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High-redshift, Restframe Far-infrared Selected Galaxies

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Abstract. I discuss our current understanding of the properties and nature of high redshift, far-infrared luminous galaxies selected through their observed-frame submillimeter emission.

1. Introduction

The first high-redshift galaxies identified from their restframe far-infrared emission were detected in 1997 using the SCUBA submillimeter camera on the JCMT. There are now a few hundred such sources identified by SCUBA at 850μm, and at $\sim 1100\mu$m using MAMBO on the IRAM 30-m, Bolocam on the Caltech Submillimeter Observatory and recently with AzTEC on the JCMT.

To begin with we need to decide what is a submillimeter galaxy. Clearly all extragalactic sources emit some radiation in the submillimeter waveband, yet sensibly we wouldn't define them all as "submillimeter galaxies". So, for simplicity, we take a submillimeter galaxy to be a system where the luminosity emitted in the submillimeter waveband (corresponding to the restframe far-infrared for high-redshift galaxies) is a very significant fraction of the total luminosity.

As a benchmark, we note that a source with an observed 850-μm flux of $\sim 5\,$mJy corresponds to a UltraLuminous InfraRed Galaxy (ULIRG) with an infrared luminosity of $L_{IR} \sim 7 \times 10^{12} L_\odot$ if it has a canonical dust temperature of $T_d = 40\,$K and dust emissivity $\beta = 1.5$ and lies at $z \sim$ 1–6 (the negative K correction at 850μm results in an almost constant apparent flux–luminosity relation over this redshift range). Even if such a system had a restframe optical luminosity comparable to a present-day L^* galaxy, the far-infrared emission would still account for $> 90\%$ of the bolometric emission. Thus, as we will see, the definition of a submillimeter galaxy essentially corresponds to those systems which are detectable with current submillimeter and millimeter cameras.

In the future, the collecting area and resolution of ALMA will enable us to detect large numbers of very much less luminous submillimeter sources – but most of these will correspond to the far-infrared emission from "normal" galaxies, rather than the far-infrared-dominated, submillimeter galaxy population discussed here. Equally it can be seen that using this definition of a submillimeter galaxy means that understanding the energy source responsible for the submillimeter emission is crucial for understanding their total energetics.

Having made this definition, our first step in understanding what submillimeter galaxies are is to construct their number counts. Even with the handful of sources detected in the initial two maps, it was clear that the number counts

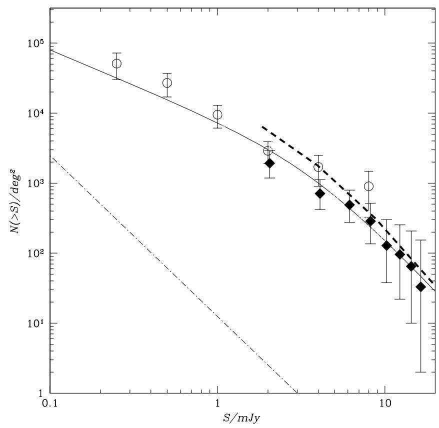

Figure 1. The cumulative number counts of submillimeter sources detected at 850μm adapted from a recent compilation by Borys et al. (2003). The bright counts come from the HDF Supermap of Borys et al. (2003, 2004) and the faint counts are from the lens survey of Smail et al. (2002). As the counts are cumulative, the data points are correlated and the error-bars are simply Poisson and so they are likely to underestimate the fluctuations in number counts due to clustering. The solid line is the two-power-law count model of Borys et al. (2003) and the dot-dashed line is the predicted number counts based on an unevolving luminosity function for submillimeter galaxies derived from *IRAS* – which falls two to three orders of magnitude short of the observed surface density. We also show, as a thick dashed line, an evolutionary model which gave the best-fit to the first number counts of the submillimeter population from Smail et al. (1997). This invokes luminosity evolution of the local *IRAS* population increasing as $(1+z)^3$ to $z = 2.6$ — close to the behaviour now believed to best explain this population (Chapman et al. 2005).

of these sources are far in excess of those predicted assuming no-evolution of the local far-infrared luminosity function (Fig. 1; Smail et al. 1997). Robust counts can now be constructed from a combination of wide/shallow (e.g. Borys et al. 2003; or the recently-finished SHADES survey, Mortier et al. 2005; Coppin et al. 2006; Ivison et al. 2006) and deep/narrow surveys (e.g. Hughes et al. 1998; Blain et al. 1999a; Cowie et al. 2002; Knudsen et al. 2006), with the deepest of the latter exploiting the amplification by gravitational lensing from massive galaxy clusters to probe beyond the confusion limit (the 850-μm confusion limit of the JCMT is ~ 2 mJy). As Fig. 1 demonstrates, the number densities at a few mJy are some three orders of magnitude above the no-evolution predictions. Such an excess suggests very strong redshift evolution in this population (Blain et al. 1999b). As Chapman et al. (2003a, 2005; see §2) demonstrate, the majority of these sources lie at high-redshifts and hence based on their apparent submillimeter fluxes they are ULIRGs, a population which contributes a negligible fraction, $\ll 1\%$, of the total luminosity density at the present-day (Takeuchi et al. 2005). Yet the strong evolution in the submillimeter number counts shows that similarly far-infrared-bright galaxies must be a much more important component of the galaxy population at high redshifts.

The submillimeter counts from current surveys cover only a narrow range in flux: a mere two decades from ~ 20 mJy down to ~ 0.2 mJy (Fig. 1). These cumulative counts hint at a change in the slope somewhere in the range ~ 2–

5 mJy, with a shallower slope at fainter fluxes. This roughly corresponds to the confusion limit of blank-field maps and raises the concern that this feature arises from problems matching the blank field and lens survey results. We note that similar problems do not occur in surveys of Extremely Red Objects using identically-constructed lens models (Smith et al. 2002; McCarthy 2004) and so this feature is probably real. The change in slope in the integrated submillimeter counts indicates an even sharper break exists in the differential counts – with a very strong flattening of the counts below ~ 3 mJy. This behaviour suggests a potential difference in the nature of the submillimeter galaxy population at the sub-mJy and mJy levels. Indeed, the form of the cumulative counts is even consistent with a peak in the differential counts at fluxes around 2–5 mJy, which might have bearing on the suggestion that there is a dearth of high-redshift sources with submillimeter fluxes of a few mJy (Pope et al. 2005).

One reason for believing the break is real is that there *must be* a flattening in the slope of the counts at faint fluxes if their integrated flux density is to remain consistent with the total flux in the submillimeter background measured by *COBE*. The deepest counts (adopting the shallow slope in Fig. 1) suggest that up to 80% of the background may already be resolved by ~ 0.5 mJy (Smail et al. 2002) leaving little opportunity for increasing the number counts at this depth. More importantly, this result demonstrates that the bulk of the submillimeter background arises from galaxies where the far-infrared emission is likely to be either bolometrically dominant or, at the least, very important – justifying the definition of a submillimeter galaxy as an unique and important population.

2. Redshifts for Submillimeter Galaxies

Having determined the surface density of submillimeter galaxies and their contribution to the background at this wavelength, the next questions which arise are: i) what are their redshifts; ii) what are their dynamical and stellar masses; iii) what are their power sources?

It was clear from the earliest identification of submillimeter sources that determining the correct counterparts in the optical/near-infrared was going to be the rate-limiting step in making progress on the question of their redshift distribution (Barger et al. 1999). The first, and so-far most successful, approach has been to identify counterparts in the radio waveband (Ivison et al. 1998; Smail et al. 2000). This relies on the observationally well determined far-infrared–radio correlation for star-forming galaxies (Helou et al. 1985) which implies that almost all bright, $\gtrsim 5$ mJy at 850-μm, submillimeter galaxies at $z < 3$–4 will show radio counterparts brighter than a few μJy at 1.4 GHz (Chapman et al. 2001). There are two drawbacks with this technique: i) sensitivities of a few μJy are difficult to achieve with the VLA – with typical 4-σ limits more usually being a few 10's μJy (e.g. Ivison et al. 2002), and ii) that some fraction of submillimeter sources could lie at very high redshifts, $z \gg 3$, and will be missed in the radio due to the difference in the K corrections in the radio and submillimeter (Fig. 2).

Both of these problems are shared to various degrees with the other main technique used to identify the counterparts to submillimeter sources: using extreme or unusual colors in the optical, near-infrared or mid-infrared (Smail et al. 1999, 2002; Webb et al. 2003; Pope et al. 2006). For this reason the identification rates for any individual technique is rarely better than ~ 70–80%, with

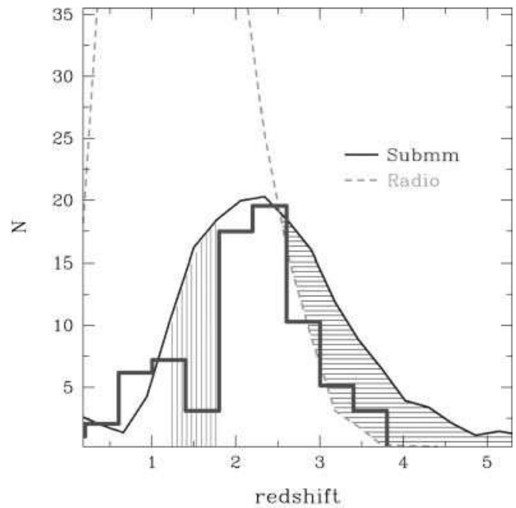

Figure 2. The histogram of the spectroscopic redshift distribution of submillimeter galaxies from Chapman et al. (2005), showing a sharply peaked distribution with a median redshift of $z = 2.2 \pm 0.5$ and a tail out to $z = 3.6$. The solid curve shows an evolutionary model from Blain et al. (2002) which describes our best estimate of the redshift distribution of the full > 5 mJy submillimeter galaxy population. There are two differences between this and the measured distribution which reflect the sample selection. Firstly, the dashed curve illustrates the likely selection boundary for our radio flux limit of 30μJy using a family of spectral energy distributions (SEDs) tuned to reproduce the distribution of submillimeter to radio flux limits (Chapman et al. 2003b, 2005). The horizontal shaded region between this and the submillimeter sample curve represents those $\sim 30\%$ of submillimeter sources which are below our radio detection limit, these lie predominantly at $z > 2.5$. The sample also suffers some spectroscopic incompleteness (vertical shading) at $z \sim 1.5$ due to the dearth of strong features in the bandpass of the spectrograph.

significant overlap between the identified sources, leaving open the possibility of a tail of high redshift sources (Aretxaga et al. 2003). However, we also have to recognise the low-significance of the typical sources in submillimeter catalogs (3–4σ), which may mean that some fraction (most?) of the unidentified sources are simply spurious, thus reducing the number of potentially high redshift sources (Greve et al. 2004).

The physical basis for the radio-identification route is the most robust of any of the approaches, relying on the direct link between the activity powering the submillimeter and radio emission, it therefore unequivocally provides the position of the submillimeter source. In contrast, it is difficult (without additional observations) to prove that the photometric identifications techniques are doing anything more than finding galaxies which are associated with the submillimeter source – but are not coincident with it. This distinction is important when we try to investigate their physical properties in detail.

Chapman et al. (2003a, 2005) present the results of the first large-scale redshift survey of submillimeter galaxies. This survey uses radio counterparts to localise the submillimeter source, with subsequent optical spectroscopy using the LRIS spectrograph on Keck. Radio counterparts are detectable for $\sim 70\%$ of submillimeter sources at the depth of this survey ~ 5 mJy (Ivison et al. 2002), with the subsequent spectroscopy being roughly $\sim 75\%$ complete (due to the high frequency of strong emission lines in the restframe UV spectra of submillimeter galaxies). The median redshift for the 73 galaxies in the final sample is $z = 2.2$, with a distribution which is well-described by the expected selection function (Fig. 2). On the basis of this, we expect that the underlying submillimeter population has a median of $z = 2.3$ (Chapman et al. 2005).

With precise redshifts for these submillimeter sources we can use their measured 850-μm and 1.4-GHz fluxes, along with the far-infrared–radio correlation, to derive their characteristic dust temperatures and bolometric luminosities. We have confirmed the reliability of these estimates using 350 μm observations of a subset of the sources with SHARC-2 on the CSO (Kovacs et al. 2006). The typical submillimeter galaxy in the Chapman et al. (2005) sample has a infrared luminosity of $L_{IR} = 8 \times 10^{12} L_\odot$ and a temperature of $T_d \sim 38$ K. The flux limit of the radio data means we start to miss the cooler sources at $z > 2.5$ and can detect only the hottest sources ($T_d > 45$ K) at $z > 3$. Hence of the $\sim 30\%$ of the > 5 mJy submillimeter population which lack radio counterparts brighter than $\sim 30\mu$Jy, we expect that roughly half lie within our sample volume, but are slightly colder than our typical galaxy, and the other half are comparable sources at somewhat higher redshifts – meaning $\lesssim 10\%$ of bright submillimeter galaxies are likely to be at $z \gg 3$. A recent analysis of submillimeter sources in the GOODS-N using photometric identifications confirms this – indicating that the radio-identified submillimeter sample is representative of the bulk of the population (Pope et al. this volume; but see also Knudsen et al. this volume). In part this may explain the modest overlap between submillimeter galaxies and Lyman-break galaxies at $z \sim 3$ (Chapman et al. 2000).

3. The Astrophysics of Submillimeter Galaxies

Masses. The critical advantage of the submillimeter sample from Chapman et al. (2005) is the availability of precise and unambiguous redshifts for these galaxies. To gauge the dynamical properties of submillimeter galaxies we use observations of the Hα emission line – which is bright and relatively unaffected by the obscuration in these dusty galaxies. The complication is that at the redshifts of the submillimeter galaxies the Hα emission line is redshifted in to the near-infrared (H- or K-bands). The combination of limited wavelength coverage of typical spectrographs and high backgrounds then make blind searches for Hα emission from submillimeter galaxies observationally challenging (e.g. Simpson et al. 2004). Nevertheless, with precise UV redshifts for a large sample of bright submillimeter galaxies it is possible to efficiently target their Hα emission using both long-slit observations (Swinbank et al. 2004), as well as more powerful integral-field studies (Swinbank et al. 2005, 2006). These observations give both estimates of the line width from individual sources and the relative velocities between components (frequently seen in these merging systems). These provide rough estimates of the masses within the central ~ 10 kpc of a typical submillimeter galaxy of $\sim 2 \times 10^{11} M_\odot$ (Swinbank et al. 2004, 2006). These are some of the most massive galaxies present at $z \sim 2$–3.

These mass estimates are confirmed by observations of the dynamics of the cold gas within the systems – through its CO emission in the millimeter waveband (Greve et al. 2005; Tacconi et al. 2006). The relatively narrow-band widths of correlators on millimeter interferometers means that this test can

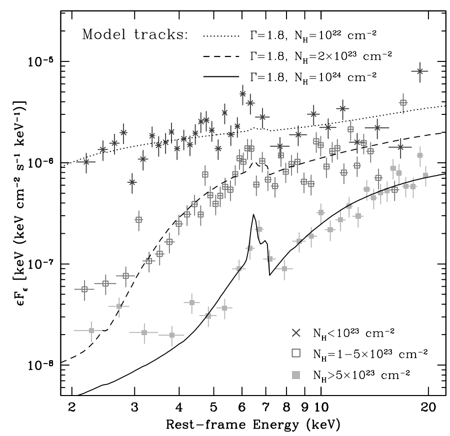

Figure 3. The combined restframe X-ray spectra for three samples of submillimeter galaxies using data from the 2-Ms *Chandra* observations of the CDF-N, from Alexander et al. (2005b). The galaxies have been grouped according to their X-ray colors, used to infer their likely absorbtion (N(HI) $< 10^{23}$, 1–5×10^{23} and $> 5 \times 10^{23}$), and then coadded – yielding spectra with cumulative integration times of 12 Ms each. The spectra show the Fe Kα emission line and have continuum slopes which are well-described by models of absorbed AGN (overplotted lines), giving us confidence that the estimates of the HI columns are reliable. These can then be used to correct the observed X-ray luminosities of the AGN to determine their intrinsic luminosities.

only be applied where we have very precise redshifts. The CO observations also constrain the gas mass of the systems – showing that roughly 25% of the dynamical mass in this region is contributed by the cold gas.

To determine what the total mass of baryons is within these galaxies we need to add the contribution from stars to that measured from the gas. We can do this by using the near- or mid-infrared observations to estimate the restframe V- or K-band luminosities and then adopt M/L appropriate to their stellar populations to convert these to masses. Smail et al. (2004) used IJK photometry to derive a median reddening-corrected V-band luminosity of $2 \times 10^{11}\mathrm{L}_\odot$, assuming a reddening of $\mathrm{A}_V \sim 2.5$ consistent with the restframe optical colors, from a large sample of submillimeter galaxies. Adopting an $\mathrm{M/L}_V \sim 0.15$ typical of a $\sim$ 100's Myr-old starburst then gives a stellar mass of $\mathrm{M}_* \sim 3 \times 10^{10}\mathrm{M}_\odot$ – similar to the cold gas masses – but with a considerable uncertainty. These estimates are very sensitive to the adopted reddening and the age of the stellar population. For that reason it is preferable to use the restframe near-infrared luminosity of the galaxies, accessible through mid-infrared observations with IRAC on-board *Spitzer*. Borys et al. (2005) presented such an analysis for a smaller sample of submillimeter galaxies in the GOODS-N – obtaining significantly higher masses – $2 \times 10^{11}\mathrm{M}_\odot$. This implies that the majority of the mass in the central regions of submillimeter galaxies is in baryons, as is the case for the similar regions of massive local elliptical galaxies. Confirmation of this result using more detailed modelling of a larger mid-infrared sample is urgently needed. Unfortunately, the complex mix of obscuration and contributions from stellar and non-thermal emission make this a challenging problem.

Power source. The typical bolometric luminosity of a submillimeter galaxy from the Chapman et al. (2005) sample, $8 \times 10^{12} L_\odot$, corresponds to an immense star formation rate of 0.1–100 $M_\odot$ stars: $\sim 2 \times 10^3\, M_\odot\, yr^{-1}$ (adopting a Salpeter initial mass function). The restframe far-infrared luminosity is dominated by the most massive stars and hence it is fairer to set a firm lower limit to the star formation rate of $\gtrsim 300\, M_\odot\, yr^{-1}$, counting only those stars more massive than $\sim 5\, M_\odot$. However, this is only a true if the bulk of the far-infrared emission is powered by star formation. Similarly, the conversion in the previous section of the restframe optical/near-infrared luminosities to yield stellar masses also implicitly assume that the bulk of the continuum emission in these bands comes from stars. Borys et al. (2005) demonstrate that this is a reasonable assumption for the restframe near-infrared emission in $\sim 75\%$ of submillimeter sources.

There is clear evidence though that many submillimeter galaxies host active galactic nuclei (AGN), from either their UV or restframe optical spectra (Chapman et al. 2005; Swinbank et al. 2004). Is it possible that these AGN are significant contributors to the immense bolometric luminosities, reducing the need for extreme star formation rates in these galaxies.

The most reliable tracer of the intrinsic luminosity of the AGNs in these galaxies is their hard X-ray emission. In particular, for the spectroscopically-identified submillimeter galaxies in the CDF-N we can exploit the unparalleled depth of the 2-Ms *Chandra* X-ray observations (Alexander et al. 2003) to constrain their X-ray luminosities. Alexander et al. (2005a) present the X-ray properties of these submillimeter galaxies, showing that their rate of detection in the X-ray waveband, 70% have counterparts, is significantly higher than any other known $z \sim 2$ galaxy population, indicating a close link between the far-infrared activity and AGN fueling, and hence supermassive black hole (SMBH) growth, in these systems. Building upon this result, Alexander et al. (2005b), construct restframe X-ray spectra for subsamples of the submillimeter galaxies classified on the basis of their X-ray colors (Fig. 3) which demonstrate that the X-ray emission from these galaxies is well-described by moderately absorbed power-law spectra, $\log N(HI) \sim 22$–24. Correcting the observed X-ray luminosities for this absorbtion indicates intrinsic luminosities of $L_X(0.5\text{–}8\,\mathrm{keV}) \sim 6 \times 10^{43}\,\mathrm{erg\,s^{-1}}$. Assuming a standard bolometric correction for QSOs (Elvis et al. 1994), this corresponds to a bolometric luminosity of the AGN of $3 \times 10^{11} L_\odot$, or just $\sim 4\%$ of the total luminosity of these galaxies. Thus the X-ray observations confirm that the bulk of the far-infrared emission from submillimeter galaxies arises from star formation at rates of 100's to 1000's $M_\odot\, yr^{-1}$.

4. Conclusions

Submillimeter galaxies with fluxes of a few mJy appear to be uniquely associated with the most active phase of galaxy formation in the history of the Universe. A spectroscopic survey of an unambiguously located sample of submillimeter sources shows that their median redshift is $z \sim 2.3$. While these galaxies frequently have an active nucleus (or two, Alexander et al. 2003), a detailed X-ray analysis indicates that these AGN likely contribute $\lesssim 10\%$ of the bolometric emission – the remainder is powered by star formation. The precise redshifts for this sample have also allowed us to use other tools to study their dynamics

– confirming that these are massive galaxies whose central regions are baryon-dominated with significant stellar and gas masses.

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References

Alexander, D.M., et al., 2003, AJ, 126, 539
Alexander, D.M., et al., 2005a, Nature, 434, 738
Alexander, D.M., et al., 2005b, ApJ, 632, 736
Aretxaga, I., et al., 2003, MNRAS, 342, 759
Barger, A.J., et al., 1999, AJ, 117, 2656
Blain, A.W., et al., 1999a, ApJ, 512, L87
Blain, A.W., et al., 1999b, MNRAS, 302, 632
Blain, A.W., et al., 2002, Phys. Rep. 369, 111
Borys, C., et al., 2003, MNRAS, 344, 385
Borys, C., et al., 2004, MNRAS, 355, 485
Borys, C., et al., 2005, ApJ, 635, 853
Chapman, S.C., et al., 2000, MNRAS, 319, 318
Chapman, S.C., et al., 2001, ApJ, 548, L147
Chapman, S.C., et al., 2003a, Nature, 422, 695
Chapman, S.C., et al., 2003b, ApJ, 588, 186
Chapman, S.C., et al., 2005, ApJ, 622, 772
Coppin, K.E.K., et al., 2006, in prep
Cowie, L.L., et al., 2002, AJ, 123, 2197
Elvis, M., et al., 1994, ApJS, 95, 1
Greve, T., et al., 2004, MNRAS, 354, 779
Greve, T., et al., 2005, MNRAS, 359, 1165
Helou, G., et al., 1985, ApJ, 298, L7
Hughes, D.H., et al., 1998, Nature, 394, 241
Ivison, R.J., et al., 1998, MNRAS, 298, 583
Ivison, R.J., et al., 2002, MNRAS, 337, 1
Ivison, R.J., et al., 2006, in prep
Knudsen, K., et al., 2006, this volume
Kovacs, A., et al., 2006, ApJ, submitted
Mortier, A., et al., 2005, MNRAS, 363, 509
McCarthy, P., 2004, ARAA, 42, 477
Pope, A., et al., 2005, MNRAS, 358, 149
Pope, A., et al., 2006, this volume
Simpson, C., et al., 2004, MNRAS, 353, 179
Smail, I., et al., 1997, ApJ, 490, L5
Smail, I., et al., 1999, MNRAS, 308, 1061
Smail, I., et al., 2000, ApJ, 528, 612
Smail, I., et al., 2002, MNRAS, 331, 495
Smail, I., et al., 2004, ApJ, 616, 71
Smith. G.P., et al., 2002, 330, 1
Swinbank, A.M., et al., 2004, ApJ, 617, 64
Swinbank, A.M., et al., 2005, MNRAS, 359, 401
Swinbank, A.M., et al., 2006, ApJ, submitted
Tacconi, L., et al., 2006, ApJ, 640, 228
Takeuchi, T.T., et al., 2005, A&A, 440, L17
Webb, T.M.A., et al., 2003, ApJ, 597, 680