Confirmation of the effectiveness of sub-mm source redshift estimation based on rest-frame radio–FIR photometry

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ABSTRACT

We present a comparison between the published optical, IR and CO spectroscopic redshifts of 15 (sub-)mm galaxies and their photometric redshifts as derived from long-wavelength (radio–mm–FIR) photometric data. The redshift accuracy measured for 12 sub-mm galaxies with at least one robustly-determined colour in the radio–mm–FIR regime is $\delta z \approx 0.30$ (r.m.s.). Despite the wide range of spectral energy distributions in the local galaxies that are used in an un-biased manner as templates, this analysis demonstrates that photometric redshifts can be efficiently derived for sub-mm galaxies with a precision of $\delta z < 0.5$ using only the rest-frame FIR to radio wavelength data.

Key words: surveys – galaxies: evolution – cosmology: miscellaneous – infrared: galaxies – submillimetre

1 INTRODUCTION

The next generation of wide-area extragalactic submillimetre and millimetre (hereafter sub-mm) surveys, for example from the Balloon-borne Large Aperture Submillimetre Telescope (BLAST, Devlin et al 2001), LABOCA on the Atacama Pathfinder Experiment (APEX*), the SCUBA 2 camera† on the James Clerk Maxwell Telescope (JCMT) and BOLOCAM-II on the Large Millimetre Telescope (LMT‡), will produce large samples ($\sim 10^3$–$10^5$) of distant, luminous starburst galaxies. The dramatic increase in the number of submillimetre detected galaxies requiring follow-up observations makes it unreasonable to expect that a large fraction of their obscured or faint optical and IR counterparts will have unambiguous, spectroscopically-determined redshifts. An alternative method to efficiently and robustly measure the redshift distribution for large samples of submillimetre galaxies is clearly necessary.

Given the underlying assumption that we are witnessing high rates of star formation in these submillimetre galaxies, then we expect them to have the characteristic FIR peak and steep submillimetre (Rayleigh-Jeans) spectrum which is dominated by thermal emission from dust heated to temperatures in the range $20 - 70$ K by obscured young, massive stars. The observed radio–FIR luminosity correlation in local starburst galaxies (e.g. Helou et al. 1985), that links the radio synchrotron emission from supernova remnants with the later stages of massive star formation, is also expected to apply to the submillimetre galaxies.

Thus, in recent years, a considerable amount of effort has been invested in assessing the accuracy with which these broad continuum features in the spectral energy distributions (SEDs) of submillimetre galaxies at rest-frame mid-IR to radio wavelengths can be used to provide photometric-redshifts (Hughes et al. 1998; Carilli & Yun 1999, 2000; Dunne, Clements & Eales 2000; Rengarajan & Takeuchi 2001; Yun & Carilli 2002; Wiklind 2003; Blain, Barnard & Chapman 2003). In a contribution to this general investigation Hughes et al. (2002, Paper I) described Monte-Carlo simulations that used a library of multi-frequency template SEDs, derived from observations of local starbursts and AGN with a wide-range of FIR luminosities ($9.0 < \log L_{\text{FIR}}/L_\odot < 12.3$) and temperatures ($25 < T/K < 65$), to measure the accuracy of photometric redshifts that could be derived from future 250, 350, 500$\mu$m extragalactic surveys with BLAST and Herschel, and complementary 850$\mu$m surveys from SCUBA. Aretxaga et al. (2003, Paper II) then applied the techniques described in Paper I to the catalogues of submillimetre galaxies identified in various SCUBA surveys, and derived photometric redshifts for individual sources using existing radio–submillimetre data.

In this paper we use new optical and IR spectroscopic observations of submillimetre galaxies published by Chapman et al. (2003a), and Simpson et al. (2004) to update our previous comparison of spectroscopic and long-wavelength
photometric redshifts (Paper II). In section 2 we explain the selection criteria for the sub-mm sources with spectroscopic redshifts included in our analysis, and demonstrate how the accuracy of the photometric redshift prediction varies according to the quality of the radio-mm–FIR photometric data. In section 3 we discuss the significant agreement between the spectroscopic and photometric redshifts, and use these results to challenge the suggestion by Blain et al. (2003) that it is not possible to derive photometric redshifts with an accuracy of $dz \simeq 0.5$ or better without adopting an unreasonably tight dispersion in the luminosity-temperature (L-T) relation or a limited range of SEDs in the analysis. Finally, our conclusions are summarized in section 4.

The cosmological parameters adopted throughout this paper are $H_0 = 67$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$.

2 ANALYSIS

2.1 New spectroscopic redshifts for sub-mm sources

Over the last year several new optical and IR spectroscopic redshifts have been published for sub-mm sources (Chapman et al. 2003a, Simpson et al. 2004), enhancing substantially the number of sources available for checking the reliability of photometric estimates. Many of the sub-mm galaxies selected for spectroscopic study have been extracted from the 8-mJy SCUBA survey (Scott et al. 2002), aided by deep follow-up observations with the VLA (Ivison et al. 2002).

Of the 10 optical redshifts published by Chapman et al. (2003a), we include in our analysis only those 5 sources with photometric data of sufficient quality. We briefly discuss the SED properties of the excluded sources:

- SMM105224.6+572119 ($z_{opt} = 2.429$), also known as LE850.15 from the UK 8-mJy SCUBA survey of the Lockman Hole East, is rejected because the sub-mm source has since been shown to be a spurious 850μm detection. In Scott et al. (2002) this source was originally listed as a low $S/N$ (3-$\sigma$) sub-mm source, having been extracted from one of the more noisy regions of the 8-mJy maps. Subsequently it was highlighted by Ivison et al. (2002) to be very likely erroneous on account of its lack of a radio counterpart (despite its very bright apparent sub-mm flux). The spurious nature of this source has been supported by the failure to detect the source in a reanalysis of the 8-mJy maps conducted as part of SHADES (Mortier et al. 2004; \texttt{www.roe.ac.uk/~ia/shades}), and by its non-detection in the IRAM MAMBO mm-wavelength maps of the 8-mJy Lockman East field (Greve et al. 2004).

- SMM105207.7+571907 ($z_{opt} = 2.698$) or LE850.12, also from the UK 8-mJy SCUBA survey, has a bright and statistically secure radio counterpart (Ivison et al. 2002). This object, however, is a known AGN, with strong, flat-spectrum, variable radio emission. Therefore, it must be excluded from the analysis presented here, which relies on the fitting of non-variable starburst-dominated spectral templates. As we show in Fig 3, no SED in our local template library can reproduce the high radio fluxes of this variable radio-source at the spectroscopic redshift, and indeed, in Paper II we already reported that the SED could not be matched at any redshift with the local templates.

- SMM123600.2+621047 ($z_{opt} = 1.998$), whose position (J2000) corresponds to a 1.4 GHz radio source (123600.150+621047.17) in Richards (2000), has a spectrum which presumably arises from an optically-faint ($I = 23.6$) VLA radio-source that was followed up with submillimetre photometry, but the robustness of the radio-submm association cannot be determined from the published information.

- SMM131201.2+424208 ($z_{opt} = 3.419$) and SMM131212.7+424423 ($z_{opt} = 2.811$) still do not have published 1.4GHz data from the SSA13 field (Fomalont et al., in prep), and we therefore cannot reconstruct the radio-submm SED of this source.

In the analysis described in §2.2 we include the remaining 5 sub-mm sources from the 8-mJy survey studied by Chapman et al. (2003a), namely N2850.1, N2850.4, N2850.8, LE850.6 and LE850.18, which have unambiguous radio identifications from Ivison et al. (2002). The spectroscopic redshifts for all these sources also appear to be secure, and indeed redshift information for two of them has been published elsewhere: N2850.4 (Smail et al. 2003) and N2850.1 (Chapman et al. 2002a).

From deep near-infrared spectroscopy with the Subaru telescope, Simpson et al. (2004) have measured spectroscopic redshifts based on two or more emission lines with secure radio and near-infrared identifications for 2 additional 8-mJy SCUBA sources (N2850.2 and N2850.12 in the ELAIS N2 Field, Scott et al. 2002). We therefore include these two sources in the expanded sample analysed here. We note that Simpson et al. also suggested a tentative redshift for LE850.3 estimated from a single 2.5σ emission-line, and also a redshift for CUDSS14.9 from the putative HK Ca absorption lines that need confirmation (Simpson, priv. communication). These latter two redshifts are not considered robust enough for inclusion in our analysis.

2.2 New photometric redshifts

We thus have 7 new redshifts for robust sub-mm sources from the UK 8-mJy SCUBA survey, which can be added to the heterogeneous collection of 8 sub-mm sources with spectroscopic redshifts previously considered by Aretxaga et al. (2003). Thus, the new spectroscopic data have effectively doubled the size of the comparison sample, as well as extending the redshift baseline out to $z \simeq 4$.

Since our original analysis in Paper II, new photometric data at 1.2mm obtained with MAMBO (Greve et al. 2004) have also become available for the sub-mm galaxies first identified in the UK 8-mJy SCUBA survey areas (Scott et al. 2002). We have therefore incorporated this additional photometric information in a re-derivation of the photometric redshifts of UK 8-mJy SCUBA sources in the current spectroscopic sample. We also include N2850.12 which has a 3.4σ flux determination at 850μm, and hence failed our selection criteria in Paper II, but which now has a spectroscopic redshift (Simpson et al. 2004) based on an IR counterpart associated with the 3σ peak in the radio observations of Ivison et al. (2002).

We have adopted the fiducial evolutionary model le2 (the least restrictive one in Paper II, which applied a non-informative prior at $z > 2.3$, and $(1+z)^3$ luminosity evolution to $z \leq 2.3$) to derive the new photometric-redshift
Table 1. Photometric redshifts for the sources with reported spectroscopic redshifts. The first column gives the name; the second column gives the most probable mode and the 68% confidence interval for the mode among 100 Monte Carlo realizations; the third column gives the 68% confidence interval for the redshift distribution of the source; the fourth one, the 90% confidence interval; the fifth and sixth columns give respectively the detected bands (at a ≥ 3σ level) and the upper-limits used for the computation of the photometric-redshifts; and the seventh column gives the spectroscopic redshifts and their references: Ba99 for Barger et al. 1999; Ch02a for Chapman et al. 2002a; Ch02b for Chapman et al. 2002b; Ch03 for Chapman et al. 2003a; Ea00 for Eales et al. 2000; Fr98 for Frayer et al. 1998; HR94 for Hu & Ridgway 1994; Si04 for Simpson et al. 2004; and Sm03 for Smail et al. 2003.

| object          | $z_{\text{phot}}$ mode | 68% CL | 90% CL | ≥ 3σ detections | < 3σ / upper limits | $z_{\text{spec}}$ |
|-----------------|-------------------------|--------|--------|-----------------|---------------------|-----------------|
| LH850.6         | 2.6±0.4                 | (2.5–3.7) | (2.0–4.2) | 850µm, 1.2mm, 1.4GHz | 450µm, 5GHz | 2.610 (Ch03) |
| LH850.18        | 3.8±0.3                 | (3.0–5.4) | (2.6–6.0) | 850µm, 1.2mm, 1.4GHz | 450µm, 5GHz | 3.699 (Ch03) |
| N2850.1         | 2.85±0.15               | (2.5–3.8) | (2.0–4.1) | 450, 850µm, 1.4GHz | 1.2mm | 0.840 (Ch02a) |
| N2850.2         | 2.35±0.05               | (2.0–2.7) | (1.5–3.1) | 450, 850µm, 1.2mm, 1.4GHz | — | 2.45 (Si04) |
| N2850.4         | 2.6±0.2                 | (2.0–3.8) | (2.0–4.6) | 850µm, 1.2mm, 1.4GHz | 450µm | 2.376 (Sm03) |
| N2850.8         | 2.5±0.3                 | (1.5–3.5) | (1.0–4.5) | 850µm | 450µm, 1.2mm, 1.4GHz | 1.189 (Ch03) |
| N2850.12        | 2.5±0.2                 | (1.6–4.0) | (1.5–5.0) | 850µm | 450µm, 1.2mm, 1.4GHz | 2.43 (Si04) |
| CUDSS14.18      | 0.7±0.1                 | (0.3–1.5) | (0.0–1.8) | 5.1GHz | 450, 850µm | 0.66 (Ea00) |
| SMMJ02399–0134  | 2.3±0.3                 | (1.5–3.1) | (1.0–3.8) | 850µm, 1.4GHz | — | 1.056 (Ba99) |
| SMMJ0399–0136   | 2.85±0.05               | (2.5–3.7) | (2.0–5.0) | 450, 850µm, 1.3mm, 1.4GHz | 2mm | 2.808 (Fr98) |
| SMMJ14011+0252  | 2.85±0.05               | (2.0–3.3) | (2.0–4.4) | 450, 850µm, 1.3mm, 1.4GHz | 3mm, 2.8GHz | 2.550 (Ba99) |
| W–MM11          | 3.7±1.0                 | (2.5–5.3) | (2.0–5.8) | 850µm | 450µm | 2.98 (Ch02b) |
| HR10            | 1.95±0.25               | (1.5–2.3) | (1.5–2.9) | 450, 850µm, 1.3mm, 8GHz | 100µm, 1.4GHz | 1.44 (HR94) |
| N1–40           | 0.8±0.3                 | (0.5–1.2) | (0.5–1.5) | 175, 850µm, 1.4GHz | 450µm | 0.45 (Ch02c) |
| N1–64           | 1.05±0.25               | (0.9–2.0) | (0.5–2.1) | 175, 850µm, 1.4GHz | 450µm | 0.91 (Ch02c) |

estimates which are given in Table 1. We produce simulated catalogs of sources in mock surveys to the same depth as those in which the real sub-mm galaxies were detected. The corresponding redshift distributions are then derived by the joint probability of identifying the particular radio-mm–FIR colours and fluxes of the real sources with the mock galaxies in the simulated catalogs. In order to check the stability of the redshift solutions found, we have calculated 100 different Monte Carlos for each source, and for each of these realizations we have derived its redshift probability distribution, its mode and 68% and 90% confidence level intervals. As expected, the sources with photometric redshifts based on 2 or more colours are the most stable and show well defined peaks and little variation in the mode of the redshift distribution of the different simulations. It is important to note that these photometric redshift estimates include absolute calibration errors of 5-20% in the individual radio–submillimetre fluxes, and assume no correlation between the luminosity and shape of an SED (or temperature).

From our sample of 15 sub-mm galaxies, Fig. 1 shows the photometric-redshift spectroscopic-redshift regression plot for those 12 sources that have at least one robust colour based on two or more detections (≥ 3σ) in the radio-mm–FIR regime. The remaining 3 sources (N2850.8, N2850.12, and W-MM11) have a robust detection at only one wavelength and various upper-limits and hence are not included in Fig. 1.

Figs. 2 and 3 show the comparison of the observed SEDs of the sources analysed in this paper and the template SEDs considered in the photometric redshift analysis, illustrating the cases where there is good agreement and catastrophic disagreement, respectively. All SEDs in our template library are accepted by more than one of these sources.

2.2.1 The case of N2850.1

Among the photometric redshifts based on at least two colours (with well measured fluxes, i.e. ≥ 3σ, in three or more bands) the submillimetre galaxy which departs most clearly from the $z_{\text{phot}} = z_{\text{spec}}$ line is N2850.1 ($z_{\text{phot}} - z_{\text{spec}} = 2.01$). Our new photometric redshift of N2850.1, using the most recent upper limit at 1.2mm (Greve et al. 2004) together with the 450, 850µm and 1.4GHz fluxes, is $z_{\text{phot}} = 2.8±0.3$ at a 68% confidence level, and $z_{\text{phot}} = 2.8±0.3$ at a 90% level. These values are consistent with the estimates presented in Paper II, but remain strongly inconsistent with the optical spectroscopic redshift ($z_{\text{spec}} = 0.840$) reported by (Chapman et al. 2003a). This is not surprising as there has already been considerable debate over whether the optical identification for this sub-mm source is correct. The optical spectrum and redshift for this counterpart, originally published by Chapman et al. (2002a), led these authors to argue that the optically-bright galaxy coincident (within ~ 0.2″) with the radio position of N2850.1 was possibly a foreground galaxy that lenses the sub-mm source. This argument was based primarily on the fact that the temperature of the dust emission $T_D = 23 ± 5$ K deduced for the sub-mm source at the optical spectroscopic redshift was 4σ below that of the local dusty galaxies with the same intrinsic luminosity. In Chapman et al. (2003a), N2850.1 has a revised temperature of 16.0±1.2 K or 6σ below the temperature distribution of local analogs, and colder than SMM22173+0014, which Chapman et al. (2002a) also claim is lensed.

It is clear therefore that among the sources considered here, N2850.1 is the most likely example of a bright sub-mm source produced by gravitational lensing by an intermediate redshift galaxy, analogous to the case of HDF850.1 studied in detail by Dunlop et al. (2004). Proving this beyond doubt remains a challenge, as astrometric information of the qual-
at the 90% level); \( N2850.12 \) has a photometric redshift of \( z = 5.0 \) at a 68% confidence level (1.5 to 5.0 at the 90% level), which is consistent with the \( z_{\text{spec}} = 2.43 \) (Symon et al. 2004); and W-MM11 at \( z_{\text{spec}} = 2.98 \), as determined in Paper II, has a \( z_{\text{phot}} = 3.7^{+1.2}_{-0.5} \) at a 68% confidence level (2.0–5.8 at the 90% level).

Despite the strong suspicion that N2850.1 is a lensed SCUBA galaxy at a redshift \( z > z_{\text{opt}} = 0.840 \), even if we include N2850.1 in our analysis the rms dispersion about \( z_{\text{phot}} = z_{\text{spec}} \) is \( \delta z = 0.38 \). This result considers only those 10/15 sub-mm galaxies with at least two measured colours based on 3 or more \( \geq 3\sigma \) detections in the radio–mm–FIR regime. The precision significantly improves to \( \delta z = 0.20 \) if we exclude N2850.1. Extending this analysis to the 12/15 sources with at least one colour determined from detections at two or more bands, the measured mean accuracy of the photometric redshifts in the range \( 0.5 < z < 4 \) is \( \delta z = 0.42 \) and \( \delta z = 0.28 \), including and excluding N2850.1, respectively. Finally if we also include sources with only upper-limits in the colours (for example a single submillimetre detection with a non-detection at radio wavelengths), we measure \( \delta z = 0.48 \) and \( \delta z = 0.37 \), including and excluding N2850.1, respectively.

### 3 DISCUSSION

Blain et al. (2003) have stated that the technique described in Papers I and II assumes a narrow-range of local SED templates, with a tight distribution of dust temperatures, and luminosities, to derive the photometric redshifts. We emphasise again that the range of dust temperatures in our template library ranges from 25 – 65 K, and that we include 20 local galaxies (starbursts and AGN) with well-measured SEDs and FIR luminosities spanning the range \( 9 < \log L_{\text{FIR}}/L_\odot < 12.3 \). Furthermore, it is misleading to suggest that a wide range of dust temperatures (that may be correlated with luminosity) should translate directly into a similar redshift uncertainty in our calculations, since the redshift distributions are dominated by those SEDs that best fit the radio–mm–FIR data. Although all SEDs contribute to the redshift distributions at some level, but with varying degrees of significance, a well-defined peak can be measured.

The comparison presented here provides reassurance that, by allowing the variety of local template SEDs to be selected at random, and then scaled to the required FIR luminosity to populate the evolving luminosity function, we have offered the photometric-redshift method a library of galaxies with a sufficiently broad range of dust-temperatures, SED shapes and levels of star formation and AGN activity from which to find a solution. We also note that the sensitivities of the current submillimetre experiments in blank-field surveys select only those starburst galaxies with \( L_{\text{FIR}}/L_\odot > 10^{11} \). This being the case, then perhaps the future choice of SEDs should be restricted to those galaxies more luminous than this sensitivity limit, in which case our library of SEDs will only be lacking the highest-luminosity local counterparts (12.3 \( < L_{\text{FIR}}/L_\odot < 13 \)). If we consider that there exists a luminosity–temperature dependence in the SEDs of starbursts, then we will be missing the SEDs that peak at the shortest wavelengths in our library, and thus we will be underestimating the redshifts for some fraction of SCUBA sources.

#### 2.2.2 Overall accuracy of photometric redshifts

In general the agreement between photometric and spectroscopic redshifts is encouraging. The three sources for which photometric-redshifts are based on a solid detection (\( \geq 3\sigma \)) at just one wavelength, however, are the least precise due to insufficient photometric constraints, although we note that they are still formally consistent with the spectroscopic redshifts found: N2850.8 at \( z_{\text{spec}} = 1.189 \) has a photometric redshift \( z_{\text{phot}} = 2.5^{+1.0}_{-0.5} \) at a 68% confidence level (1.0–4.5 at the 90% level); N2850.12 has a photometric redshift of \( z_{\text{phot}} = 2.5^{+1.0}_{-0.5} \) at a 68% confidence level (1.5 to 5.0 at the 90% level), which is consistent with the \( z_{\text{spec}} = 2.43 \) (Symon et al. 2004); and W-MM11 at \( z_{\text{spec}} = 2.98 \), as determined in Paper II, has a \( z_{\text{phot}} = 3.7^{+1.2}_{-0.5} \) at a 68% confidence level (2.0–5.8 at the 90% level).

Despite the strong suspicion that N2850.1 is a lensed SCUBA galaxy at a redshift \( z > z_{\text{opt}} = 0.840 \), even if we include N2850.1 in our analysis the rms dispersion about \( z_{\text{phot}} = z_{\text{spec}} \) is \( \delta z = 0.38 \). This result considers only those 10/15 sub-mm galaxies with at least two measured colours based on 3 or more \( \geq 3\sigma \) detections in the radio–mm–FIR regime. The precision significantly improves to \( \delta z = 0.20 \) if we exclude N2850.1. Extending this analysis to the 12/15 sources with at least one colour determined from detections at two or more bands, the measured mean accuracy of the photometric redshifts in the range \( 0.5 < z < 4 \) is \( \delta z = 0.42 \) and \( \delta z = 0.28 \), including and excluding N2850.1, respectively. Finally if we also include sources with only upper-limits in the colours (for example a single submillimetre detection with a non-detection at radio wavelengths), we measure \( \delta z = 0.48 \) and \( \delta z = 0.37 \), including and excluding N2850.1, respectively.
Figure 2. Observed SEDs of sources for which acceptable photometric redshifts were derived. The SEDs, normalised to the flux density at 850 µm are shown as squares and arrows. The arrows indicate 3σ upper limits. The squares denote detection at a level ≥ 3σ, with 1σ error bars. The template SEDs (lines) are redshifted to the spectroscopic redshift published in the literature, and scaled to maximize the likelihood of detections and upper limits through survival analysis (Isobe, Feigelson & Nelson 1986). The template SEDs at this redshift compatible within 3σ with the observations of the sources are displayed as darker lines.
The photometric method currently relies on limited data, restricted to a few low S/N detections at observed radio, millimetre and submillimetre wavelengths. No optimization of the current method has been made, based on the data at λ < 850µm, that sample the rest-frame FIR–sub-mm peak, place initial constraints on the photometric redshifts (Fig. 4b). The 850µm–radio spectral index has been shown to also provide a useful one-colour measure of photometric-redshifts for the sub-mm population (e.g. Carilli & Yun 2000), with the ability to robustly identify galaxies at z > 2 from those at lower redshifts. Hence the use of data in the radio regime (1.4–8 GHz) in this analysis continues to improve the photometric-redshift accuracy (Fig. 4c) by providing confirmation, and therefore adding more weight to the results determined from the data at λ ≤ 850µm. Finally, with the addition of further mm-wavelength data at 1–2 mm, we eventually derive a photometric-redshift accuracy of ±0.42 or ±0.28 for all 12 galaxies with at least one well-measured colour if we include or reject N2850.1, respectively (Fig. 4d).

4 CONCLUSIONS

We have complemented our previous comparison of photometric-redshifts and spectroscopic redshifts for 8 submillimetre galaxies (Aretxaga et al. 2003) with 7 new spectroscopic redshifts (Chapman et al. 2003a, Simpson et al. 2004) and recently published MAMBO 1.2mm data (Greve et al. 2004). The increased number of available spectroscopic redshifts for submillimetre galaxies with sufficient accompanying rest-frame radio to FIR photometry confirms the reliability of our previous simulations and predictions for the redshifts of sub-mm sources. This accuracy is all the more impressive given that the photometric-redshifts for 6 of new sources were effectively predicted before the additional 7 spectroscopic redshifts were available (Paper II).

If we consider all available data for those sub-mm galaxies that have at least one colour determination based on two detections, we conclude that the rest-frame radio-FIR photometric method can provide redshifts with an accuracy of ~±0.28 over the redshift interval 0.5 < z < 4. This redshift uncertainty increases to ±0.42 if the true spectroscopic redshift of the brightest sub-mm source N2850.1 in the northern ELAIS2 field is z_spec = 0.840 (Chapman et al. 2003a). There is, however, a more natural explanation for the discrepancy between the photometric-redshift and spectroscopic-redshift of N2850.1, namely that the sub-mm source is lensed by the foreground optical counterpart (as already suggested by Chapman et al. 2003a), analogous to the situation for HDF850.1, the brightest object in the Hubble Deep Field (Dunlop et al. 2004).

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Figure 4. Dissection of the role played by progressive addition of the available photometric data in the final construction of the comparison of estimated and spectroscopic redshifts presented in Figure 1. From top to bottom, the photometric redshifts have been calculated using (a) only the 850µm flux, (b) the 850 and 450µm fluxes and upper limits, and if available (for N=40, N64 and HR10) also the ISO 170µm and IRAS 100µm fluxes and upper limits; (c) 850, 450, 170, 100µm fluxes combined with radio data (1.4 and 8GHz fluxes and upper limits); (d) all available data, including 1–3mm fluxes and upper limits. The colour code indicates sources with just one robust flux determination (≥ 3σ) in light grey, sources with at least two robustly determined fluxes in dark grey, and sources with 3 or more robustly determined fluxes any prior knowledge of those local SED templates that are consistent with the rest-frame data. Despite the lack of any assumption in our simulations and analysis about a dependence between the shape of a local SED and luminosity of the redshifted submillimetre source, the method clearly works to a useful accuracy (e.g. van Kampen et al. 2004).

The inclusion of such a dependence and measurements with greater S/N can only reduce the dispersion of possible SEDs that are consistent with the observational data, and hence this will reduce the width of the redshift probability distributions for individual targets.

One of the difficulties in this analysis has been to select from the limited publically-available information which sub-mm galaxies have secure spectroscopic redshifts derived from unambiguous optical or IR counterparts. It is therefore encouraging to look forward to the next few years as the essential radio, (sub)millimetre and FIR photometric data become available from facilities such as the VLA, GBT, LMT, APEX, BLAST, Herschel, Spitzer and Astro-F for complete and substantial samples of sub-mm sources. Thus we are confident that the combination of these high S/N multi-wavelength rest-frame radio–FIR data will generate photometric-redshifts with accuracies of Δz ≲ 0.3 for the majority of the individual sub-mm selected galaxies. Given this, it will be possible to accurately measure the entire redshift distribution and star formation history of the high-z population of heavily-obscured starburst galaxies without having to measure a spectroscopic redshift for every sub-mm source.

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REFERENCES

Aretxaga I. et al., 2003, MNRAS, 342, 759 (Paper II)
Barger A.J. et al., 1999, AJ, 117, 2656
Blain A.W., Barnard V.E., Chapman S.C., 2003, MNRAS, 338, 733
Carilli C.L., Yun M.S., 1999, Ap.J., 513, L13
Carilli C.L., Yun M.S., 2000, Ap.J., 530, 618
Chapman S.C., Smail I.R., Ivison R.J., Blain A.W., 2002a, MNRAS, 335, L17.
Chapman S.C. et al., 2002b, ApJ, 572, L1.
Chapman S.C. et al., 2002c, ApJ, 573, 66.
Chapman S.C., Blain A.W., Ivison R.J., Smail I.R., 2003a, Nature, 422, 695
Chapman S.C. et al., 2003b, ApJ, 585, 57
Devlin M. et al., 2001, in Lowenthal J., Hughes D.H., eds., Deep Millimetre Surveys: Implications for Galaxy Formation and Evolution, World Scientific, p. 59.
Dunlop J.S. et al., 2004, MNRAS, 350, 769
Downe L., Clements D.L., Eales S.A., 2000, MNRAS, 319, 813
Eales S. et al., 2000, AJ, 120, 2244.
Frayer D.T. et al., 1998, ApJ, 506, 7
Greve T.R. et al., 2004, MNRAS, submitted (astro-ph/0405361)
Helou G., Soifer B.T., Rowan-Robinson M., 1985, ApJL, 289, 7
Hu E.M., Ridgway S.E., 1994, AJ, 107, 1305
Hughes D.H. et al., 1998, Nat, 394, 241
Hughes D.H. et al., 2002, MNRAS, 335, 871 (Paper I)
Isose T., Feigelson E.D., Nelson P.L., 1986, ApJ, 306, 490
Ivison R.J., et al., 2002, MNRAS, 337, 1
Mortier, A. et al., 2004, MNRAS, submitted
Rengarajan T.N., Takeuchi T.T., 2001, PASJ, 53, 433
Richards E.A., 2000, ApJ, 533, 611
Simpson C., et al., 2004, MNRAS, 353, 179.
Smail I. et al., 2003, MNRAS, 342, 1185
van Kampen et al. 2004, MNRAS, submitted (astro-ph/0408552)
Wiklind T., 2003, ApJ, 588, 736
Yun M.S., Carilli C.L., 2002, ApJ, 568, 88.
Scott S., et al., 2002, MNRAS, 331, 817.