The evolution of submillimetre galaxies: two populations and a redshift cut-off

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Abstract

We explore the epoch dependence of number density and star-formation rate for submm galaxies found at 850\,µm. The study uses a sample of 38 submm galaxies in the GOODS-N field, for which cross-waveband identifications have been obtained for 35/38 members together with redshift measurements or estimates. A maximum-likelihood analysis is employed, along with the ‘single-source-survey’ technique. We find a highly significant diminution in both space density and star formation rate at \( z > 3 \), closely mimicking the redshift cut-offs found for QSOs selected in different wavebands. The data further indicate that two separately-evolving populations are present, with distinct luminosity functions. These results parallel the different evolutionary behaviours of LIRGs and ULIRGs, and represent another instance of ‘cosmic down-sizing’.

Key words: galaxies: starburst – galaxies: evolution – galaxies: luminosity function – submillimetre – methods: statistical

1 INTRODUCTION

'Submm galaxies' (SMGs) represent a major population of massive star-forming galaxies (e.g. Hughes et al. 1998; Blain et al. 2002). Found in limited-area sky surveys at 850\,µm with the Submm Common-User Bolometric Array (SCUBA; Holland et al. 1999) on the James Clerk Maxwell Telescope, they are believed to be dust-enshrouded starbursts, with the dust heated by UV radiation from young stars. They may be the distant early equivalents of the local prodigious star-formers, the ULIRGs and LIRGs (‘Ultra-Luminous IR Galaxies’, ‘Luminous IR Galaxies’, Sanders & Mirabel 1996). SMGs appear to carry much of the star-formation rate density (SFRD) of the early Universe on their shoulders. Understanding these objects is thus fundamental to our understanding of galaxy formation. Several attempts have been made to track their contribution to the global SFRD as a function of epoch (e.g. Lilly et al. 1999; Chapman et al. 2003). These efforts have been hampered by incomplete cross-waveband identifications and hence incomplete redshifts. Recently, Pope et al. (2005, 2006) succeeded in identifying 35 out of a sample of 38 SMGs from the SCUBA survey in the GOODS-N field, and secured redshift estimates for all identifications. It is the object of this paper to use this sample to form a picture of the space density of these SMGs, and of the epoch-dependence of both their space density and the corresponding SFRD.

The distinctive feature of the spectral energy distributions of SMGs is the dominance of the cold-dust spectrum, approximately that of a \( \beta \approx 1.5 \) greybody at 35 K, peaking (rest frame \( \nu L_\nu \)) at frequencies near 3200 GHz, wavelengths near 90\,µm. Such a spectrum implies that the K-correction is generally negative (i.e. we ascend the Rayleigh-Jeans tail as the object moves to higher redshifts), and that there is nothing to stop such objects being visible out to redshifts of 5 or more (e.g. Blain & Longair 1993). In fact we know that the redshift distribution peaks at \( \sim 2.2 \), with little high-redshift tail beyond 4 (Chapman et al. 2003; Pope et al. 2006), so that there is qualitative evidence for a redshift diminution at early epochs. One of the aims of this paper is to quantify this diminution.

The wide-spread phenomenon of ‘cosmic down-sizing’ appears to be at variance with the modern picture of hierarchical build-up of galaxies. In cosmic down-sizing, the dominant activity becomes carried by more numerous, lower-luminosity, lower-mass objects at progressively later times. The ‘down-sizing’ (Cowie et al. 1996) originally described how dominant star formation in galaxies shifted from luminous rare galaxies at earlier epochs to more numerous and less luminous galaxies at recent epochs. The concept has been familiar in the radio-AGN literature for 40 years, under the guise of ‘differential evolution’ (Longair 1966). In addition to star formation and radio AGN activity, cosmic down-sizing is known to apply to X-ray QSOs (Ueda et al. 2003) and ULIRGs+LIRGs (Pérez-González et al. 2005; Le Floc’h et al. 2005; Chary 2006). This paper examines...
whether the concept further extends to SMGs and the ‘cold dust’ star formation rate (SFR) associated with them.

2 THE SUBMILLIMETRE SAMPLE

Currently, the largest SMG sample which is almost completely identified is from the GOODS-N field; all SCUBA data from several extensive imaging campaigns in the GOODS-N field have been combined into one 850-µm map, referred to as the ‘supermap’ (see Borys et al. 2003 and references therein). This supermap has noise properties that vary strongly with position, but this can be accounted for in the source extraction procedure. The most recent published version of the supermap contains 35 850-µm sources detected above 3.5σ and satisfying a flux 'de-boosting' threshold (Pope et al. 2006). The inclusion of additional twobolometer chopping photometry data in the supermap has resulted in three new 850-µm sources. The changes to the supermap as a result of these new data and the identifications of these three sources will be described by Pope et al. (in preparation).

Using the multi-wavelength data available in GOODS-N, likely counterparts were found for 35 preparation). The inclusion of additional twobolometer chopping photometry data in the supermap has resulted in three new 850-µm sources. The changes to the supermap as a result of these new data and the identifications of these three sources will be described by Pope et al. (in preparation).

Using the multi-wavelength data available in GOODS-N, likely counterparts were found for 35/38 of the submm sources. The extensive optical and infrared data yielded reliable photometric redshifts in the absence of spectroscopic redshifts (Pope et al. 2006); 17 of the sample have spectroscopic redshifts and the remaining 18 have photometric redshift estimates. This sample of 35 objects is the basis for the following analysis of space density. Throughout we use a concordance cosmology with Ω_{m} = 0.3, Ω_{β} = 0.7 and h = 0.7.

3 EXPLORING SPACE DISTRIBUTION

For each galaxy, we calculated the specific submm luminosity (at rest frame, 850 µm) using only the 850-µm flux and the redshift, and assuming a greybody spectral energy distribution with emissivity β = 1.5 and dust temperature T = 35 K. While there will be some scatter in T and β, these values provide a good description of the data as found in a number of submm surveys (Chapman et al. 2005; Kovács et al. 2006; Pope et al. 2006).

The objects are shown in a luminosity–redshift (L–z) plot in Fig. 1. It is clear from this figure that some standard luminosity function analyses will not work. The unique geometry means that the 1/V_{max} method in particular is problematic, because most sources ‘see’ no survey limit. Moreover, beyond establishing the reality of evolution or otherwise, the 1/V_{max} method is poorly suited to small samples. We therefore adopt a maximum-likelihood approach, as first advocated by Marshall et al. (1983) and used recently in the detailed analysis of X-ray QSOs by Ueda et al. (2003).

Thus, consider the sample as a single homogeneous set of i objects, for which ρ(z, L)(dV/dz)dz dL is the number in volume element (dV/dz)dz in luminosity element dL. The sky fraction Ω_{i}(z, L) accessible to each object i is unique – each of our objects is: (a) observable over an area of different physical size; and (b) has its own flux-density limit line in the L–z diagram. This factor Ω_{i}(z, L) is thus essential in introducing the feature of the single-source-survey

Figure 1. The L–z plane for all 35 SMGs. The curved lines represent the 35 different survey cut-offs for these objects; every one of the objects lies above its cut-off line and these cut-off lines differ because of the great differences in local noise properties. Dividing the sample at the median value in log(L) (see ), black lines/dots represent the lower-luminosity objects; red lines/dots represent the higher-luminosities, and dot size is representative of log(L). Note the remarkable form of these cut-off lines, so dissimilar to more familiar optical or radio survey limit lines. Some of these objects can be seen out to effectively infinite redshifts because of the inverse K-correction. This plot already suggests the basic result – a dearth of luminous sources below z ≃ 1.5 and a dearth of weaker sources above z ≃ 3.

(Wall et al. 2005) by which each object is treated as having unique access to the L–z plane (Fig. 1). The treatment is analogous to the final survey having been done as 35 individual surveys finding a single source each. The unique area accessible to each object on the L–z plane is multiplied by its unique effective survey area to determine the final value of its Ω(z, L). This effective survey area is a function solely of flux density, with the relation as determined by Blake et al. (2002).

The L(likelihood) function for the i object is the probability of observing one object in its (dz, dL) element times the probability of observing zero objects in all other (dz, dL) elements accessible to it. The Poisson model is the obvious one for the likelihood:

$$f(x : μ) = \frac{e^{-μ} μ^x}{x!}$$

where μ is the expected number. If x = 1, the function is μe^{-μ}, if x = 0 it is e^{-μ}.

With ρ(z, L) as the full description of space density, μ = λ(z, L) dz dL, for λ = ρ(z, L)Ω(z, L)(dV/dz).

Hence

$$L = Σ_i Ω(z_i, L_i) dz dL e^{-λ(z_i, L_i)} dz dL \cdot Σ_{j \neq i} e^{-λ(z_j, L_j)} dz dL$$

where i denotes the elements of the (z, L) plane in which SMGs are present and j denotes all others. From this, if S = −2 \ ln L, then

$$S = -2 Σ_{i=1}^{N} \ln ρ(z_i, L_i) + Σ_{i=1}^{N} \int L Ω(z, L) \frac{dV}{dz} dz dL + \text{constant}.$$
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Figure 2. The single-source-survey technique: the $L - z$ plane for one member of the sample (plotted as a dot). The curve represents its own survey cut-off, and in this instance the calculation of space density (see text) is for a redshift range 1.5 to 2.5. The function $\Omega_i(l, z)$ is shown as the green area, over which it has a constant value equal to the individual area relevant to the single source (see text); the function is zero (red) elsewhere.

form $\rho(L, z) = \rho(z=0, L) \cdot \phi(z)$. In this formulation we adopt a power-law luminosity function,

$$\frac{dN}{dL} = \frac{\rho_0}{L^*} \phi(z) \left( \frac{L}{L^*} \right)^{-\alpha}. \quad (5)$$

With $l \equiv L/L^*$, we have the local luminosity function as $\rho(z=0, L) = \left( \frac{\rho_0}{L^*} \right) l^{-\alpha}$. For the evolution function we again adopt a power-law, $\phi(z) = (1 + z)^k$.

If we substitute these assumptions into equation 4 and set the derivative with respect to $\rho_0$ to zero, we get a maximum-likelihood estimate for $\rho_0$:

$$\rho_0 = \frac{N}{\sum_{i=0}^{N} \int_z \int_l (1 + z)^k l^{-\alpha} \Omega_i(z, l) \left( \frac{\partial V}{\partial z} \right) dz dl} \quad (6)$$

Putting this back into equation 4 gives

$$S = -2 \sum_i^{N} \ln[(1 + z_i)^k l_i^{-\alpha}] + 2N \ln \left[ \sum_i^{N} \int_z \int_l (1 + z)^k l^{-\alpha} \Omega_i(z, l) \left( \frac{\partial V}{\partial z} \right) dz dl \right] + (2N - 2N \ln N). \quad (7)$$

Inspection of Fig. 1 shows immediately that a single-power-law function to describe density evolution will not work. The density of dots clearly rises with increasing redshift before $z = 2$ and falls after $z = 3$. Accordingly, we calculated the value of this likelihood function using a grid in $(k, \alpha)$ for slices in redshift, with results shown in Fig. 3. This figure shows that: (a) the slope of the luminosity function does not change drastically with redshift; and (b) $k$, the $(1 + z)$ exponent, changes from values around 5 at redshifts $< 1.5$, to about zero for $1.5 < z < 2.5$, to negative values at $z > 2.5$.

We then used this simple formulation of the evolution function as follows – ascribe zero evolution ($k = 0.0$) across individual small redshift slices, adopt a (best) single-valued power law for the luminosity function ($\alpha = 2.5$), and calculate the maximum-likelihood value of $\rho_0$, the normalization of this luminosity function in each slice. The results should roughly map space density with epoch, and are shown in Fig. 4.

This evolution of the luminosity function with redshift
was examined with a simple modification of the previous density evolution: replacing the original power of \((1 + z)\), namely \(k\), with the modified power \((k + \gamma z)\), i.e.

\[
\rho(L, z) = \rho_o(1 + z)^{(k+\gamma z)}L^{-\alpha}.
\]

There is as little physical justification for introduction of the \(\gamma z\) term in the exponent as there was for the assumption of the initial power law, or for the factorization. However, the term provides a generic description of redshift behaviour – if \(\gamma\) is negative, there is a roll-off in density toward higher \(z\).

The results are again shown in Fig. 4. The red curve is a minimization of the likelihood function \(S\) for all three parameters \(k\), \(\gamma\) and \(\alpha\), determined with a downhill simplex routine (Press et al. 1992). The maximum likelihood was found at \(k = 6.0 \pm 2.5\), \(\gamma = -1.2 \pm 0.4\), and \(\alpha = 2.5 \pm 0.3\). The curves describe the individual slice normalizations reasonably. The exponent of the initial rise \((k)\) is similar to those found in investigations of objects at other frequencies (radio and X-ray AGN; see e.g. Wall et al. 1980); the roll-off shows a maximum space density of the SMGs at about \(z = 2.0\), in accordance with the appearance of the \(L – z\) plane (Fig. 4).

Fig. 4 includes data from a bootstrap analysis; 100 end-to-end bootstrap results from the original sample of 35 objects are shown. Some 200 were done in all and none produced a value of \(\gamma\) approaching zero.

These results were stable against moderate changes of equivalent temperature with redshift (a potential concern because of our choice of rest-frame 850 \(\mu\)m as the luminosity measure). We tried for example a dependence of the form \(T(z) = 10(1+\alpha)K\) (Kovács et al. 2006), and the parameters resulting were \(k = 5.6 \pm 2.5\), \(\gamma = -1.1 \pm 0.4\), and \(\alpha = 2.4 \pm 0.3\), unchanged within the uncertainties. It thus appears that we are viewing predominantly density or luminosity evolution rather than spectral evolution.

Other forms of evolution were tried, in particular an exponential roll-off:

\[
\rho(L, z) = \rho_o(1 + z)^k \exp[-(z/z_n)^n]L^{-\alpha}.
\]

The best fit for \(n = 1\) (Fig. 4) light blue lines) gives a likelihood function markedly worse than that for the original form, while the best fits for \(n = 2\) and \(n = 3\) are close in likelihood value to the best fit for the original form. Fig. 4 shows why – these latter two forms are very similar, and are encompassed by the bootstrap results. Note, however, that these forms introduce a fourth parameter.

To consider how the three missing redshifts in the total sample of 38 objects might affect the reality of the cut-off, we adopted the most conservative position: we ascribed a redshift of 4.0 to each of the three unidentified sources in the complete sample of 38 objects. Running the minimization procedure for all 38 produced the result shown as the dotted line in Fig. 4. It is encompassed by the bootstrap trials; the missing redshifts do not change our conclusion. As a further conservative test, we ran the minimization for: (a) the 33/35 objects with secure (probability > 90 per cent) identifications; and (b) the 24/35 objects with redshift determinations from spectroscopy or other optical data. The resulting parameters do not differ significantly from those for the sample of 35 objects.

The interplay between the parameters \((\alpha, k, \gamma)\) can best be seen by marginalization over each of them in turn, a process to examine degeneracies. Fig. 5 shows the marginalized posterior probability density functions for pairs of the 3 parameters, assuming flat priors. The only degeneracy is the one anticipated – large values of \(k\) (steep initial evolution) require correspondingly large negative values of \(\gamma\) to ‘restore’ the space density to its observed low values at high redshifts. There is no significant dependence of the slope of the luminosity function on the evolution parameters. Marginalizing over all parameters to find the probability distribution of \(\gamma\) gives a clear indication of the need for a redshift cut-off to describe the data. This probability distribution is shown in Fig. 6. It indicates that the probability of \(\gamma\) being positive is essentially zero – the data demand a formulation of the evolving luminosity function which specifies a redshift cut-off.

Fig. 4 shows a comparison of the epoch behaviour of the luminosity function with the space-density dependence established for QSOs selected in different wavebands. The coincidence in form is remarkable.

The bootstrap results in this analysis indicate broad agreement with the simple adopted model, but do not inspire confidence in either the model details or the param-
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4 THE STAR FORMATION RATE

From the spectral assumptions of a greybody with $\beta = 1.5$ and $T = 35$ K, we calculated the total IR luminosity and converted it to star formation rate for each galaxy using the relationship for starburst galaxies given byKennicutt (1998). This ‘cold-dust’ SFR assumes aSalpeter (1955) initial mass function and applies to starbursts with ages less than 100 Myr. It also assumes little or no AGN contribution to the IR luminosity, a reasonably good assumption for SMGs. 

we are not including any contribution of warm dust and/or mid-IR spectral features to the IR luminosity – the values we use here are for the cold dust only, which is expected to dominate in these systems. Because of these and other systematic effects, our results will be difficult to compare in detail with SFRD derived from samples selected in other wavebands. Nevertheless, the results should give reasonable estimates for SFRD evolution, provided that the dust properties do not vary appreciably with redshift.

Dividing space up into redshift shells, the volume contribution for each galaxy was calculated from $\Delta V = V_{\text{max}} - V_{\text{min}}$, where $V_{\text{min}}$ is the lower redshift limit of the shell, and $V_{\text{max}}$ is either the shell upper redshift limit or the $V_{\text{max}}$ value determined from the redshift at which the galaxy encounters its individual survey limit line (Fig. 1) – whichever is smaller. Each galaxy then makes a contribution to the SFRD in the shell of $(\text{SFR}_i / \Delta V_i) \times (4\pi/A_i)$ where $A_i$ is the area of each ‘single-source-survey’, as described earlier. The result of such a calculation for redshift shells of $\Delta z = 0.6$ is shown in Fig. 8 – of course the results are not very different from a scaled version of Fig. 4.

Although these estimates are noisy, there is evidence from the plot that the SFRD from SMGs declines at redshifts beyond 3. Fig. 9 shows the points of Fig. 8 in comparison with numerous other recent estimates of the epoch dependence of star formation rate density.

5 TWO POPULATIONS

The unsatisfactory bootstrap results shown in Fig. 4 suggest non-Gaussianity and more specifically a dichotomy, indicating that we may be looking at two populations. This bootstrap structure is not the result of ‘preferred’ redshift estimates; applying significant Gaussian errors to the redshifts and re-running the bootstrap tests yielded the same appearance. The distribution suggests that the data have something more to tell us.

We therefore divided the sample of 35 at the median luminosity of $\log L_{850 \mu m} = 23.2$ and repeated the likelihood analysis for each subsample. The minimization routine yielded the results set out in Table 1.

The differences between the parameters for the subsamples strongly suggest the presence of two distinct populations. Although the individual parameters do not differ at
A global minimization solution of the likelihood function for each subsample using the maximum-likelihood parametric fit obtained for the other subsample. The respective differences for the low-luminosity sample and the high-luminosity sample were 25.6 and 19.0 in χ² for 3 degrees of freedom. This indicates rejection of the model for each subsample by the data of the other subsample, at the > 0.001 level of significance. In addition we ran 1000 bootstrap tests on each subsample to find how frequently the resultant model parameters overlapped those determined from the maximum-likelihood solution for other subsample. Considering for example the high-luminosity sample bootstraps, how many times out of 1000 would we find (see Table 1) α ≲ 2.1, k ≲ 5.3 and γ ≳ −1.3? In fact we found 0/1000, and for the low-luminosity sample we found 3/1000. This test again indicates a difference between the subsample models at a significance level of about 0.001. (Note that these tests are valid only because we split our sample into high and low-luminosity subsamples a priori, i.e. without optimization.)

The single-dimensional distribution of SMG luminosities shows no strong indication of a dichotomy. However, this is not an argument against the presence of two populations; samples of 100s of radio sources likewise show no clear dichotomy in the luminosity distribution, despite the known presence of low-luminosity and high-luminosity populations, largely distinct in morphology and evolving very differently (Dunlop & Peacock 1990; Jackson & Wall 1999; Sadler et al 2000). Beyond the inevitable correlations of flux...
and luminosity with redshift, Pope et al. (2006) found no additional correlations of spectral properties with redshift.

Finally, we carried out the star-formation-rate calculation individually for the two subsamples. The procedure as described in §4 was followed, with the results appearing in Fig. 12. The diagram shows that the star-formation rate dependence on epoch differs for the two sub-populations, the SFRD peaking around $z \sim 1.5$ for the lower luminosities and around $z \sim 2.5$ for the higher luminosities. Of course this result is not at all independent of the different forms of

SMG volume-density evolution found for the two subsamples (Table I and Fig. 10).

6 DISCUSSION AND CONCLUSIONS

We have shown that there is a significant decline in the space density of SMGs beyond a redshift of 3. Bootstrap testing plus the investigation of different forms for the evolution add weight to this conclusion.

Several authors (e.g. Sanders et al. 1988, Genzel et al. 1998, Archibald et al. 2002, Stevens et al. 2003, Di Matteo et al. 2005) have suggested a connection between the formation of powerful QSOs and ULIRGs (or their high-z counterparts the SMGs). A popular picture has emerged of an evolutionary sequence in which the forming galaxy is initially far-infrared luminous but X-ray weak, similar to the sources discovered as SMGs. As the black hole and spheroid grow with time, a point is reached when the central QSO becomes powerful enough to terminate the star formation and eject the bulk of the fuel supply. This transition is followed by a period of unobscured QSO activity, subsequently declining to leave a quiescent spheroidal galaxy. Such a scenario is consistent with our results, in which we find remarkable concordance between the space density decline shown by the SMGs, by all types of QSOs and by the SFRD from SMGs. Examining the significance of any time-lag is beyond the capabilities of the present data, but at minimum the data emphasize the strong connection between SMGs, AGN activity and SFRD.

The cold-dust-derived SFRD from SMGs shows a significant decline at redshifts beyond about 3. The larger star-formation rate from the more distant and higher-luminosity objects is inadequate to overcome the rapid decline in their volume density. If there is significant star formation beyond redshifts of 4, it is not the province of SMGs, but must be carried by different and generally lower-luminosity populations, such as the Lyman-break galaxies (Steidel et al. 1999), BzK galaxies (Daddi et al. 2004, 2005) or galaxies found in very deep searches at optical wavelengths (Bouwens et al. 2004, Giavalisco et al. 2004). Semi-analytic modelling of the SFRD from SMGs (e.g. Baugh et al. 2005) suggests a broad peak at $2 < z < 3$, although the predicted diminution to higher redshifts is less than that indicated by the results here.

The data are remarkably consistent on the presence of two sub-populations of objects, divided by luminosity. These evolve in distinctly different ways and their luminosity functions have different shapes. Their SFRD histories are likewise very different. The ULIRG/LIRG dichotomy is of particular relevance here, and our results are similar to those discussed in some earlier studies of lower redshift populations (e.g. Kim & Sanders 1998, Guiderdoni et al. 1998, Chary & Elbaz 2001, Lagache et al. 2003, Sajina et al. 2003, Xu et al. 2003), sometimes more loosely described as a distinction between 'starbursts' vs more normal galaxies. At higher redshifts Chary (2006) illustrated (his figure 4) how SFRD dominance shifted from ULIRGs at $z \geq 2.5$ to LIRGs at $z \sim 1$ (see also Caputi et al. 2007 and other Spitzer-based studies). Our dividing line in luminosity is somewhat more extreme than the LIRG/ULIRG boundary, normally taken at $10^{12}L_\odot$; our di-
vision at log \( L_{\text{50\,\mu m}} \approx 23.2 \) corresponds to about \( 3 \times 10^{12} \, L_\odot \), and to an SFR per galaxy of around \( 600 \, M_\odot \, \text{yr}^{-1} \), well above the generally accepted range of SFR for LIRGs of 10–100 \( M_\odot \, \text{yr}^{-1} \). Despite our higher adopted dividing line, our results parallel those for LIRGs/ULIRGs: we find the most IR-luminous objects dominating the energy output (or SFRD) at \( z \sim 2.5 \), while the less luminous objects dominate the SFRD at \( z \sim 1 \). We are seeing a down-sizing in the luminosity of the dominant contributors to the energy budget.

We conclude that a redshift cut-off is established for SMGs in both object density and SFRD, both of which are similar in form to cut-offs found for powerful AGN. We also conclude that two populations are likely to be present amongst SCUBA-detected SMGs, showing distinctly different evolutionary histories and luminosity functions. We can be optimistic that with much larger samples soon to be collected using SCUBA-2 [Holland et al. 2004], it will be possible to test ideas and issues such as: the AGN–SFR connection and its time-lag; what role merging plays in this process; details of how and why SMGs organize themselves into sub-populations to manifest cosmic down-sizing; and the relation this down-sizing has to populations of LIRGs and ULIRGs selected at other wavelengths.

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