The spectroscopic redshifts of SCUBA galaxies: implications for spheroid formation

Scott C. Chapman\textsuperscript{1}, Andrew W. Blain\textsuperscript{1}, Rob J. Ivison\textsuperscript{2}, and Ian Smail\textsuperscript{3}.

\textsuperscript{1} Caltech, Pasadena, CA, 91125, USA
\textsuperscript{2} Royal Observatory, Edinburgh EH9 3HJ, UK
\textsuperscript{3} University of Durham, Durham DH1 3LE, UK

Abstract. We present spectroscopic identifications for a sample of 55 submillimeter (submm)-selected ‘SCUBA’ galaxies, lying at redshifts $z = 0.7$ to 3.7, that were pinpointed in deep 1.4-GHz VLA radio maps. We describe their properties, especially the presence of active galactic nuclei (AGN) in the sample, and discuss the connection of the SCUBA galaxies and the formation of spheroidal components of galaxies, which requires knowledge of their masses and the timescales of their very luminous activity. For a subset of the galaxies, we show their disturbed and diverse Hubble Space Telescope (HST) optical morphologies.

1. Introduction

SCUBA galaxies (Smail, Ivison & Blain 1997; Barger et al. 1998; Hughes et al. 1998; Eales et al. 1999) are an important population (Blain et al. 1999, 2002), but frustratingly difficult to mesh with semi-analytic model frameworks (Guiderdoni et al. 1998; C. Lacey et al., in preparation). They are both numerous, with a surface density about 10\% that of optically-selected Lyman-break galaxies (LBGs; Steidel et al., 1999, 2003) at the relative depths of the current surveys, and luminous (possibly because of very high SFRs), with typical bolometric luminosities about 10 times greater than LBGs, adopting plausible spectral energy distributions (SEDs). The existing SCUBA galaxies produce most of the extragalactic submm background radiation intensity, and a significant fraction of the background at far-infrared (FIR) wavelengths (Blain et al. 2002; Smail et al. 2002; Cowie et al. 2002). They represent a population which is often difficult to detect at optical wavelengths, with at least the fainter half clearly being missed in current optical cosmological surveys. Unfortunately, the SCUBA galaxy population is notoriously difficult to study! Until now, we have been able to gather almost nothing about their redshifts and morphologies as fundamental observable properties. As a consequence, deriving properties such as total mass and dust temperature, and finding both the fraction of power contributed by AGN and starbursts, and their connection to optically-selected star-forming LBGs, have been the topic of largely idle speculation over the five years since their discovery.
The principal hurdle has always been identification at other wavelengths. SCUBA/MAMBO surveys have large beam sizes (10″–15″), a situation that will remain true for upcoming single-antenna, wide-field instruments: Bolocam, SHARC-II, a bolometer camera on the APEX telescope and SCUBA2. Candidate counterparts to SCUBA galaxies cannot therefore be identified unambiguously without interferometry to pinpoint their positions. However, mm/submm interferometry is currently an arduous process, with tens of hours of integration required to detect a single object at the OVRO MMA or IRAM PdB interferometers.

As a consequence, the 20-cm radio emission from SCUBA galaxies has become an important, but second best surrogate with which to probe both the energy generation processes and morphology of submm galaxies (Ivison et al. 1998; Smail et al. 2000; Barger, Cowie & Richards 2000; Chapman et al. 2001, 2002a, 2003a; Ivison et al. 2002). The problem remains that in order to use a radio wavelength as a surrogate for submm/FIR emission, we would like a clear physical principle connecting the emission at the different wavelengths. We don’t yet, but we do have a strong empirical connection: the far-IR–radio correlation (e.g., Helou et al. 1985), which has an RMS dispersion of only 0.2 dex over a large range in luminosity at low redshifts. Radio identification of SCUBA galaxies has allowed their optical properties to be explored in detail (Chapman et al. 2003a; Ivison et al. 2002). A large range of optical properties is observed for the radio-selected SCUBA galaxies, with 65% fainter than $I > 23.5$. They have red optical-IR colors with $I - K = 3$ to 6 and $< I - K >= 4.3$, but they are not all extremely red objects (EROs). Deep radio observations allow SCUBA galaxies to be pre-selected with an efficiency of about 40%.

2. Redshifts for SCUBA galaxies

We have been able to secure redshifts for 55 radio-identified submm galaxies through deep Keck/LRIS observations (Chapman et al. 2003b, S.C. Chapman, in preparation.), and the sample is growing rapidly. The sources lie in several distinct fields: CFRS03hr, Lockman-Hole, HDF, SSA13, CFRS14hr, Elais-N2, SSA22. The spectra for several new examples are shown in Fig. 1. The redshifts allow, for the first time, accurate calculation of luminosities and dust temperatures for the SCUBA galaxy population. We emphasize that obtaining redshifts is not easy, relying heavily on the superb blue sensitivity of the new LRIS-B multilobject spectrograph (Steidel et al. 2003), and often have no detectable continuum emission with which to extract the spectrum. In addition the galaxies are hard to identify, typically being faint, messy, composite objects in optical images. Because of their small radio/optical offsets ($\sim 0.5''$) it is often difficult to assess the best position at which to align the slit. Often we designated several slit positions on different masks for each target. Our spectroscopic completeness is $\sim 50\%$ over the magnitude range of the sample from $I = 22$ to 27.

---

1Data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership between Caltech, the University of California and NASA. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation.
While the issue of correctly identifying the submm galaxy is concerning, three (out of 3) CO detections with IRAM-PdB have already been made, realizing an unequivocal confirmation of the redshifts (Neri et al. 2003), as well as dynamical mass estimates > $10^{11} M_{\odot}$. One goal of the IRAM-PdB program is to obtain CO detections for a statistical sample ~30 of our submm galaxies, to understand the range in molecular gas properties. We also note that beyond the radio positional identification, we are finding the correct type of object through optical spectroscopy. The identifications are at high-$z$, have apparent SFRs of several $100 M_{\odot}$ yr$^{-1}$, often show AGN features, and are very rare objects in the LBG distribution. We ask, what else can they be?

We further note that we believe we have spectroscopically identified a sample of blank-field SCUBA galaxy counterpart candidates without radio detections, effectively through trial and error by targeting faint optical sources lying within the SCUBA beam using otherwise redundant spectrograph slits. Observations of these identifications were tried based on our cumulative experience of with the properties of the radio-identified sample: often faint, distorted blue/red composite sources near the SCUBA beam centroid, are found to have Type-II AGN spectra and/or inferred star formation rates of order $100 M_{\odot}$ yr$^{-1}$. Again, CO detection will be the final arbiter concerning the validity of the identifications. These identifications overlap significantly in redshift with our radio-submm sample, their radio non-detections implying colder dust temperatures.

In Fig. 2, we show the observed redshift distribution, and a toy model for the radio and submm distributions derived from an evolving far-IR luminosity function (Chapman et al. 2003c, Lewis et al. 2003). The model is very useful for understanding selection effects, and in particular the bias against the highest-redshift galaxies due to the requirement of a radio selection. This bias has a strong dependence on dust temperature ($T_d$). The sources missed by the radio are expected to fill the region lying between the model radio and submm distributions, overlapping significantly in redshift with the radio-identified sample if their dust temperatures are in the cold to warm regime ($T_d < 35$ K). The redshift distribution of a radio-selected QSO sample (Shaver et al. 1998) (which is unlikely to be affected by dust obscuration) is overplotted, suggesting a remarkable correspondence with the submm galaxy population.

If our identifications for submm galaxies without radio detections are correct, then this leaves only a ~ 20% tail of submm galaxies which can lie above $z > 4$. With a surface density of ~ 200/deg$^2$, this 20% tail is still considerably larger than the $z > 4$ QSOs detected in the mm/submm (Carilli et al. 2001, Isaak et al. 2002). Continued effort to identify these sources will be a worthy pursuit of the newest instruments and techniques.

3. Spheroids in Formation?

We have presented a plausible redshift distribution for submm galaxies, the most important ingredient for addressing whether they could be spheroids in formation. Encouragingly, they lie at the correct redshifts to be proto-ellipticals or the forming bulges of spiral galaxies. (all the stellar population constraints point to most stars being formed at $z=2-3$). In particular, we have demonstrated that most submm galaxies do not lie at $z > 4$, and thus most are not very high
redshift Population-III sources. Quite surprisingly, even this small sample of spectroscopic identifications reveals a redshift clustering signal, bolstering their association with massive halos (Blain et al. 2003).

However, to assess what type of formation mechanism is at work we must study the AGN/starburst contribution to the dust heating, the timescales of their luminous phase, and compare their HST morphologies. The AGN versus starburst issue is always difficult to address. We have firstly from our restframe UV spectra, the possibility of diagnosing the presence of an AGN through high ionization lines. Indeed, we find signs of CIV, and other lines which cannot easily be excited in a starburst, in approximately 50% of our sources. Our single near-IR spectrum thus far (Smail et al. 2003) reveals an OIII/Hβ ratio typical of Seyfert-2 galaxies as well as strong NeV emission. X-ray detections of 7 submm galaxies in the Chandra Deep Field North were presented in Alexander et al. (2003), while we have measured significant X-ray flux from a further seven of our sample, together implying that ∼70% of the radio-identified SCUBA galaxies have X-ray detections. However, only 1/3 of these are too X-ray bright to be generated by star formation alone (scaling from Nandra et al. 2002 for LBGs). Finally, ∼20% of our sources appear to be unusually bright at radio wavelengths, departing significantly from the far-IR–radio distribution for low-redshift starburst galaxies. Together, this suggests that AGN are prevalent in the sample (as expected from the likely coeval evolution of the BH and bulge required to generate the tight correlation between their masses; Magorrian et al. 1998), but not necessarily dominant in the bolometric energy released by SCUBA galaxies.

The duration of the very luminous activity of the SCUBA galaxies are important: are their timescales 10 Myr or 1 Gyr? If the former, then several bursts would be required to form a massive elliptical galaxy. In the spectra with the highest signal-to-noise ratios, stellar and interstellar features have been observed. These can be fitted using starburst synthesis models, to yield a timescale for the starburst activity visible at ultraviolet (UV) wavelengths, and a relation between the star-formation rates at observed optical and submm wavelengths. For our brightest object, N2.4 (Smail et al. 2003) the best fit is for a ∼5 Myr-long instantaneous burst of star formation. The implied star formation rate is about 1000 M⊙ yr⁻¹, which is similar to that inferred directly from its submm and radio flux densities. While not all sources may contain such a short burst of star-formation dominated energy output, this example is likely to define the paradigm for the nature of a significant fraction of SCUBA galaxies.

The morphologies of a subset of SCUBA galaxies have recently been studied with HST-STIS by Chapman et al. (2003d). Fig. 3 shows a montage of several representative examples, typically revealing multi-component, distorted galaxy systems that are reminiscent of mergers in progress. There are no examples of isolated, compact sources, and we conclude generally that the morphologies of SCUBA galaxies are generally consistent with hierarchical galaxy formation scenarios in which the most intense activity occurs when gas-rich, high-redshift galaxies collide and merge. Although they could be the sites of spheroid formation, most spheroids do not form in a monolithic collapse of primordial gas clouds at extreme redshifts.
Figure 1. The rest-UV spectrum of several radio–SCUBA galaxies in our sample: upper left N2.4, showing P-Cygni absorption line profiles, and a host of stellar and interstellar features. The spectrum is best fit by a $\sim$5 Myr-old starburst, with an inferred star-formation rate of $1000 \ M_\odot \ yr^{-1}$. upper right N2.13 revealing strong Ly$\alpha$ and CIV suggestive of a narrow line AGN. lower left SSA13.13, showing only Ly$\alpha$, but recently detected in H$\alpha$ using near-IR narrow-band imaging (Smail et al. in preparation). lower right SSA22.4, showing strong Ly$\alpha$ and other weaker emission lines.
Figure 2. The observed histogram of the redshift distribution for our 55 radio-identified SCUBA galaxies. Curves derived for a model of the radio/submm galaxy populations are overplotted (Chapman et al. 2003c, Lewis et al. 2003), suggesting that the redshifts of the sources missed in the radio identification process lie mostly at moderate redshifts between the radio and submm model tracks. A sample of radio-selected QSOs is also overplotted, revealing a remarkable similarity with our observed distribution for submm galaxies.
Figure 3. The morphologies of 8 SCUBA galaxies as studied with HST-STIS (Chapman et al. 2003d; 4" images centered on the radio position). All are multi-component, distorted galaxy systems reminiscent of mergers in progress.

References

Alexander, D., et al., ApJ, 2003, in press (astro-ph/0211267)
Barger, A., et al., Nature, 1998, 394, 293
Barger, A., Cowie, L., Richards, E., 2000, AJ 119, 2092
Blain, A.W., Smail, I., Ivison, Kneib, J.-P., 1999, MNRAS, 302, 632
Blain, A.W., Smail, I., Ivison, Kneib, J.-P., Frayer D.T., 2002, Physics Reports, 369, 111 (astro-ph/0202228)
Blain, A.W., Chapman, S.C., Smail, I., Ivison, R., ApJ, submitted
Carilli, C., et al., 2001, ApJ, 555, 625
Chapman, S.C., Richards, E., Lewis, G., Wilson, G., Barger, A., 2001, ApJ, 548, L147
Chapman, S.C., Lewis, G.F., Scott, D., Borys, C., Richards, E., 2002a, ApJ, 570, 557
Chapman S.C., Barger A., Cowie L., et al., 2003a, ApJ, 585, 57
Chapman, S.C., Blain, A., Ivison, R., Smail, I., 2003b, Nature, April 17 issue
Chapman, S.C., Helou, G., Lewis, G., Dale, D., 2003c, ApJ, in press, astro-ph/0301233
Chapman, S.C., Windhorst, R., Odewahn, S., Haojing, Y., Muxlow, T., ApJ, 2003d, submitted
Cowie, L., Barger, A., Kneib, J.-P., 2002, AJ, 123, 2197
Eales, S., et al., 1999, ApJ 515, 518
Guiderdoni, B., et al. 1998, MNRAS, 298, 708
Helou, P., et al., 1985, ApJ 440, 35
Hughes, D., et al., Nature, 1998, 394, 241
Isaak, K., et al., 2002, MNRAS, 329, 149
Ivison, R., et al., 1998, MNRAS, 298, 583
Ivison, R., et al., 2002, MNRAS, 337, 1
Lewis, G., Chapman, S., Helou, G. 2003, ApJ, submitted
Magorrian J. et al., 1998, AJ, 115, 2285
Nandra, P., et al. 2002, ApJ,
Neri, R., et al. 2003, A&A, in preparation
Shaver, P., et al., 1998, APS Conf series 156, Highly Redshifted Radio Lines, ed. C.Carilli, S.Radford, K. Menten, G. Langston, (San Francisco: ASP163)
Smail, I., Ivison, R.J., Blain, A.W., 1997, ApJ 490, L5
Smail, I., Ivison, R.J., Blain, A.W., Kneib, J.-P., 2002, MNRAS, 331, 495
Smail, I., et al., 2003, MNRAS, in press, astro-ph/0303128
Steidel C., Adelberger K., Giavalisco M., Dickinson M., Pettini M., 1999, ApJ 519, 1
Steidel, C., et al., 2003, ApJS, in press