THE NATURE OF FAINT SUBMILLIMETER GALAXIES

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We summarise the main results on the faint submillimeter (submm) galaxy population which have come from the SCUBA Cluster Lens Survey. We detail our current understanding of the characteristics of these submm-selected galaxies across wavebands from X-rays to radio. After presenting the main observational properties of this population we conclude by discussing the nature of these distant, ultraluminous infrared galaxies and their relationship to other high-redshift populations.

1 Introduction

The results of the highly successful far-infrared (FIR) survey undertaken by IRAS led to a widespread realisation of the ubiquity and importance of highly-obscured star-forming and active galaxies in the local universe. More recent work in the FIR and submm wavebands has produced a similar revolution in our understanding of obscured galaxies in the distant universe. These observations employ the COBE and ISO satellites and the Sub-millimeter Common User Bolometer Array (SCUBA) on the 15-m JCMT and have shown that obscured galaxies contribute a substantial fraction of the total emitted radiation at high redshifts.

The rough equivalence of the energy density in the optical background and that detected in the FIR/submm by COBE suggests that, averaged over...

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aThe JCMT is operated by the Joint Astronomy Centre on behalf of the United Kingdom Particle Physics and Astronomy Research Council (PPARC), the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.
all epochs, approximately half of the total radiation in the universe came from obscured sources (either stars or AGN). Clearly including these class of galaxies in models of galaxy evolution is critical to obtain a complete understanding of the formation and evolution of galaxies.

As we will show in the next section, the bulk of the emission in the FIR/submm comes from a relatively small population of extremely luminous, dusty galaxies. These galaxies lie at high redshifts, \( z \gtrsim 1–4 \), are both massive and gas-rich and they may dominate the total star formation in the universe at these early epochs. The analogs of this population in the local universe are the Ultra-Luminous Infrared Galaxies (ULIRGs) uncovered by IRAS. As a benchmark for the following discussion we note that a ULIRG similar to Arp 220 with a far-infrared luminosity of \( L_{\text{FIR}} \sim 3 \times 10^{12} L_\odot \) and a star-formation rate (SFR) of \( \sim 300 M_\odot \, \text{yr}^{-1} \) would have a 850-\( \mu \)m flux density of \( \gtrsim 3 \, \text{mJy} \) out to \( z \sim 10 \) in a spatially flat Universe.

2 Submm number counts and the FIR background

The advent of sensitive submm imaging with SCUBA has allowed a number of groups to undertake ‘blank’-field surveys for faint submm galaxies. Results on the number density of sources in blank fields as a function of 850-\( \mu \)m flux density have been published by three groups. Unfortunately, due to the modest resolution of the SCUBA maps, 15\( \arcmin \) FWHM, these surveys are confusion limited at \( \sim 2 \, \text{mJy} \) and resolve \( \sim 50\% \) of the COBE background.

Our collaboration has taken a complimentary approach to these ‘blank’ field surveys by using massive gravitational cluster lenses to increase the sensitivity and resolution of SCUBA. This survey covers seven lensing clusters at \( z = 0.19–0.41 \) (new results from two similar lensing surveys with SCUBA were also reported at this meeting). Our analysis uses well-constrained lens models to correct the observed source fluxes for lens amplification. For the median source amplification, \( \sim 2.5 \times \), this survey covers an area of the source plane equivalent to 15 arcmin\(^2\) at a 3\( \sigma \) flux limit of \( \sim 2 \, \text{mJy} \). The amplification also results in a factor of two finer beam size at this depth so that these counts have a fainter confusion limit than the blank field observations. The surface density of sources at the limit of our survey (0.5 mJy) is \( \sim 8 \, \text{arcmin}^{-2} \) (the equivalent density of ‘normal’ field galaxies is reached at \( I \sim 23.5 \)) and we resolve \( \sim 100\% \) of the COBE background. We conclude that the majority of the extragalactic submm background arises in a relatively sparse population of extremely luminous galaxies, \( L \gtrsim 10^{12} L_\odot \).

\(^b\)We assume \( q_0 = 0.5 \) and \( h_{100} = 0.5 \) unless otherwise stated.
3 Optical counterparts to submm galaxies

Figure 1. $15'' \times 15''$ images of the 17 sub-mm sources in our full sample. These are ordered from the upper-left on the basis of the reliability of their proposed optical counterparts – with the first two rows containing those sources which were probably correctly identified in the optical imaging. Possible counterparts are identified with ‘?’, those which are unlikely to be the correct counterpart are marked with an ‘X’. The bottom row shows those submm source where subsequent near-infrared and radio analysis has brought into question the identification of the proposed optical counterparts.

The first attempts at identifying counterparts to the submm sources in our survey concentrated on exploiting the high-quality, archival Hubble Space Telescope WFPC2 imaging which existed for the majority of these fields. These frames typically reach limits of $I \sim 27$ on the background source-plane and we felt confident of identifying a large fraction of the submm galaxies (reflecting the optical bias of the author). Figure 1 shows the identifications from Smail et al. (1998) but ordered in terms of our current understanding of the reliability of the proposed counterparts (based on the near-infrared and radio follow-up discussed in the next section).

If we remove the two central cluster galaxies from our sample (SMM J21536+1741 and SMM J14010+0252) – we conclude that only about half of the original identifications which were proposed are likely to be correct. Indeed, of all the submm galaxies detected in all the SCUBA surveys, only three have confirmed counterparts: SMM J02399−0136, SMM J14011+0254, and SMM J02399−0134 (Fig. 1), where the confirmation comes from identification of CO emission at the same redshift as the proposed counterpart. For a handful of other sources, their continuum
detections with millimeter interferometers and the improved astrometry which these provide, have been used to identify likely counterparts. Equally, identifications of counterparts have been claimed when a galaxy with sufficiently unusual characteristics is found within the submm error box (e.g. an ERO\textsuperscript{18}), but so far none of these have been confirmed in CO.

The relatively low identification rate, even with the high-quality optical imaging we have available, results partly from the fact that source confusion with the large SCUBA beam is compounded by clustering, potentially leading to deviations of the order of the beam-size. Indeed the clearest route to identifying counterparts is usually to overlay the raw SCUBA map onto the optical image and to use the information present in the shape of the submm emission to search for possible merging of sources. We believe that source confusion may have contributed to the ambiguities in the identification of counterparts for SMM J21536+1742, SMM J22471−0206 and SMM J02400−0134. However, the main difficulty with identifying optical counterparts arises because the majority of the submm population are extremely faint at optical wavelengths: at least half and perhaps up to 75% of galaxies in Fig. 1 have optically faint counterparts, \( I \gg 25–27 \) (i.e. Classes 0 and 1\textsuperscript{20}). Removing the known AGN from the sample, the proportion of starburst-powered submm galaxies which have optically faint counterparts rises to 90%. We now briefly discuss some of the observations which have led us to this conclusion.

4 Near-infrared and radio counterparts to submm galaxies

The first indication that things might not be as clear-cut as the proposed optical identifications suggested came from \( K \)-band imaging of our SCUBA fields using UKIRT\textsuperscript{c}. These images reach \( K \sim 21 \) in the source plane and uncovered new candidates (H5 and N4 in Fig. 2) within the submm error-boxes of two of the submm sources. These galaxies are undetected in very deep \( HST \) and Keck \( R \)- and \( I \)-band imaging (\( I \gtrsim 27 \) corrected for lens amplification), but are relatively bright in the \( K \)-band. Their colours, \((I−K) \gtrsim 6.0 \) and \( \gtrsim 6.8 \) for H5 and N4 respectively, place them firmly in the rare class of Extremely Red Objects (EROs).\textsuperscript{18} The surface density of ERO-submm galaxies in our survey means that they account for around half of all ERO’s – providing an important link between these two populations. Moreover, the extreme submm to optical ratios of these galaxies, \( L_{FIR}/L_B \gtrsim 300 \) (assuming they lie at \( z \sim 2.5–3 \), as suggested by fits to their SEDs), combined with their high inferred star formation rates underlines the difficulties faced when attempting

\textsuperscript{c}UKIRT is operated by the Joint Astronomy Centre on behalf of PPARC.
to use UV-selected samples to audit star formation at $z \gg 1$.

Figure 2. ERO counterparts to two submm sources in our survey. The two panels for each source show deep $I$- and $K$-band images with the 850 $\mu$m and 1.4 GHz maps overlayed. The faintest sources visible in the $I$-band exposure have observed magnitudes of $I \sim 25.5$–26.0 and $K \sim 20.5$. The original counterparts proposed for the submm sources are marked on the $K$-band images, as well as the new ERO candidates, H5 for SMM J09429+4658 and N4 for SMM J04433+0210. Each panel is 30$''$ square and is centred on the 850-$\mu$m position.

The next phase of the identification process used very deep 1.4 GHz maps of our fields from the VLA. These maps allow us to identify radio counterparts or place stringent limits ($\lesssim 20$ $\mu$Jy in the source plane) on the radio flux of the submm galaxies. Moreover, the recent work on submm-to-radio spectral indices for distant star forming galaxies has provided us with a useful tool for estimating the redshift distribution of a complete submm-selected sample. We can compare the redshift limits derived in this manner with the spectroscopic redshifts for individual candidate optical counterparts and hence determine the reliability of these proposed counterparts as shown in Fig. 1. On the basis of this analysis we conclude that the submm population brighter than $\sim 1$ mJy has a median redshift of at least $<z> \sim 2$, and using the available spectral index models, probably $<z> \sim 2.5$–3. The high median redshift means that the submm population, if predominately powered by starbursts (rather than AGN), contributes a substantial fraction of the total star formation density at high redshifts.

Our on-going program of observations of this sample of submm galaxies, using near-infrared imaging and spectroscopy and millimeter interferometry is reported elsewhere in this volume.

5 The submm population at other wavelengths

To understand the role of the submm galaxies in galaxy formation and evolution we first have to determine the relative contributions to their extreme luminosities from AGN and starburst-powered emission. Hard X-ray observations can uncover the presence of a dominant AGN power source in even highly obscured sources, and hence provide a simple estimate of the AGN
fraction in the submm population. Unfortunately, even for high-redshift
sources, Chandra provides relatively poor hard X-ray response, and hence to-
date all the X-ray studies of submm galaxies have achieved is to confirm
the presence of modestly-obscured AGN in those galaxies in which optical
spectroscopy had already identified AGN emission. These galaxies ac-
count for 10–20% of the submm population, in-line with estimates from the
models of the X-ray background. Much more interesting limits on the
fraction of highly-obscured AGN in this population will come from Newton
observations. Equally useful constraints on the fraction of obscured AGN
and the breakdown of AGN- versus starburst-powered emission in individual
galaxies will come from high-resolution, mid-infrared observations (using OS-
CIR or Michelle on Gemini) which are sensitive to emission from hot-dust
and PAHs. However, we conclude that, on present evidence, it seems safe
to assume that the majority of the emission from the submm population is
powered by star formation.

6 The relationship between FIR- and UV-selected galaxies

Finally, we briefly discuss the relationship of submm galaxies to other classes
of high-redshift sources. Recently it has been claimed that UV- and optically-
selected galaxy samples at $z \sim 0–3$ can completely account for the extragalac-
tic background, not only in the optical/UV, but also in the far-infrared and
submm. This calculation relies upon the correction of the UV luminosities
of these samples for the effects of dust extinction, using a correlation between
reddening (measured through the spectral slope in the UV) and UV luminos-
it from observations of normal galaxies at low redshifts. Unfortunately, as
was graphically illustrated at this conference, this correlation doesn’t hold
(even locally) for galaxies with bolometric luminosities typical of the popula-
tion we have found at higher redshifts which dominate the submm counts and
produce the bulk of the COBE background. This clearly calls into question
the reliability of this type of calculation.

The argument that UV-selected samples can provide a complete picture
is supported using optical/UV and submm observations of an example of a
‘representative’ submm galaxy, SMM J14011+0252 (Fig. 3). However, this
galaxy is far from typical of the majority of the submm population – which
would be better described using the ERO, HR 10, as an archetype. Moreover,
even within the SMM J14011+0252 system it appears from interferometry
observations that the dominant bolometric component resides, not in the UV-
bright companion J2, but in the much redder galaxy J1. Using a UV-weighted
spectral slope (which has a substantial contribution from J2) in an attempt
to predict the unobscured star formation rate (which mostly occurs in J1) in this system seems questionable – why should the UV properties of J2 have any bearing on the degree of obscuration and star formation in J1?

Figure 3. These panels show two of the submm galaxies detected through the lensing cluster A 1835. The left-hand panels illustrate the morphology of the two components, J1/J2, of the z = 2.55 starburst galaxy SMM J14011+0252, from the U- to K-bands. The central panel gives a zoomed view of the WFPC2 R-band image of this galaxy, demonstrating the complex, merger-like morphology of the bolometrically-dominant component J1. The right-hand panels show R- and K-band views of a more typical submm galaxy, SMM J14009+0252, for which a very faint near-infrared companion, J5, has been identified. This galaxy is clearly undetected in the deep HST R-band exposure. The major tickmarks are every 5″, except for the central panel where they are every 1″.

Instead, if we adopt HR 10 as a template for a typical submm galaxy then we find that: as HR10 has a far higher ratio of far-IR to far-UV luminosity than the other galaxies considered it would not be included in UV-selected surveys despite its large star formation rate. We conclude therefore that UV light is an inappropriate tracer of star formation in the highly-obscured galaxies that contain a large fraction of the star formation in the high-redshift universe. Further study of this remarkable population is essential for a complete understanding of the formation of massive galaxies.

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