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UV/Optical Spectroscopy of Submillimeter Galaxies

Scott C. Chapman[1], Andrew W. Blain[1], Ian Smail[2], and Rob J. Ivison[3]

[1]*Department of Astronomy, Caltech 105-24, Pasadena, CA 91125, USA*
[2]*Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK*
[3]*UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK*

Abstract. We summarize the astrophysical properties of the submillimeter galaxy population gleaned from our optical and near-IR spectroscopic surveys of radio-identified SCUBA galaxies. Precise redshift information allows basic evolutionary properties to be measured, but also facilitates a large range of ancilliary science, including clustering and comparisons with the inter-galactic medium, and detection of CO molecular gas. We demonstrate that the rest-frame UV offers rich astrophysical diagnostics both from individual spectra (AGN characterization and wind outflows) and from stacked spectra of SMGs in different classes (UV-bright and faint starbursts, and type 2 AGN).

1. Introduction

The sub-millimeter galaxies (SMGs– galaxies undergoing large, $> 10^{12}\,L_\odot$ bursts of bolometric luminosity, selected at wavelengths $\sim 850\,\mu$m) are an ideal probe of luminous dust-obscured activity at $z > 1$. Spectroscopic identification and analysis of SMGs is of utmost importance for placing them in a cosmological context. The first hurdle to spectroscopic studies of the SMGs has been identifying them at other wavelengths. The radio (1.4 GHz) has been a preferred means for SMG identification (Ivison et al. 1998; Smail et al. 2000; Barger et al. 2000; Chapman et al. 2001), because of a known tight correlation between the far-IR luminosity and the synchrotron radio emission (which holds for SMGs to $z \sim 2.5$: Kovács et al. 2006), and precise interferometric source positions. Radio wavelengths also offer a useful spatial resolution ($\sim 1.5''$ in VLA A array), and with resolutions as high as $\sim 0.3''$ with MERLIN offer the chance to compare directly with *HST* imaging (Chapman et al. 2004). *Spitzer* is now also proving very useful for SMG identification (Ivison et al. 2004; Frayer et al. 2004; Egami et al. 2004; Pope et al. 2006), albeit without the clear mapping to bolometric energy that the radio affords; star formation rates estimated at $24\,\mu$m can vary by factors of > 10 compared to the radio (Dale et al. 2005).

Identifying the counterparts in the radio immediately led to their morphological characterization: both *HST* and radio wavelengths reveal large, merging galaxies (Chapman et al. 2004). SMGs are in fact the largest UV and optical galaxies at their epoch (Chapman et al. 2003c; Smail et al. 2004; Borys et al. 2006; cf. Almaini et al. 2007).

However, it is redshift surveys that have given us tremendous insight into a hyper-luminous population of cool dust starburst-dominated galaxies (Chapman et al. 2003a, 2005; Swinbank et al. 2004; Simpson et al. 2004), revealing a $\langle z \rangle = 2.3$ and a peak epoch of formation in stark contrast with galaxies traced by their UV light (e.g., Bouwens & Illingworth 2006). Pinning down precise redshifts has allowed millimeter interferometers to directly measure the enormous reservoirs of cool molecular gas in large representative samples of SMGs, spatially resolving the CO emission in some cases, and showing that SMGs represent very massive, merging, and gas-rich systems (Neri et al. 2003; Greve et al. 2005; Tacconi et al. 2006).

This contribution begins by outlining the UV-based spectroscopic context and results for SMGs. Secondly, we present implications for the UV/optical spectral followup of next-generation SMG surveys.

2. Redshifts for SMGs

From a radio-detected sample of SMGs (median $I = 24.5$, radio = $72\,\mu$Jy, submm = 6 mJy), Chapman et al. (2003a, 2005, 2007) were able to obtain spectroscopic redshifts in the rest-frame UV for > 100 SMGs. The task was made easier than expected by strong emission lines, especially Ly α, in $\sim$50% of the radio-SMGs, yielding a 70% spectroscopic completeness. However, the difficulty of the task should also not be underestimated: assembly of the requisite data (ultra-deep radio $\sim$ 50 hr VLA, deep optical, and the submm itself, which remains a difficult atmospheric window to work in), detection and identification of the SMGs (e.g., Ivison et al. 2002, 2005; Chapman et al. 2003b), spectroscopic sensitivity < 4000Å = Keck/LRIS-B (many at $z \sim 2$), faith in radio position, cooperation of $10^{13}\,L_\odot$ objects (extended ionized gas in Lyα, merging pieces), and confirmation with Keck/NIRSPEC Hα, narrow-band imaging, and CO.

Blain et al. (2007) have done further spectroscopic work on the SHADES SMG sample (Mortier et al. 2005), filling in some of the previous incompleteness by focusing on the red ($\sim$1 μm) where Keck/DEIMOS spectroscopy finds sources in the $z = 1.2 - 1.5$ *redshift desert* using the [O II] 3727 doublet.

Photometric redshifts for SMGs are now reasonably constrained from the UV (Chapman et al. 2005; Pope et al. 2005). Indeed, Pope et al. (2006) have used photo-zs to constrain a similar $N(z)$ for complete SMG samples as inferred previously from the radio-SMG fraction. Aretxaga, Hughes, & Dunlop (2005, and this volume) as well as Kovács et al. (2006) have shown the strengths and weaknesses of mm through submm approaches to photometric redshift estimation. The submm clearly has some merit for rough photo-zs if enough bands are included.

3. UV Estimates of SFRs

UV estimation of star formation rates (SFRs) is nowhere as much of a concern as with the SMG population. Figure 1 shows that the UV is clearly not representing $L_{\rm bol}$ on average, with *dust-corrected* UV still underpredicting the far-IR emission by an average factor of 100.

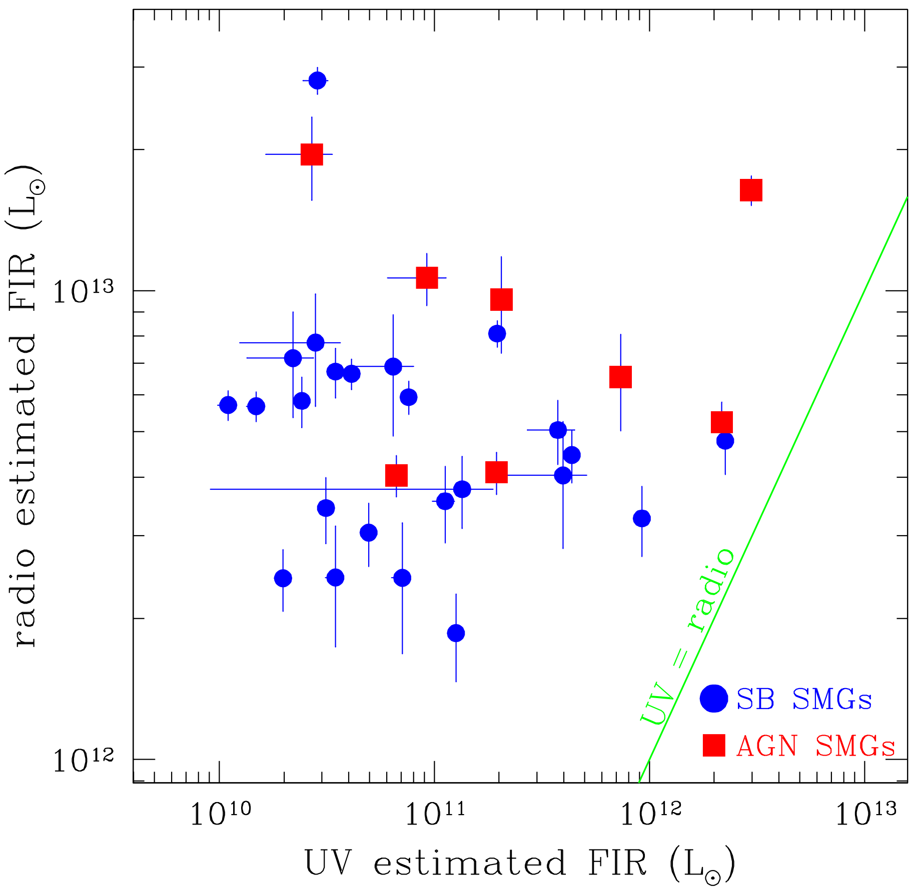

Figure 1. The FIR luminosities of SMGs (used as a proxy for their SFRs) as measured from the radio and submm flux density ratio, compared with the FIR luminosity estimated from the UV luminosity and spectral slope. The line is a simple equality, $L_{\rm FIR}(\rm radio) = L_{\rm FIR}(\rm UV)$, the expected correlation if the dust-corrected UV luminosity is a reliable measure of the total star formation rate in these systems. Note the large offsets of most SMGs from this line. Error bars are derived from uncertainties on the radio, submm, B or g, and R-band fluxes. SMGs showing obvious AGN spectra are plotted as large squares.

We note on the positive side, however, that it is possible to detect many SMGs across the optical spectrum (U, B, R, I, J, H, K), and that SMGs are generally quite bright in *Spitzer*/IRAC bands (Ivison et al. 2004; Borys et al. 2005). The fact that the far-IR luminosities are severely underpredicted does mean that we need submm and radio to get the true luminosities of these galaxies, which are indeed lurking in UV surveys.

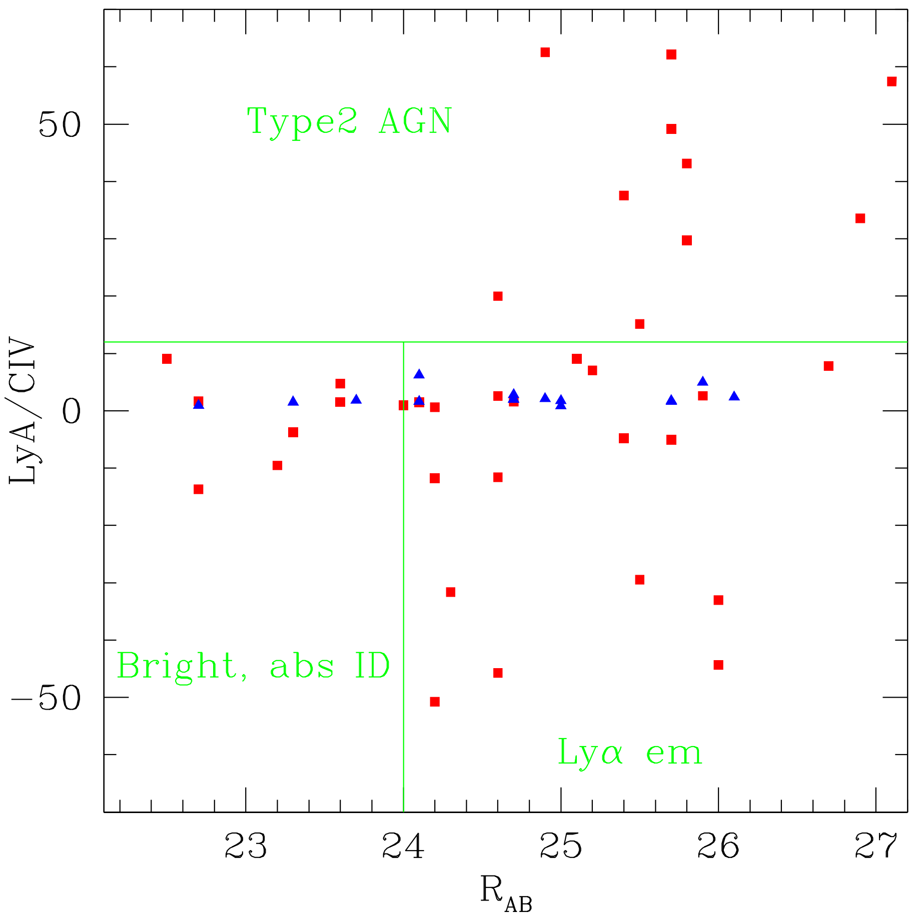

Figure 2. The division of SMGs by their Ly α to C IV rest-EW ratio (squares have Ly α in emission, triangles have Ly α in absorption). Negative ratios imply Ly α in emission and C IV in absorption, while positive ratios have both in emission. The latter subset are candidates for type 2 AGN dominated spectra. UV-bright and UV-faint starburst-dominated spectra have low Ly α to C IV ratios, where $R_{\rm AB} \sim 24$ marks the boundary to clearly distinguish interstellar wind lines for diagnostic purposes.

4. Spectral Classes: SMG Demographics

Using the sample of radio-identified SMGs, we assess the general UV spectroscopic properties of the SMG population. We note firstly that the radio-SMGs overlap significantly with the $R < 25$ UV-selected surveys of Steidel et al. (2005) at the ∼50% level. 25% of the radio-SMGs show clear starburst features, 25% show AGN emission lines (3% are broad-line AGN), and 50% are too faint to classify unambiguously (potentially starbursts, but half have Ly α as the only identifiable spectral feature and half have no clear ID at all).

In Figure 2 we show a plot of C IV versus Ly α equivalent width, primarily serving as a diagnostic of the starburst versus AGN dominance in the UV spec-

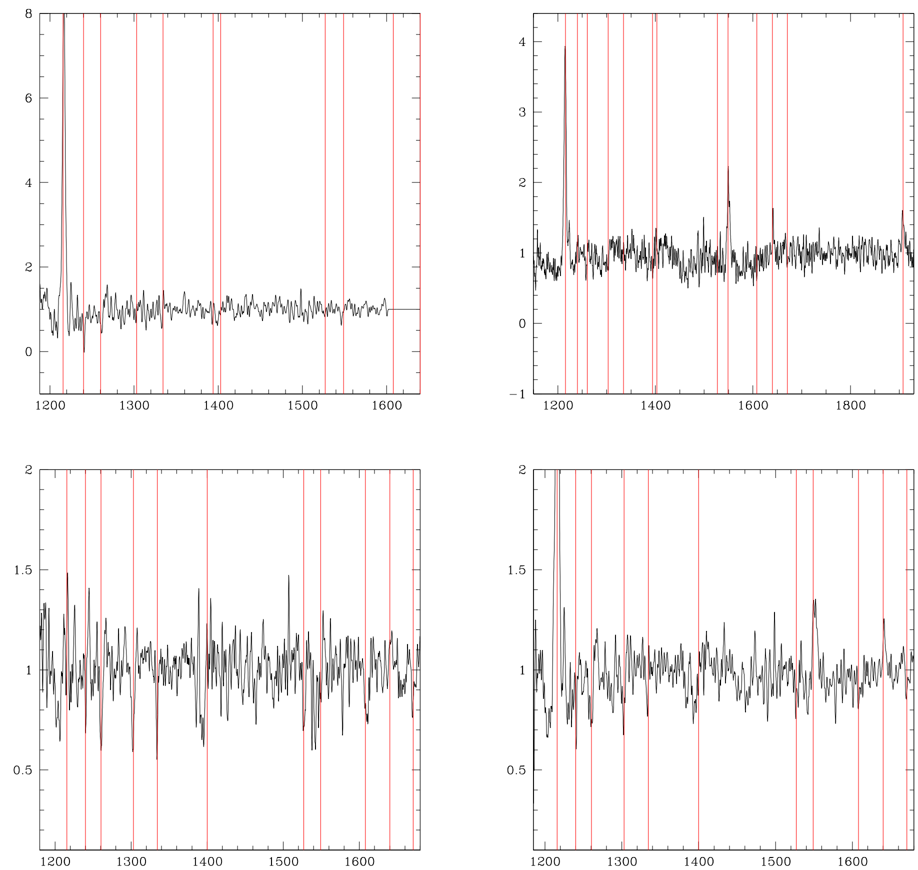

Figure 3. Upper left: UV-faint SMG composite spectra (includes all Ly α emission-line IDs with $R > 24$). Remarkably, no AGN emission features turn up strongly, and ISM absorption lines are detected, suggesting a starburst dominance in these UV-faint SMGs. Upper right: type 2 AGN dominated spectra. Lower left: UV-bright spectra, revealing a range of stellar and interstellar absorption lines. Lower right: The weighted average of all SMG UV spectra, revealing the nature of the characteristic SMG.

tra. We can therefore discuss the different UV *types* of SCUBA galaxies. Stacks of Keck/LRIS rest-UV spectra, divided by their place in the Figure 2 diagnostic diagram, are shown in Figure 3. The stacked spectra reveal clearly the type 2 AGN properties, the dominant starbursts where absorption line identifications were possible, and finally the stack of SMGs identified only through their Lyα emission. Remarkably, in this last category we see no evidence at all for AGN, and in fact there are low-S/N detections of interstellar wind absorption lines suggestive of a dust-obscured starburst dominating in the UV.

With the UV-brightest starburst IDs, we can begin to study the average IGM lines and metallicities, as was done with the LBG and BX galaxies (Shapley et al. 2003; Steidel et al. 2004). Finally, with the type 2 AGN (at all magnitudes), we can compare to other AGN populations at similar redshifts and dis-

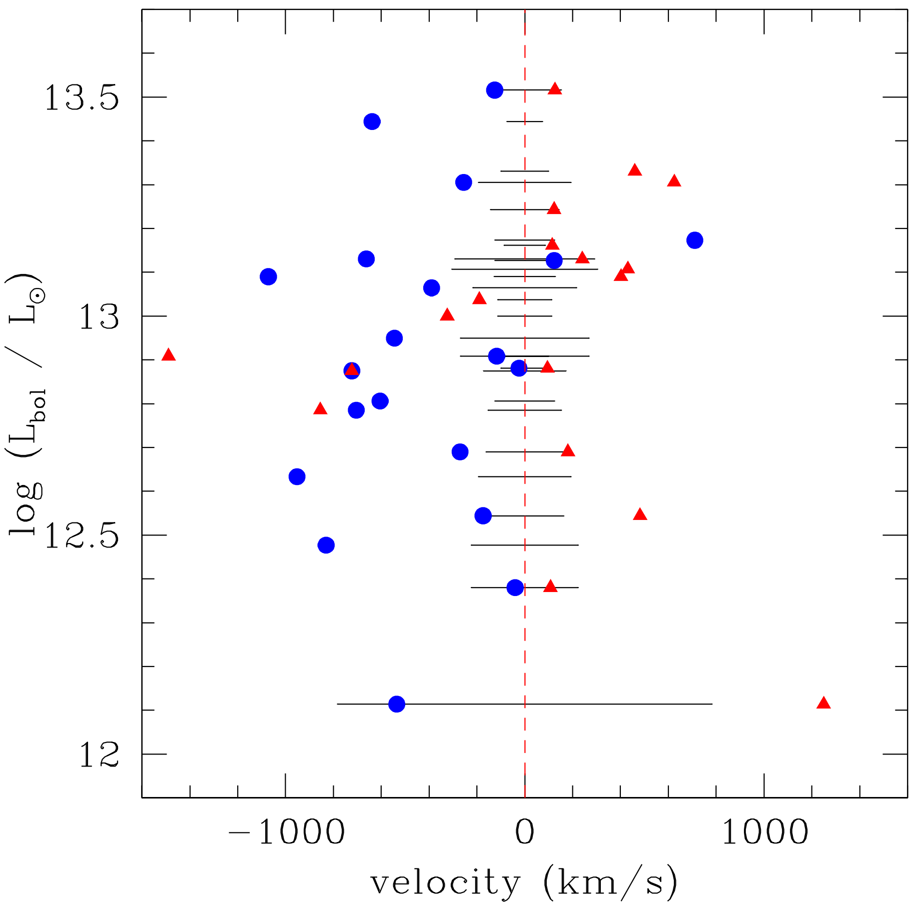

Figure 4. Velocity offsets of the interstellar absorption lines (circles) and Ly α emission (triangles) relative to the systemic redshifts defined by the nebular emission lines (vertical long-dash line), and as a function of bolometric luminosity. The Hα velocity widths are shown as error bars.

cern which AGN phase appears to dominate the submm population when AGN are clearly active. For completeness, Figure 3 shows the weighted combination of all three SMG UV stacks, revealing the average SMG properties in the UV.

The brighter SMGs also allow the wind outflows to be characterized by comparing the nebular line redshifts to the UV absorption lines and the Ly α emission line (Fig. 4). The wind properties are comparable to those found for UV-selected galaxies at similar redshifts (Steidel et al. 2005; Erb et al. 2006).

5. Other Uses of Redshifts

Many other uses of spectroscopic redshifts were touched upon in this conference contribution. The 3D clustering of SMGs (Blain et al. 2004) links the distribution of dark matter to the visible galaxy populations. If SMGs are as

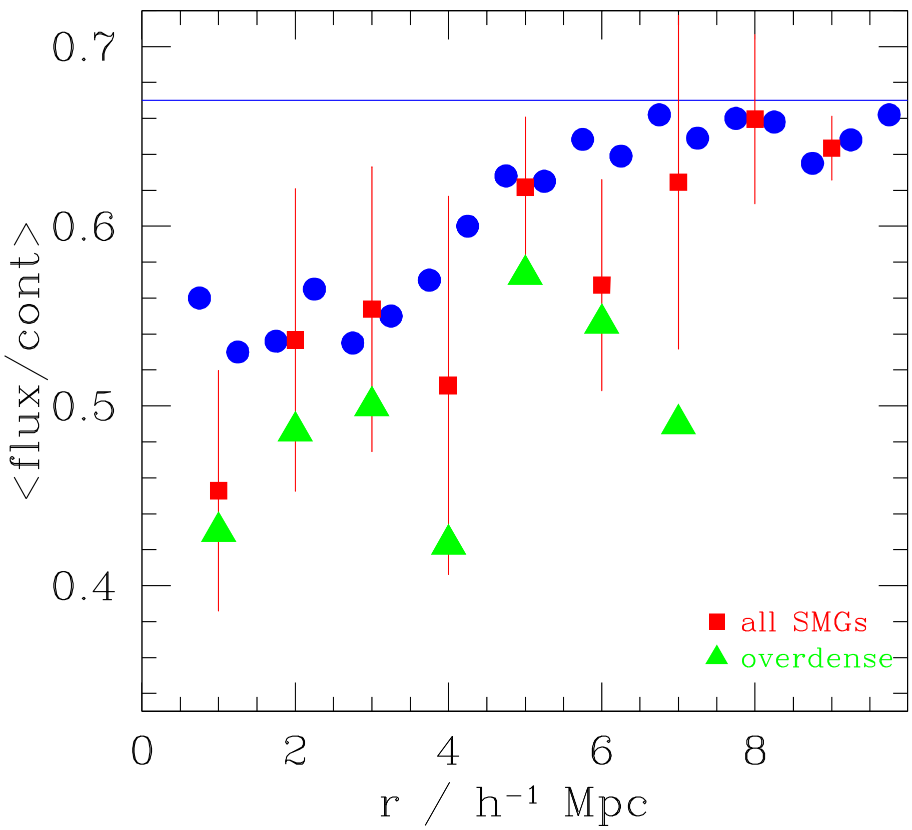

Figure 5. Comparison of the neutral hydrogen clustering strength of $z \sim 3$ LBGs versus SMGs (and SMGs in the most overdense environments).

massive as implied by the CO gas (Greve et al. 2005; Tacconi et al. 2006), then they should be strongly clustered. Blain et al. (2004) found groupings of SMGs within $< 1200\,\mathrm{km\,s^{-1}}$ in redshift space alone, from pairs all the way up to a quintet, finding a $< 0.1\%$ likelihood of random chance and an implied clustering scale length of $R_0 \sim 8h^{-1}$ Mpc This implies that SMGs are very strongly clustered (given the wide SCUBA selection function), and in particular more clustered (massive) than UV-selected galaxies (e.g., Adelberger et al. 2005). The spectroscopic redshifts for our sample of $\sim$ 100 SMGs currently provide the best estimate of clustering we have for SMGs, and spectroscopic redshift measurements will likely aid considerably in studying next-generation submm surveys.

Another area of study that clearly requires spectroscopic redshift precision is the comparison of the intergalactic medium with the SMGs (as done for UV galaxies by Adelberger et al. 2003). In five of our SMG fields, there are sufficiently bright background AGN and/or QSOs to attempt such a comparison.

We probe the relative distributions of SMGs and neutral H I, expecting a strong correlation for these biased massive galaxies in light of the work of Adelberger et al. (2003) for LBGs. The SMGs correlate as strongly as or more strongly than LBGs. (Fig. 5).

6. Implications for Next-Generation Submm Surveys

We now come to the point of asking a difficult question: to what extent will the arduous UV spectroscopic measurements of SMGs be a requirement for followup of the large and efficient next generation submm surveys (e.g., SCUBA-2). There is first the difficulty in identifying SCUBA galaxies at all in other wavelenths (the first requirement for UV/optical spectroscopy). SMGs are too faint on average in the optical for positional coincidence as an identification approach (given the large 15″ SCUBA beam, for instance). We currently need deep 20 cm radio and also *Spitzer* to identify SMGs uniquely and as completely as possible. While this is a hurdle for the large fields to be covered by SCUBA-2, it is not impossible if the science requires it.

However, do we truly require UV/optical spectroscopy of the wide-field SCUBA-2 surveys? Or have we learned everything we need to know from the UV from the existing samples?

In favor, we have reviewed that interesting and complementary astrophysical diagnostics (IGM wind lines, masses, and kinematics) can be gleaned directly from UV/optical spectroscopy. These are diagnostics that continue to be useful and perhaps crucial with larger statistical samples. Further, the precise redshifts essential for many studies (IGM, redshift clustering, dust SED modeling, stacked X-ray spectroscopy) cannot be obtained in any other manner until wide-band receivers on ALMA and large single submm dishes can obtain CO redshifts directly. If we want to do this science with SMGs, we need dedicated UV/optical spectroscopic campaigns over the next five years.

Against obtaining UV/optical spectroscopy of the large next-generation submm samples, we emphasize again that procuring the data is relatively expensive in telescope time (coupled with a relatively low source density, making efficient multiplexing impossible with current spectrographs).

We conclude that although it is expensive to obtain complete IDs with radio/*Spitzer* for the submm samples, this aspect of the data taking will likely be done to exploit many classes of science on SMGs. With samples in hand, there is a clear case for UV and optical spectroscopy of SMGs in the pre-ALMA era. Is UV spectroscopy on SMGs a valuable endeavor in ALMA era (where we are already obtaining directly the spectroscopic redshift from CO, the gas dynamics, the dust morphologies, etc.)? Here too, we suggest that UV spectroscopic diagnostics will continue to be scientifically interesting as a complement to the direct gaseous probes.

7. Conclusions

SCUBA galaxies have many of the expected properties of proto-ellipticals, many derived from the UV/optical spectroscopy. There is, however, some danger as to the inferences that can be drawn from the UV (spatial offsets from the bolometrically emitting region being the main concern). There are many unknowns with regard to the astrophysics of the submm-emitting region, which cannot be probed without ALMA-class instruments.

As to the UV spectroscopy of SMGs from future large submm surveys? YES: valuable astrophysical information. CAUTION: expensive, careful with justification! QUESTION: still valuable in ALMA era?

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References

Adelberger, K. L., Steidel, C. C., Shapley, A. E., & Pettini, M. 2003, ApJ, 584, 45
Adelberger, K. L., Steidel, C. C., Pettini, M., Shapley, A. E., Reddy, N. A., & Erb, D. K. 2005, ApJ, 619, 697
Almaini, O., Dunlop, J. S., Conselice, C. J., Targett, T. A., & McLure, R. J. 2007, MNRAS, submitted (astro-ph/0511009)
Aretxaga, I., Hughes, D. H., & Dunlop, J. S. 2005, MNRAS, 358, 1240
Barger, A. J., Cowie, L. L., & Richards, E. A. 2000, AJ, 119, 2092
Blain, A. W., Chapman, S. C., Smail, I., & Ivison, R. 2004, ApJ, 611, 725
Blain, A. W., et al. 2007, ApJ, in preparation
Borys, C., et al. 2006, ApJ, 636, 134
Borys, C., Smail, I., Chapman, S. C., Blain, A. W., Alexander, D. M., Ivison, R. J. 2005, ApJ, 635, 853
Bouwens, R. & Illingworth, G. 2006, New Astronomy Reviews, 50, 152
Chapman, S. C., Richards, E. A., Lewis, G. F., Wilson, G., & Barger, A. J. 2001, ApJ, 548, L147
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
Chapman, S. C., Windhorst, R., Odewahn, S., Yan, H., & Conselice, C. 2003c, ApJ, 599, 92
Chapman, S. C., Smail, I., Windhorst, R., Muxlow, T., & Ivison, R. J. 2004, ApJ, 611, 732
Chapman, S. C., Blain, A. W., Smail, I., & Ivison, R. 2005, ApJ, 622, 772
Chapman, S. C., et al. 2007, ApJ, in preparation
Dale, D. A., et al. 2005, ApJ, 633, 857
Egami, E., et al. 2004, ApJS, 154, 130
Erb, D. K., Steidel, C. C., Shapley, A. E., Pettini, M., Reddy, N. A., & Adelberger, K. L. 2006, ApJ, 646, 107
Frayer, D. T., et al. 2004, ApJS, 154, 137
Greve, T. R., et al. 2005, MNRAS, 359, 1165
Ivison, R. J., Smail, I., Le Borgne, J.-F., Blain, A. W., Kneib, J.-P., Bezecourt, J., Kerr, T. H., & Davies, J. K. 1998, MNRAS, 298, 583
Ivison, R. J., et al. 2002, MNRAS, 337, 1
Ivison, R. J., et al. 2004, ApJS, 154, 124
Ivison, R. J., et al. 2005, MNRAS, 364, 1025
Kovács, A., Chapman, S. C., Dowell, C. D., Blain, A. W., Ivison, R. J., Smail, I., & Phillips, T. G. 2006, ApJ, 650, 592
Mortier, A., et al. 2005, MNRAS, 363, 563
Neri, R., et al. 2003, ApJ, 597, L113
Pope, A., Borys, C., Scott, D., Conselice, C., Dickinson, M., & Mobasher, B. 2005, MNRAS, 358, 149
Pope, A., et al. 2006, MNRAS, 370, 1185
Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, ApJ, 588, 65
Simpson, C., Dunlop, J. S., Eales, S. A., Ivison, R. J., Scott, S. E., Lilly, S. J., & Webb, T. M. A. 2004, MNRAS, 353, 179

Smail, I., Ivison, R. J., Owen, F. N., Blain, A. W., & Kneib, J.-P. 2000, ApJ, 528, 612
Smail, I., Chapman, S. C., Blain, A. W., & Ivison, R. J. 2004, ApJ, 616, 71
Steidel, C. C., Shapley, A. E., Pettini, M., Adelberger, K. L., Erb, D. K., Reddy, N. A., & Hunt, M. P. 2004, ApJ, 604, 534
Steidel, C., Shapley, A., Pettini, M., Adelberger, K., Erb, D., Reddy, N., & Hunt, M. 2005, in Multiwavelength Mapping of Galaxy Formation and Evolution, ed. A. Renzini and R. Bender (Berlin: Springer), 169
Swinbank, A. M., Smail, I., Chapman, S. C., Blain, A. W., Ivison, R. J., & Keel, W. C. 2004, ApJ, 617, 64
Tacconi, L. J., et al. 2006, ApJ, 640, 228

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