RevMexAA (Serie de Conferencias), **23**, 60–63 (2005)

A PHOTOMETRIC VIEW OF THE REDSHIFT DISTRIBUTION OF DUST-ENSHROUDED GALAXIES

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RESUMEN

Describimos la aplicación de corrimientos al rojo fotométricos basados en los flujos en reposo del infrarrojo lejano–radio para derivar la distribución espacial de las galaxias rodeadas por polvo, oscurecidas ópticamente que se detectan en los relevamientos de campos vacíos cosmológicos submilimétricos de nueva generación.

ABSTRACT

We describe the application of photometric redshifts based on rest-frame FIR–radio wavelength fluxes to derive the spatial distribution of optically-obscured dust-enshrouded galaxies detected in the current generation of blank-field cosmological sub-mm surveys.

Key Words: **GALAXIES: HIGH-REDSHIFT — SUBMILLIMETER — SURVEYS**

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 2004), LABOCA on the Atacama Pathfinder Experiment (APEX[2]), the SCUBA 2 camera[3] on the James Clerk Maxwell Telescope (JCMT) and AzTEC on the Large Millimetre Telescope (LMT[4]), 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 $\sim 20 - 70$ 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 (e.g. Hughes et al. 1998, Carilli & Yun 2000).

2. PHOTOMETRIC REDSHIFT TECHNIQUE

In a contribution to this general investigation Hughes et al. (2002) described a Monte Carlo (MC) photometric method to determine the redshift of a sub-mm source from its 250–850μm colours, taking into account constraining prior information on the obscured galaxy population as a whole, such as the number counts of sub-mm sources, the favored evolutionary model of the sub-mm population, and the amplification and clustering properties of a certain field.

We only offer a brief summary of the technique here. We generate a catalogue of 60μm luminosities and redshifts for mock galaxies from an evolutionary model for the 60μm luminosity function that fits the observed 850μm number-counts. Randomly selected template SEDs are drawn from a library of local starbursts, ULIRGs and AGN, to provide FIR–radio fluxes. The fluxes of the mock galaxies include both photometric and calibration errors, consistent with the quality of the observational data for the sub-mm galaxy detected in a particular survey. We reject from the catalogue those mock galaxies that do not

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[2]www.mpifr-bonn.mpg.de/div/mm/apex/

[3]www.roe.ac.uk/ukatc/projects/scubatwo/index.html

[4]www.lmtgtm.org

respect the detection thresholds and upper-limits of the particular sub-mm galaxy under analysis. The redshift probability distribution of a sub-mm galaxy is then calculated as the normalized distribution of the redshifts of the mock galaxies in the reduced catalogue, weighted by the likelihood of identifying the colours and fluxes of each mock galaxy with those of the sub-mm galaxy in question. In order to quantify the sensitivity of the individual redshift distributions on the assumed evolutionary history of the sub-mm galaxy population, we consider a variety of models that are able to reproduce the observed 850μm number-counts within the uncertainties.

Fig. 1 shows, as an example, the resulting redshift distribution for the brightest sub-mm source, HDF850.1, in a survey area towards the Hubble Deep Field (Hughes et al. 1998) which has extensive multi-wavelength coverage and, so far, no published spectroscopic redshift.

3. ACCURACY OF PHOTOMETRIC REDSHIFTS

Over the last two years an increasing number of optical and IR spectroscopic redshifts have been published for sub-mm sources (Chapman et al. 2003, 2005, Simpson et al. 2004), enhancing substantially the number of sources available for checking the reliability of photometric estimates. These spectroscopic redshifts are obtained with the aid of deep 1.4GHz interferometry data that helps to identify the optical/IR counterpart of the sub-mm emission.

We have recently performed a check on the photometric redshift accuracy using a sample of 15 sub-mm galaxies with reliable available spectroscopic redshifts among those published (Aretxaga et al. 2005). Fig. 2 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 ($\geq 3\sigma$) in the radio-mm-FIR regime. The remaining 3 sources have a robust detection at only one wavelength and various upper-limits and hence are not included in Fig. 2.

Among the photometric redshifts based on at least two colours (with well measured fluxes, i.e. $\geq 3\sigma$, in three or more bands) the submillimetre galaxy which departs most clearly from the $z_{\rm phot} = z_{\rm spec}$ line is N2850.1 ($z_{\rm phot} - z_{\rm spec} = 2.01$). Our photometric redshift of N2850.1, using the most recent upper limit at 1.2mm together with the 450, 850μm and 1.4GHz fluxes, is $z_{\rm phot} = 2.8\pm^{1.0}_{0.3}$ at a 68% confidence level, and $z_{\rm phot} = 2.8\pm^{1.0}_{0.8}$ at a 90% level. These values are strongly inconsistent with the optical spectroscopic redshift ($z_{\rm spec} = 0.840$) reported

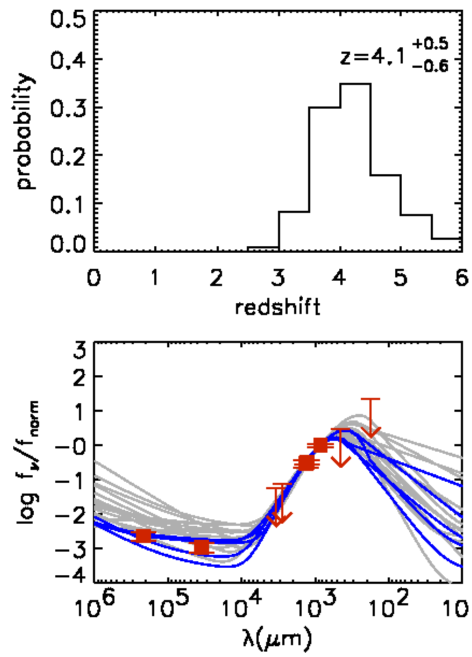

Fig. 1. *Top:* Redshift probability distribution of HDF850.1. *Bottom:* The observed SED of HDF850.1 normalised to the flux density at 850μm is shown as squares (detections) and arrows (3σ upper limits). The template SEDs (lines) are redshifted to the mode of the resulting redshift probability distribution, $z = 4.1$, coming from the MC. The template SEDs *at this redshift*, compatible within 3σ error bars with the SED of HDF850.1, are displayed as darker lines.

by (Chapman et al. 2003). 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 originally published by Chapman et al. (2002), led these authors to argue that the optically-bright galaxy coincident (within $\sim 0.2''$) 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 $T_{\rm D} = 23 \pm 5$ 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. (2003), N2850.1 has a revised temperature of $16^{+4.1}_{-2.2}$ K or 6σ below the temperature distribution of local analogs, and colder than SMM22173+0014, which Chapman et al. (2002) 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 quality available to Dunlop et al. (2004) does not yet exist for N2850.1.

Whatever the correct explanation for its properties, it is obvious that N2850.1 is an unusual source, being the only object in the sample of 15 galaxies which cannot be fit by any of our SED templates when redshifted to $z = 0.840$. For the sake of transparency and completeness in what follows we therefore quote the overall accuracy of the redshift estimation procedure both with and without the inclusion of N2850.1 in the statistical calculations.

3.0.1. *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 only one wavelength, however, are the least precise due to insufficient photometric constraints. We note however that they are still formally consistent with their associated spectroscopic redshifts.

Despite the strong suspicion that N2850.1 is a lensed SCUBA galaxy at a redshift $z \gg z_{\rm opt} = 0.840$, even if we include N2850.1 in our analysis the rms dispersion about $z_{\rm phot} = z_{\rm spec}$ 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.

The comparison presented here provides reassurance that, by allowing the variety of local template SEDs to be selected at random, which are 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, levels of star formation and AGN activity from which to find a solution.

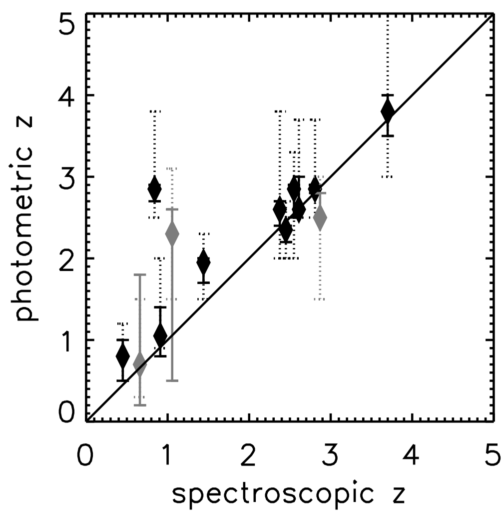

Fig. 2. Comparison of photometric-redshifts, using model le2 as a prior (see Aretxaga et al. 2003, 2005) and the true redshifts for the 12 sub-mm sources with at least one robust radio/sub-mm/far-infrared colour. The diamonds represent the most probable mode derived from 100 Monte Carlos calculated for each object using model le2. The solid error bars represent the range of modes (68% confidence level) measured in the corresponding redshift distributions of the 100 realizations, and the dotted lines show the 68% confidence interval of a representative redshift distribution for each object. Sources represented in black (in increasing redshift: N1–40, N2850.1, N1–64, HR10, N2850.4, N2850.2, SMMJ14011+0252 , LE850.6, SMMJ02399−0136 and LE850.18), have photometric redshifts derived from measurements ($\geq 3\sigma$) in at least three passbands of the radio–mm–FIR regime with the addition of some upper limits, and are the most precise estimates. Sources represented in dark grey (in increasing redshift: CUDSS14.18, SMMJ02399–0134) have photometric redshifts derived from measurements ($\geq 3\sigma$) in just two passbands and some additional upper limits.

4. RESULTS FOR THE POPULATION

The cumulative redshift distribution for the sub-mm galaxy population is simply the coaddition of the individual probability distributions. We have included in this calculation of the cumulative distribution only those 50 sub-mm sources identified in already published wide-area blank-field SCUBA surveys with $\geq 3.5\sigma$ significance (Aretxaga et al. 2003). Half of the sources in complete flux-limited sub-mm samples, such as these, have only a single 850μm detection with one, or more, additional upper-limits at other wavelengths. Since the redshift distributions of these sources are the most dependent on the priors used, the interpretation of the combined redshift distributions should be based on the range of results given by the different evolutionary models.

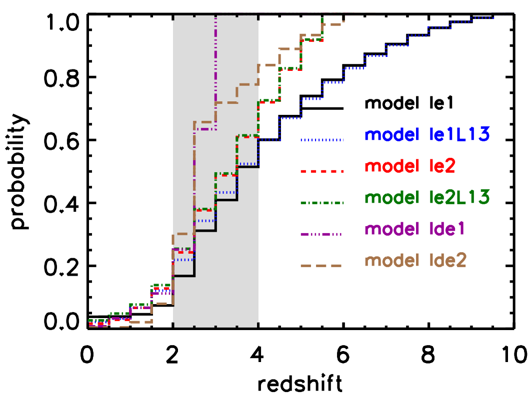

Fig. 3. Cumulative redshift distribution for the population of 50 sub-mm galaxies detected in wide-area blank-field surveys. The different lines represent different evolutionary models assumed for the sub-mm galaxy population in the MC (Aretxaga et al. 2003).

This analysis implies that 50 – 90% of the sub-mm galaxies lie between $z \sim 2-4$. This result is in agreement with the latest redshift distributions derived from optical/IR spectroscopic follow-up of sub-mm sources with radio counterparts (Chapman et al. 2005). The remainder of the galaxies, $\sim 10\%$, lie at $z < 2$. Fig. 3 also shows that $\leq 50\%$ of the galaxies have colours that are also consistent with $z > 4$. Most of these are detected only at 850μm, and not at 1.4GHz or any other sub-mm band. The upper limits at other wavelengths do not usually help to constrain their redshifts between $2 \leq z \leq 10$, and hence their probability distributions are very flat in those regimes. Shorter-wavelength sub-mm data ($250-500\mu$m) from a future balloon-borne experiment, BLAST (Devlin et al. 2004), will provide powerful additional constraints ($\Delta z \sim \pm 0.5$) on the redshift distribution of all the sub-mm galaxies at $z > 2$ (Hughes et al. 2002).

5. SHADES

The SCUBA Half Degree Survey (SHADES) is a major new blank field extragalactic sub-mm survey currently underway at the James Clerk Maxwell Telescope (JCMT). The SHADES consortium consists of nearly the entire UK cosmology community coupled with the BLAST collaboration, and other researchers from Mexico, USA, Spain, Italy and Austria. SHADES is designed to cover half a square degree to a 4σ depth of 8 mJy at 850μm, evenly split between two fields, the Subaru/XMM-Newton Deep field (SXDF, $02^h\ 18^m$, -05^o) and the Lockman Hole East ($10^h\ 52^m$, $+57^o$), and to provide a statistically meaningful sample of at least a few hundred sub-mm galaxies. The two survey areas have been selected on the basis of low galactic confusion at sub-mm wavelengths, and a wealth of existing or anticipated supporting multi-frequency data from radio to X-ray wavelengths. BLAST will provide the short sub-mm data that can constrain the position of the FIR peak in these high-z galaxies, and thus increase the accuracy of their photometric redshifts.

Preliminary maps from SHADES acquired at the JCMT since December 2002 are provided by Dunlop (2005), and the detailed strategy of survey planning and analysis is presented elsewhere (Mortier et al. 2005). With 40% completion the survey has identified 130 new sources, confirmed by four independent reductions carried out by the consortium, the majority of which have VLA and Spitzer counterparts (Dunlop 2005).

The survey has three main aims: to investigate the population of high-redshift mm galaxies to derive the history of star formation enshrouded by dust; to derive the clustering properties of sub-mm selected galaxies in order to determine whether these objects could be the progenitors of present-day massive ellipticals; and thirdly to determine the fraction of sources that harbour active galactic nuclei. The feasibility of acheiving sufficient photometric redshift precision to meet the first two goals have been shown in detail by Hughes et al. (2002) and van Kampen et al. (2005).

This work has been supported by CONACyT grants 39548-F and 39953-F.

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