase in depth and area ($\sim 10\,\mathrm{deg}^2$) of the next generation of confusion-limited sub-mm surveys (§4.3, 4.4). Aretxaga et al. (2003) demonstrated that future radio surveys must reach a 5σ sensitivity of 5–8μJy at 1.4 GHz if ∼80% of the bright sub-mm population (> 6 mJy at 850μm, or > 2 mJy at 1.1 mm) are expected to have a radio counterpart with a valid measurement of the flux density.

3.3. *X-ray, Optical, IR and CO spectroscopy*

There has been considerable effort to obtain (rest-frame) spectroscopic redshifts for the optically-bright ($I < 26$) sub-mm galaxies (e.g. Chapman et al. 2003). At the time of this conference (June 2003) only 14 blank-field sub-mm galaxies had spectroscopic redshifts. More recently, Smail et al. (2003b) - see their Fig.3 - presented the spectroscopic-redshift distribution for 41 sub-mm galaxies which have a median redshift of $z \sim 2.3$, and 50% of the sources are found in the range $1.9 < z < 2.6$. From these optical spectra it has also been possible to measure the fraction of AGN (10–20%) hosted in a sub-mm galaxy (Barger et al. 1999b; Smail et al. 2000). Recent results from the spectral analysis of the 2 Ms Chandra Deep Field North (Alexander et al. 2003), however, suggest that a higher fraction (∼ 50%) of sub-mm galaxies host heavily obscured AGN (observed only in hard X-rays). Considering the depth of the 2 Ms Chandra survey that was required to make the sub-mm–X-ray connection, and the fact that the X-ray AGN spectra generally show Compton-thin absorption, lends further support to the argument that star formation processes (and not AGN) dominate the high bolometric luminosities.

In some cases for which a rest-frame optical spectroscopic redshift exists (e.g. Chapman et al. 2003; Frayer et al. 2003), CO receivers, operating at ∼ 90 GHz (with a typical band-width of $\Delta\nu \sim 1 - 0.5$ GHz, which provides a redshift range $\delta z \sim 0.02 - 0.06$ at $z \sim 2 - 4$), can be tuned to detect the molecular gas component in these high-z sources. As anticipated, the CO observations indicate that the sub-mm galaxies are massive gas-rich systems with sufficient fuel ($M_{H_2} \sim 10^{10} - 10^{11} M_\odot$) to drive the high-levels of star-formation suggested by their rest-frame FIR luminosities (e.g. Frayer et al. 1999; Neri et al. 2003; Genzel et al. 2003). These CO detections, however, do not come cheaply - even after the lengthy initial sub-mm, radio, optical and IR imaging and spectroscopic observations, the confirmation of the optical spectroscopic redshifts currently takes 15–40 hours per target with either the IRAM Plateau de Bure or OVRO interferometers. Partly as a result of the required sensitivity and limited receiver band-width, only 5 published CO detections, and hence only 5 confirmed optical redshifts (in the range $z \sim 2.4 - 3.3$), exist for sub-mm galaxies. Thus it has proven difficult and extremely time-consuming to build up large secure samples of sub-mm galaxies with spectroscopic redshifts.

There is also a natural bias towards the optical spectroscopic detection of lower-redshift (unlensed) sources. The common path of (i), initial sub-mm detection, to (ii), radio identification, to (iii), optical and IR imaging and association with the faint radio-source, and finally (iv), to optical spectroscopy and then to CO spectroscopy, breaks down at redshifts > 3 when the level of radio emission drops below even the deepest detection thresholds. This selection bias, which explains the redshift cut-off (upper-quartile $z \sim 2.6$) observed in the sub-mm galaxy population (Chapman et al. 2003; Smail et al. 2003b), prevents the identification of the highest redshift sub-mm sources and hence the objects that would present the most extreme test of galaxy formation models. The degree of incompleteness in the spectroscopic redshift distribution ($\geq 30\%$, consisting of galaxies at $z > 3$) is highly dependent on the prediction from the imprecisely-known evolutionary model for the sub-mm population. This same uncertainty in the evolutionary model is one of the reasons the upper-bound of the redshift distribution, determined from photometric colour information (§4), is still poorly constrained.

4. MEASURING THE LARGE-SCALE DISTRIBUTION AND EVOLUTIONARY HISTORY OF SUB-MM GALAXIES

The initial SCUBA and MAMBO surveys are too small to measure the clustering properties of the sub-mm population on scales $> 9h^{-1}$ Mpc, and have demonstrated the necessity for larger-area surveys and also complementary shorter-wavelength (90–500μm) observations. Although the on-going sub-mm surveys (e.g. SHADES, see §4.2) are now mapping $\sim 0.5\,\mathrm{deg}^2$, the required investment of telescope time (180 x 8-hour shifts) makes this the maximum area that can reasonably be considered until faster mapping speeds, due to larger-format array cameras (e.g. SCUBA-2 on the JCMT, 90 GHz Penn array on the GBT), are available.

With these new instruments, future sub-mm surveys from balloon-borne (BLAST), airborne (SOFIA), satellite (SIRTF, ASTRO-F, Herschel) and ground-based facilities (JCMT, CSO, IRAM, GBT, LMT, APEX) will map significant areas of the FIR – millimetre sky to their respective confusion-limits, whilst higher resolution experiments (SMA, CARMA, IRAM PdB and ALMA) will provide the more detailed studies over restricted fields.

This next generation of wide-area submillimetre surveys will naturally produce much larger samples ($\sim 10^3 - 10^6$) of luminous starburst galaxies than the previous surveys described above (§2). Thus, whilst there has been a tremendous advance in the number of spectroscopic redshifts (assuming the associations to be correct), there remains a growing need for an alternative efficient and independent measurement of the redshift distribution for large numbers of sub-mm galaxies; one that does not depend on the security of the faint optical or IR identification, or the necessity for a prior radio-detection.

4.1. *Photometric redshifts at sub-mm wavelengths*

This "*redshift deadlock*" hinders the development of models to explain the evolutionary history of sub-mm galaxies since, without redshifts, one cannot derive robust measurements of the rest-frame FIR luminosities or SFRs for this optically-obscured population. In recent years there has been considerable effort in assessing whether broad continuum features in the spectral energy distributions (SEDs) of sub-mm galaxies at rest-frame mid-IR to radio wavelengths can provide photometric-redshifts with sufficient accuracy (Hughes et al. 1998, 2002; Carilli & Yun 1999; Barger et al. 1999b; Smail et al. 2000; Yun & Carilli 2000; Rengarajan & Takeuchi 2001; Aretxaga et al. 2003; Wiklind 2003).

In the case of the sub-mm population, their expected characteristic FIR peak and steep sub-mm (Rayleigh-Jeans) spectrum produced from thermal emission from dust heated by obscured young, massive stars, and the radio/FIR luminosity correlation that links the radio synchrotron emission from SN remnants with the later stages of massive star formation, together provide the necessary spectral features to apply to a photometric method for measuring redshifts.

The accuracy of the photometric redshifts and evolving luminosity density that is expected from sub-mm observations of high-z dusty starburst galaxies was illustrated by Hughes et al. (2002). Using a library of multi-frequency template SEDs, derived from observations of local starbursts and AGN with a wide-range of FIR luminosities ($9.0 < \log L_{\rm FIR}/L_\odot < 12.3$), and an evolving 60$\mu$m local luminosity function (Saunders et al. 1990) that is consistent with the observed 850μm source-counts, a series of Monte-Carlo simulations showed that photometric redshifts can be measured from future 250, 350 and 500μm BLAST and Herschel/SPIRE surveys with an accuracy of $\delta z \leq 0.5$ (which included accounting for observational and calibration errors). The addition of longer wavelength sub-mm and radio data for individual galaxies can reduce this redshift uncertainty (and is one of the reasons to combine 850μ SCUBA data and BLAST data in the SHADES survey, §4.2). Aretxaga et al. (2003) applied a similar analysis to the catalogues of sub-mm galaxies in completed SCUBA surveys, and derived photometric redshifts for individual sources using their existing ground-based radio–sub-mm data. The results of this latter work, and other studies (Smail et al. 2002; Ivison et al. 2002), was a redshift probability distribution for the sub-mm galaxy population which places the majority of the sources at $2 < z < 4$, with a median redshift $z \sim 3$ - a result that is to similar to the spectroscopic measurements (§3.3). Wiklind (2003) concluded that even greater accuracy was possible ($dz \sim \pm 0.3$), based on just the 450/850μm flux ratio, although the range of FIR and radio properties in the adopted SED templates was narrower - which raises an important point.

There is an intrinsic level of degeneracy between the temperature of the dust emission (or shape of the FIR SED) and the photometric redshift, in the sense that hot high-z sources will have the same observed colours as cold low-z sources. This has led Blain et al. (2003) to argue that, unless a strong luminosity-temperature relationship exists for the sub-mm population and the galaxies used to calibrate the technique, then photometric redshifts will have insufficient accuracy to be useful. These issues will be undoubtedly be revisited until there exist a sufficient number of robust (optical or CO) spectroscopic redshifts, and sensitive, accurately calibrated rest-frame FIR-sub-mm data for the same targets. Only then

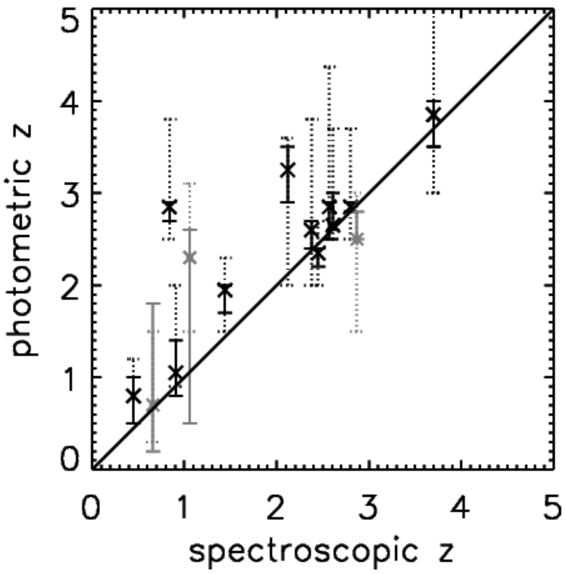

Fig. 2. Comparison of photometric redshift estimates and "true" redshifts for submm galaxies with published optical and IR spectroscopic observations. The crosses represent the most probable mode derived from 100 Monte Carlo simulations for each object calculated for a particular evolutionary model. Details of this analysis are given in Aretxaga, Hughes & Dunlop (2004). The solid-line and dotted-line error-bars represent the range of modes expected to be found in the derived photometric-redshift distributions and a typical example of a photometric-redshift distribution for each object respectively. In both cases the error-bars indicate the 68% confidence intervals in these distributions. Sources shown as black symbols (in increasing redshifts: N1–40, N2850.1, N1-64, HR10, LH850.3, N2850.4, N2850.2, SMMJ14011+0252, LH850.6, SMMJ02399-0136, LH850.18) have photometric-redshifts derived from measurements ($\geq 3\sigma$) in at least 3 passbands and additional upper-limits, and consequently are the most precise. Sources shown as dark-grey symbols (in increasing redshifts: CUDSS14.18, SMMJ02399-0134, CUDSS14.9) have photometric redshifts derived from measurements ($\geq 3\sigma$) in just two passbands and additional upper-limits. Figure adapted from Aretxaga et al. (2004).

can we really understand the biases in the method and determine whether the derived photometric redshifts are *useful*, and if they can be used to constrain the statistical properties of the sub-mm population. In the meantime, however, we use the comparision of photometric and spectroscopic redshifts in Fig. 2 to justify the optimism of the expectation that photometric redshifts for sub-mm galaxies can achieve accuracies of order $dz \simeq \pm 0.3$ from combined radio (1.4 GHz), mm and submm data (1300, 850, 500, 350 & 250μm).

Without sufficient (spectroscopic or photometric) redshift information it is also difficult to describe the 3-dimensional clustering distribution of galaxies (Gaztañaga & Hughes 2001; van Kampen 2003). Therefore, to conclude, I describe below examples of the new sub-mm surveys that will address some of the above limitations (§2 & 3), and allow the population of dusty high-z starburst galaxies to be studied in much greater detail.

4.2. *SHADES - SCUBA Half-Degree Extragalactic Survey*[4]

The SCUBA Half-Degree Extragalactic Survey (SHADES), which is now underway on the JCMT (∼ 40% complete in spring 2004), was motivated by the need to conduct a larger-area sub-mm survey that will detect ∼ 300 sources distributed over angular scales which will provide constraints on the clustering of the sub-mm population. The observational goal of SHADES (August 2002 - July 2005), which represents the new generation of ground-based sub-mm surveys, is to generate an 850μm map covering 0.5 deg^2 (divided between two fields - Lockman Hole and Subaru Deep Field South) down to a 4σ depth of 8 mJy.

A major component of SHADES are the complementary confusion-limited BLAST surveys of the same fields at 250, 350 and 500μm (§4.3). These BLAST data will measure the rest-frame FIR peak of the spectral energy distribution (SED) at high-z, and provide the necessary photometric redshifts for the SCUBA sources. With these multi-wavelength sub-mm observations, SHADES will address 3 fundamental questions: (i) what is the cosmic history of massive dust-enshrouded star formation activity; (ii) are high-z sub-mm sources the progenitors of massive present-day elliptical galaxies; (iii) what fraction of sub-mm sources harbour an heavily-obscured AGN.

4.3. *Balloon-borne Large Aperture Submm Telescope - BLAST*[5]

The Balloon-borne Large Aperture Submillimeter Telescope (BLAST) is a NASA funded experiment (since 2000) that will fly a 2-m primary mirror, and conduct large-area ($\gg 1\,\mathrm{deg}^2$) confusion-limited extragalactic and Galactic surveys from a long-duration balloon-borne (LDB) platform. The detector arrays, which are prototypes of the SPIRE arrays (under development at JPL) for the future Herschel satellite mission, provide simultaneous imag-

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[4] www.roe.ac.uk/ifa/shades

[5] www.chile1.physics.upenn.edu/blastpublic

ing at 250, 350 and 500μm over an 86 arcmin^2 field-of-view (FOV). At a float altitude of $\sim 120,000$ ft (40 km) the expected NEFD of each array is ~ 240 mJy s$^{1/2}$. The combination of this high sensitivity, compared to ground-based observations through the low-transmission and noisy sub-mm atmospheric windows, together with the large FOV, make BLAST a powerful survey experiment. In September 2003 BLAST conducted a successful engineering test-flight. Preparations are now being made for a scientific test-flight in Spetember 2004, and a series of ($\sim 7-15$ day) LDB science-flights in 2005 onwards.

The primary science goal of BLAST, which is similar to that of SHADES, is to provide accurate source-counts, photometric-redshifts, luminosities and star formation rates for luminous sub-mm galaxies ($L_{\rm FIR} > 3\times10^{12} L_\odot$). The mapping speed of the experiment (Hughes et al. 2002) is sufficient to detect ~ 30 sources/hr at the extragalactic confusion limit of 20–30 mJy (see fig.23 in Blain et al. 2002 for comparison with other experiments). Consequently BLAST expects to detect > 5000 high-redshift dusty starburst galaxies in a single LDB flight, significantly more than the total number of sub-mm galaxies (< 300) detected todate in the various completed and on-going SCUBA and MAMBO surveys. Furthermore, with the simultaneous photometric-redshift information for sources distributed over $1-10\,\deg^2$, BLAST will be the first experiment to measure the clustering signal for the sub-mm population on scales upto $\sim 100h^{-1}$ Mpc.

4.4. *The Large Millimeter Telescope - LMT*[6]

The 50-m Gran Telescopio Milimétrico (GTM) or Large Millimeter Telescope (LMT) is a bi-national collaboration between México and the U.S.A. The institutions leading this effort are the Instituto Nacional de Astrofísica, Optica y Electrónica (INAOE) and the University of Massachusetts (UMass) respectively. The selected telescope site of Volcán Sierra Negra (lat. ~ 19 deg), in the Mexican state of Puebla, is at an altitude of 15312 ft (4,640 m) and provides excellent millimetre wavelength transmission during $> 65\%$ of the time between October and May, with an opacity $\tau_{210\,\rm GHz} < 0.2$ (1^{st} quartile < 0.08). Occasional 850μm observations will also be possible during the best conditions ($\leq 10\%$) when $\tau_{340\,\rm GHz}$ is < 0.4. During the summer months Volcán Sierra Negra remains an excellent 3 mm site. An initial surface accuracy (r.m.s.) of 100μm for the primary aperture is anticipated during the first period of operation, with an eventual goal of 70μm. First light is expected in the year 2006.

The LMT will be the largest single-aperture telescope operating at ~ 1 mm, and consequently will have an extremely low confusion limit due to extragalactic sources. The extragalactic confusion limit at 850μm, estimated from the deepest SCUBA surveys, occurs at a depth of $3\sigma \simeq 2$ mJy and corresponds to a source density N(S) $\sim 4000 \pm 1500\,\deg^{-2}$ at a resolution of 15 arcsecs. Assuming the same population of galaxies dominates at longer wavelengths, then the LMT will suffer from confusion at a source density of $\sim 24000\,\deg^{-2}$ which is expected to occur at $\sim 0.02 - 0.1$ mJy. Thus the opportunity to resolve the entire millimetre wavelength background into individual galaxies is well within the capabilities of the LMT and the first-light continuum camera, BoloCam-II (see Glenn et al. 2003 for a description of BoloCam-I). Hughes & Gaztañaga (2000) describe examples of 50 hr LMT surveys during routine operation. Other LMT surveys can be scaled from the numbers presented there.

4.5. *Measuring CO spectroscopic-redshifts with wide-band receivers*

The advantage of having constrained redshifts, or at least robust lower-limits, for large-numbers of individual sub-mm galaxies (some without optical, IR or radio counterparts), is that we can now determine the likelihood that a redshifted rotational CO transition-line falls into the frequency range of a particular mm-wavelength spectral-line receiver. For example, in the case of the LMT, an ultra-wide-bandwidth receiver is under construction for operation in the 90 GHz window. With an instantaneous bandwidth $\Delta\nu \sim 35$ GHz, this receiver is ideally suited to a search for redshifted CO-lines. At $z > 2.3$, adjacent CO lines will be separated by $\sim$ 115GHz$/(1+z) \leq 35$ GHz, and thus, given enough sensitivity, the detection of at least one CO line is guaranteed. The presence of significant masses ($M_{H_2} \sim 10^{10} - 10^{11} M_\odot$) of molecular gas in a few high-z sub-mm galaxies has already been demonstrated (§3.3), but only after an accurate optical redshift had been previously obtained. The obvious advantage of the ultra-wide-band receivers is that an accurate redshift is not needed in advance of the CO observations. Although the detection of one CO-line in the 90 GHz window is insufficient to determine a redshift, it will still allow other narrower-band receivers on the LMT or 100-m GBT to tune and then search for additional CO-transitions at higher or lower frequencies. If any of the sub-mm sources

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[6] www.lmtgtm.org

lie at $z > 6$ then, given enough sensitivity, two CO-lines in principle can be detected in the 90 GHz window, thereby providing an immediate measure of the *true* redshift. The recent detection of CO(3–2) in a quasar at $z = 6.42$ (Walter et al. 2003) proves the existence of large masses ($2 \times 10^{10} M_{\odot}$) of warm molecular gas in the early Universe which is available to fuel an AGN, and/or the violent (and possibly dust-obscured) bursts of massive star formation during the first stages of galaxy evolution.

5. FUTURE FOLLOW-UP OBSERVATIONS OF HIGH-*Z* SUBMILLIMETRE GALAXIES WITH THE GTC

We have summarised the results from the extragalactic submillimetre surveys and their multi-wavelength follow-up. In this final section we illustrate the observations that we anticipate conducting with the Gran Telescopio de Canarias and its suite of optical and IR instrumentation (see these proceedings) to improve our undertstanding of the physical nature of these high-redshift luminous starburst galaxies. The requirements for GTC follow-up observations, based on the existing optical and IR imaging and spectroscopy, imply broad-band continuum sensitivities in the range $I = 22 - 29$ and $K = 19 - 24$ mag. Optical spectroscopy must reach continuum levels of 0.1–1μJy. In this paper we consider optical observation with ELMER and IR observations with EMIR on the GTC.

5.1. *ELMER*

With an imaging field-of-view of 13 sq. arcmins, ELMER can expect to detect, given sufficient sensitivities in the observations, the counterparts to ~ 3 bright (> 5mJy at 850μm) submm sources in every optical image without re-pointing the telescope. At this sub-mm depth, we are considering the follow-up of only the upper 10–20% of the sub-mm luminosity function that contributes to the extragalactic sub-mm background. ELMER can reach $I = 29$ (S/N ~ 5) in 16 hours. At more modest depths, $I = 27$, ELMER requires only ~ 120 hours to cover a 1 sq. deg. field. The *Keck* spectroscopic observations of sub-mm galaxies (Chapman et al. 2003) provide examples of the sensitivity (e.g. $I_{continuum} = 22 - 26$) that must be obtained by the GTC in order to measure redshifts (spectroscopically). In a spectroscopic mode (0.365–1μm), ELMER can reach a continuum level of $I = 25$ (S/N ~ 5) in ~ 2.5 hours. Hence even this first-light imaging-spectrograph has the capability to efficiently detect and follow-up the brightest optical counterparts to the high-z sub-mm population.

5.2. *EMIR*

Following the arguments made above, the IR imaging-spectrograph EMIR, will have the potential to detect the IR counterparts of ~ 8 bright (> 5mJy at 850μm) sub-mm galaxies per 36 sq. arcmin field-of-view. Again, taking examples from previous efforts (§3.1), we must reach $K = 24$ to have a high probability of detecting the K-band counterparts of sub-mm galaxies. The excellent sensitivity of EMIR allows the consideration of a deep 1 sq. degree ($K = 24$, S/N ~ 5) extragalactic survey, which needs only 400 hours of integration to provide contiguous follow-up IR imaging of the widest-area sub-mm surveys that are being considered in the next few years. Spectroscopic observations can be attempted with EMIR for the brightest IR counterparts ($K < 20$). At an effective spectral resolution $R = 400$, reaching at least 10^{-18} $ergs\ s^{-1} cm^{-2} \AA^{-1}$, we predict an integration of only 4 hours (S/N ~ 6) to provide low-resolution IR spectra from which it will be possible to derive accurate redshifts.

6. CONCLUDING REMARKS

Although some overlap is expected, in general the large optical surveys planned for the GTC (e.g. COSMOS, see Guzman et al. these proceedings) will detect a galaxy population that is orthogonal to those dusty, highly-obscured starburst galaxies identified in the LMT and BLAST submm surveys. We therefore propose, in particular, that the GTC and LMT scientific communities explore the opportunities to coordinate observations of common extragalactic survey-fields. These *key projects* will take advantage of the multiplexing capabilities of the GTC instrumentation and the uniqueness and sensitivity of the LMT and BLAST, together addressing wide-ranging and fundamental questions on the formation and evolution of galaxies.

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David H. Hughes and Itziar Aretxaga: Instituto Nacional de Astrofísica, Optica y Electrónica (INAOE), Luis Enrique Erro 1, Tonantzintla, Puebla, Pue., México (dhughes@inaoep.mx).