Future Continuum Surveys

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Abstract.   A significant population of distant sub-millimeter-selected galaxies (SMGs) with powerful dust continuum emission, which matches the luminosity of the brightest QSOs and exceeds that of most extreme local galaxies detected by *IRAS*, has been known for almost a decade. The full range of powerful ground- and space-based facilities have been used to investigate them, and a good deal of information about their properties has been gathered. This meeting addresses some of the key questions for better understanding their properties. While continuum detection is relatively efficient, a spectrum is always required both to determine a distance/luminosity, and to probe astrophysics: excitation conditions, total mass, mass distribution, and degree of dynamical relaxation. Once a redshift is known, then the associated stellar mass can be found, and more specialized spectrographs can be used to search for specific line diagnostics. The first generation of submm surveys has yielded a combined sample of several hundred SMGs. Here we discuss the size and follow-up of future SMG samples that will be compiled in much larger numbers by JCMT-SCUBA-2, *Herschel*, *Planck*, LMT, ALMA, and a future large-aperture (25 m-class) submm/far-IR wide-field ground-based telescope, CCAT, planned to operate at a Chilean site even better than ALMA's. Issues concerning placing SMGs in the context of their environments and other populations of high-redshift galaxies are discussed.

1.   Introduction

1.1.   Skewering the High-Redshift Universe for Monster Galaxies

The existence of high-redshift far-IR-luminous galaxies was demonstrated using the 15 m JCMT in the 1990s (e.g., Isaak et al. 1994). The detection of redshifted thermal continuum emission from interstellar dust, with a spectral index $\alpha \simeq 3.5$– where the spectral energy distribution (SED) follows ν^{α}– is possible in several mm/submm-wave atmospheric windows, and multiband observations rule out a substantial contribution from non-thermal synchrotron emission.

The first unbiased surveys through the $450/850\,\mu$m atmospheric windows were made using the breakthrough JCMT-SCUBA 37-pixel array camera (Holland et al. 1999) starting in 1997 (Smail, Ivison, & Blain 1997). The most luminous dusty galaxies were found in very narrow pencil beams (with survey dimensions of order $1 \times 3000\,$Mpc). In principle, objects beyond re-ionization could be detected (Blain et al. 2002), but the majority appear to be at redshifts $1 < z < 3$ (Chapman et al. 2005). The geometry of these surveys remains a series of radial porcupine spikes, with a total area of less than a square degree in extent (Laurent et al. 2006; Mortier et al. 2005).

The identification of similar populations of dusty far-IR-emitting objects on the short wavelength side of the dust emission peak that lies at of order $100\,\mu$m in the rest frame was made by the ISOCAM camera (Altieri et al. 1999) at $15\,\mu$m,

yielding a cosmologically distant ($z \simeq 1$) view of the class of galaxies detected by *IRAS*. *Spitzer Space Telescope* is now finding a hugely greater number of far-IR dominated galaxies at moderate and high redshifts. By comparison with SMG surveys the *Spitzer* surveys are much wider, covering about $60 \deg^2$ to a distance in excess of $z \simeq 1$.

Deployments of other instruments at mm/submm wavelengths, including the 1.2 mm MAMBO at the IRAM 30 m telescope at Pico Veleta, Bolocam at CSO, AzTEC at JCMT, and the forthcoming $450/850\,\mu$m SCUBA-2 at JCMT and $870\,\mu$m LABOCA at the APEX 12 m telescope will soon swell the number of detected SMGs well into the thousands, while *Spitzer* surveys have cataloged more than 10^5 far-IR objects in relatively wide, deep surveys. SED measurements using the $350\,\mu$m CSO SHARC-2 camera are now being generated for existing samples (Kovács et al. 2006; Laurent et al. 2006).

In Figure 1 the ranges of luminosities and dust temperatures associated with detectable SMGs and far-IR counterparts are shown for two representative redshifts $z = 1$ and 3. The k-correction from redshifting the steep thermal Rayleigh-Jeans spectrum ensures that the submm bands longer than about $200\,\mu$m are very efficient to survey for the most luminous galaxies with only a weak dependence on redshift. However, the peak frequency of the dust emission spectrum, which is set predominantly by a dust temperature (T_{d}), also has a substantial effect on the detectability of SMGs. For a given luminosity and redshift, cooler SEDs can be more easily detected (Blain, Barnard, & Chapman 2003).

The sensitivity levels plotted in Figure 1 represent the confusion limits of existing and future telescopes, which are the ultimate limits to the depths of their surveys, imposed by spatial power fluctuations from faint unresolved sources in the telescope beam. Confusion limits the reach of existing surveys to only the most luminous galaxies. Confusion noise leads to a beam-to-beam fluctuation level that is approximately the same as the flux of the source that occurs at a surface density of one per beam. However, the fluctuation distribution is skewed to high flux values, and so the reliable identification of detections requires an intrinsic flux density of order 10 times greater (see Blain et al. 2002).

1.2. Identifying and Studying the Detected Galaxies

The key problem for identifying and studying SMGs has been their significant redshifts and modest positional accuracies. The increase in atmospheric noise with frequency ensures that higher-resolution, shorter-wavelength submm images are rarely available and have been of only modest help in making identifications. Even for the most significant detections with the CSO's $350\,\mu$m SHARC-2 camera, the target galaxies are still only detected in a 9 arcsec beam matched to a 70 kpc scale– much larger than the intrinsic extent of the galaxies.

For the future, neither space-borne nor ground-based facilites will be able to provide very accurate positions and image internal structures. The CARMA, IRAM, and SMA interferometers can contribute, but only in very long exposures (e.g., Tacconi et al. 2006). While the *Spitzer*, *Herschel*, and *Planck* space telescopes can detect many of these objects, it is difficult to identify the most distant and luminous based on submm/far-IR detections alone. Accurate locations and size measurements will be just within the capability of a 10–20 m
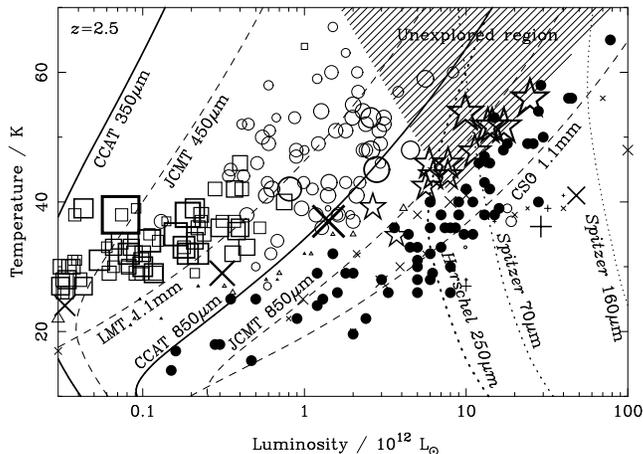
Figure 1.   The ranges of SEDs and luminosities of dusty galaxies identified at a range of redshifts (see Blain et al. 2003 for data), along with some additional *Spitzer* space telescope results (five-pointed stars). Even space-based facilities have difficulty in probing the shaded region. The overplotted curves define the confusion limits to detecting galaxies at $z = 2.5$ with a variety of facilities. Note that submm imaging is crucial to detect the range of known SEDs. Only CCAT can reach luminosities comparable to the Milky Way ($\simeq 6 \times 10^{10} L_{\odot}$) at high redshifts.

class far-IR space telescope (e.g., *SAFIR*), and an ideal goal for a space-based interferometer (e.g., *SPECS*). ALMA will be a key facility for resolving and revealing the astrophysics of these objects, providing rapid, spatially resolved images of SMGs in several bands, including a resolved spectroscopy capability. Nevertheless, ALMA will image galaxies only one by one, limiting the number of faint sources that can be imaged to the range 10–100 per hour.

1.3.   Identification-Enabled Spectroscopy

Throughout the initial studies of SMGs the bottleneck was obtaining redshifts, which enable luminosities to be derived accurately and, via more detailed spectroscopy at both near-IR and mm/submm wavelengths, provide better diagnostics of their physical conditions.

A modest number of redshifts were identified serendipitously, starting with Ivison et al. (1998), who identified a galaxy in the background of the rich cluster A370. This galaxy has turned out to be a reasonably typical, if optically relatively bright, example of the population. With a redshift, information about physical conditions was provided by CO spectroscopy, first with the OVRO Millimeter Array and then the IRAM Plateau de Bure Interferometer(PDBI). Recently, painstaking high-resolution PdBI observations have allowed the first insight into the internal motions of molecular gas fueling these galaxies (see Tacconi et al. 2006 and references therein).

A more systematic approach has been to locate the likely counterpart using wide-field, ultradeep radio images, enabling more certain spectroscopy. This relies on the detection of non-thermal radio counterparts to the SMGs, exploiting
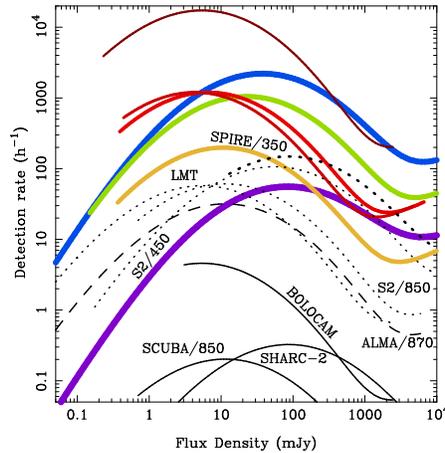
Figure 2.   Comparative detection rates for galaxies using labelled facilities/wavelengths and CCAT (at 200, 350, 450, 620, 740, 850 μm and 1.1 mm in order of decreasing line width). At faint fluxes the curve for each device is truncated at an aggressive definition of the confusion limit.

the accurate radio astrometry to aim multiobject optical spectrographs. The deepest radio images are required, in which case about 60-70% of the SMGs are identified (see Chapman et al. 2005, and this volume).

The radio-led approach has enabled a majority of the SMGs to have precise redshifts assigned, allowing the subsequent investigation of the targets using millimeter, X-ray, and near-IR spectrographs (e.g., Alexander et al. 2005; Swinbank et al. 2004; Hainline et al., this volume). These observations do not yet provide resolved velocity-position information to reveal the detailed astrophysical conditions within the SMGs. However, the SMGs can be catagorized securely as ultraluminous, massive, strongly clustered galaxies that contain relatively weak AGN (Alexander et al. 2005). Without redshifts, these investigations would either be impossible or much more expensive in observing time.

These follow-up observations typically require 2–3 hr of optical spectroscopy using a 10 m class telescope, with a significant multiplex gain at source densities of order 1 arcmin^{-2}. They also rely on 20 hr duration radio images, to enable 20 hr duration CO observations. Hence, the amount of time required to carry out this process for a sample of many thousands of galaxies would be a great challenge. Colors from combined optical, near-IR, and *Spitzer* imaging cannot be used easily to pre-select the most likely counterpart to a submm detection, owing to the large surface density of candidates.

2.   Future Continuum Surveys

The biggest surveys so far (Mortier et al. 2005; Laurent et al. 2005) provide a clear picture of the nature of the majority of the luminous SMG population when combined with suitable spectroscopy (Chapman et al. 2005). However, to compile a sample of order 100 optical spectra has required of order 20 nights of time using the Keck telescopes. Hence, the current follow-up process *cannot*

be scaled up directly to cope with the fruits of the next generation of surveys. A process to sift, prioritize, and classify the detected galaxies based on their submm properties will be important.

The detection rates estimated in Figure 2 indicate the difficulty of obtaining a large number of redshifts for galaxies found using JCMT/SCUBA-2, APEX/LABOCA, LMT/AzTEC, or ALMA. The situation will be even more challenging for surveys using the proposed Cornell-Caltech Atacama Telescope (CCAT). CCAT is a 25 m class telescope with a 20 arcmin field of view, operating at wavelengths as short as 200 μm from a mountaintop close to the ALMA site. Current first-light instrumentation for CCAT includes a short-wavelength camera consisting of 32,000 pixels, and a long-wavelength camera making multicolor 2 mm–670 μm images using an array of $\simeq$ 16,000 microwave-addressed MKIDS detectors, which produce a prodigious detection rate. If next-generation wide-field instrumentation can be accommodated, the LMT also has the capability to make very large mm-wave surveys. CCAT's multi-color submm surveys will sample the SED where the thermal spectrum starts to peak, and so should include significantly more information about the source population than detections of pure Rayleigh-Jeans thermal emission.[1]

While the clustering and colors of the SMGs that these surveys will uncover remain interesting, the key questions that need to be answered about their nature all rely in some way on spectroscopic follow up.

3.   Key Questions for Understanding the SMG Population

In light of existing surveys, there are two main outstanding questions. First, what is the nature of the significant minority of the existing samples that have not yielded redshifts via the radio-optical route? Secondly, what is the relationship between SMGs and other samples of high-redshift galaxies? These questions require additional capabilities in the mm/submm: the identification of a larger fraction of the SMGs in the surveys, and the detection of less luminous examples. Natural capabilities to help with these questions are the subjects of this meeting, "z-machines" and ALMA respectively.

The precision and flux density range of source counts, color distributions, and possibly angular correlation functions will be better established as the SMG sample sizes increase. Current counts extend from about 0.5–20 mJy, with an accuracy of order 10%, while little is known about mm-submm colors (Laurent et al. 2006; Kovács et al. 2006). Where redshift and color information coincide, the SEDs of the SMGs are consistent with a range of temperatures spread by about 30%, centered on 40 K (Kovács et al. 2006)– remarkably close to the temperature inferred by assuming that both scant samples of galaxies from the first-generation surveys by *ISO* and SCUBA in 1998 were drawn from the same strongly-evolving population (Blain et al. 1999).

Absent three-dimensional redshift information, determining clustering properties in projection with such deep surveys is hard: the 3000 Mpc depth of an SMG survey corresponds to a 110 deg swath of sky to match its width and depth

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[1]This could be even more important if additional emission components can be found, such as ices in pre-reionization objects (Dudley, Imanishi, & Maloney 2006)

at $z = 3$, while to enclose even a single realization of the minimum representative comoving volume that is matched to the largest scale observed in the galaxy distribution today (of order $10^6 \, \mathrm{Mpc}^3$) requires a field about $0.4 \, \mathrm{deg}^2$ in size for $1 < z < 3$.

Hence, covering a large area of the sky in an SMG survey is essential, both to map the evolving structure that could be highlighted by a population of SMGs biased to the densest regions, and to identify the most extreme examples of the population, including the 10–20% of 100–200 mJy galaxies at $850 \, \mu\mathrm{m}$ (at a density of order $0.1 \, \mathrm{deg}^{-2}$) that are likely to be gravitationally lensed by foreground galaxies (Blain 1998).

3.1. Links to Other Populations: a Factor of Ten Greater Depth

The kind of survey discussed above with SCUBA-2 will generate a larger sample of SMGs that are similar to or more extreme than those known currently, and not a significantly less luminous population. They thus cannot readily detect galaxies that bridge between large spectroscopic samples of optically-selected galaxies (Steidel et al. 2003) and the rarer, more luminous SMGs. The limit to their depth is imposed by the floor of confusion noise (Fig. 1). As it is difficult to determine the degree of dust extinction present from even the most extensive optical, near-IR, and mid-IR photometry, however, far-IR/submm data remain an essential supplement in order to identify the true luminosities of high-redshift galaxies, and to construct a complete and accurate luminosity function.

While ALMA can reach unprecedented depths, it can only do so in modest field areas owing to its sub-arcminute instantaneous field of view. Ultradeep pencil beam surveys will be ALMA's unique territory, and it is ideal for imaging any known or discovered target of arbitrary brightness; moreover, it is capable of unique spectroscopic imaging. Nevertheless, ALMA is not best suited to surveying a representative volume of the high-redshift Universe for typical L^* galaxies, owing to the need to expend large amounts of time that would be better devoted to detailed imaging (see Fig. 2). This is due to the modest field of view of ALMA.

While ALMA cannot survey rapidly, existing single-antenna facilities are unsuitable for beating confusion and reaching the necessary depths to feed typical galaxies to ALMA. Focal plane MMIC arrays on interferometers like CARMA, combined with giant FPGA-based programmable correlators, could provide a bridge to survey the relevant population at mm wavelengths. A 25 m-class submm telescope with excellent optical quality at an excellent site– like CCAT– could also detect and locate typical galaxies directly in great numbers for follow-up spectroscopic imaging using ALMA. Working at submm wavelengths, CCAT would also provide SED information for the detected galaxies.

The reason that CCAT is so much more capable than a 10–15 m class submm telescope, or a 50 m mm-wave telescope, is made clear by the confusion noise levels represented in Figure 1. Owing to the steep distribution of source flux densities in the submm waveband, and to the turnover in the counts at a flux density of order 1 mJy in order to match the measured finite background radiation intensity (Fixsen et al. 1998; Kashlinsky et al. 2005), the level of confusion noise drops dramatically as aperture increases beyond 15 m and observing wavelength is reduced shortwards of 1 mm. When combined with the greatest atmospheric

transparency, this is the key to the scientific power of CCAT, securely based on the direct results of existing observations.

3.2.   To Define a True 3D Distribution: Complete Spectroscopy Over a Representative Volume

To survey a volume with a cubic geometry, the existing "hypodermic needle" beams of submm surveys must be extended to 100 deg scale fields. While a less extreme pencil-beam geometry would still provide a good view of large-scale structure, a distance estimate is still required for a substantial fraction of the 2×10^5 1 mJy galaxies expected over a 100 deg^2 field. The capabilities of deep optical redshift surveys are increasing dramatically over the next decade. The WFMOS instrument for Gemini[2] will be capable of producing 4000 redshifts per hour at an efficiency similar to existing spectrographs that can obtain 30–40 in the same time. The patrol field of WFMOS is 2 deg^2, ideally matched to the density of mJy SMGs. Hence, optical spectroscopy of the detected galaxies would be a very practical proposition. Although optical spectroscopy is likely to miss about 50% of SMG targets, and accurate positions are still required for fiber positioning, substantial spectroscopic coverage for both SMGs and their companions and common structures will be available for next-generation surveys. However, it will be a stretch to keep pace with CCAT's potential 2π sky coverage to 1 mJy at 350 and 850 μm in of order 10 yr. It will be feasible to assign 10–100 hr exposures to target the faintest galaxies, given that 4000 galaxies can be targeted simultaneously with WFMOS. The difficulty of identifying the most extreme, distant, and potentially exciting targets found at submm wavelengths is difficult to assess, but SMGs are known to be Lyα emitters (Chapman et al. 2005), a trend that should increase at high redshifts as metallicity declines and morphology is likely even more irregular (Chapman et al. 2003). A spectrograph covering 0.3–1.0 μm can detect lines out to $z = 7.2$, and it is unlikely that more than a few percent of SMGs lie beyond reach.

A very deep imaging survey from a Large Survey Telescope (LST), including PanSTARRS, could provide a route to identifying many SMGs that are known to be extended and patchy and have a wide range of colors, both internally and across the population. Combining the power of the EVLA[3] to obtain μJy sensitivity maps over a 1 deg^2 field in about a day with the sub-arcsec-accuracy centroids from detections at greater than 10σ levels in 350 μm CCAT maps, there is an excellent opportunity to follow up future SMG surveys.

3.3.   Pre-Reionization SMGs: First Metals and Earliest Structures

The most exciting dusty galaxies are those found during or prior to reionization, subject to the assumption that metallicity and dust content are sufficiently great. These assumptions are reasonable following the detection of some of the most distant QSOs at mm wavelengths. These galaxies are no more difficult to detect in the continuum at submm wavelengths than those at $z \simeq 1$, but are much harder to detect at any other wavelengths. ALMA can certainly detect

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[2]http://www.noao.edu/meetings/subaru/

[3]http://www.aoc.nrao.edu/evla/

and image any such galaxies, but it will be difficult to identify, pre-select, and determine their redshifts from imaging data alone.

4.   The Role of Photometric Redshifts

4.1.   Optical/Near-IR

The industry of obtaining redshift estimates from the colors of stellar populations can be used to provide estimates for SMG counterparts. While subject to uncertainty about the correct identification and possible chance superpositions, the results of a deep LST survey are likely to be very useful for providing information about large-scale structure traced by SMGs.

4.2.   Far-IR/Submm/Radio

The huge haul of galaxies that will be found out to redshifts far beyond unity in future surveys can be identified with a variety of archived data from the space missions *Spitzer* and *Herschel*, along with the *ASTRO-F* (*Akari*), *Planck Surveyor*, and *WISE* all-sky surveys, and an EVLA (and ultimately SKA) large-area FIRST-style survey program. With benign assumptions about the range of SEDs for SMGs (Blain et al. 2003), it is possible to obtain photometric estimates of redshifts for SMGs (Carilli & Yun 1998; Aretxaga et al. 2005, and this volume), and of course owing to the thermal nature of the SED, very accurate measurements of $T/(1 + z)$ can be obtained. Surprisingly, the very different emission mechanisms responsible for the FIR-radio correlation do not break this temperature-redshift degeneracy, leading to a similar measurement of $T/(1 + z)$ from radio-submm colors (Blain 1999; Yun & Carilli 2002).

While the information on this combined T-z quantity is valuable, no increase in the number of data points or the photometric accuracy can overcome the degeneracy, unless there is prior information available about a tight relationship between the luminosity and temperature of the target sources. The best indications are that the temperatures of SMGs are scattered by of order 30% (Laurent et al. 2006; Kovács et al. 2006).

With ALMA, or a z-machine, the spectral index of the SMG thermal emission can be measured directly in the band, to provide a very similar redshift indicator, as shown in Figure 3. This provides information similar to a color measurement, but requires only a single tuning. As with a color determination, the accuracy of the fitted SED information is greater if the peak of the SED is probed at submm wavelengths.

4.3.   Radio Spectral Details

Multi-color radio observations may provide redshift probes, as the reddest radio sources are likely to be found where the more intense high-redshift CMB provides a more efficient loss mechanism for relativistic electrons than the internal magnetic fields of galaxies, especially prior to reionization. While this spectral index will not provide an accurate redshift, it might be a sufficient guide to highlight the galaxies with the faintest, reddest, and steepest radio spectral indices that could be the best targets for detailed follow-up study as potential pre-reionization examples of the population.
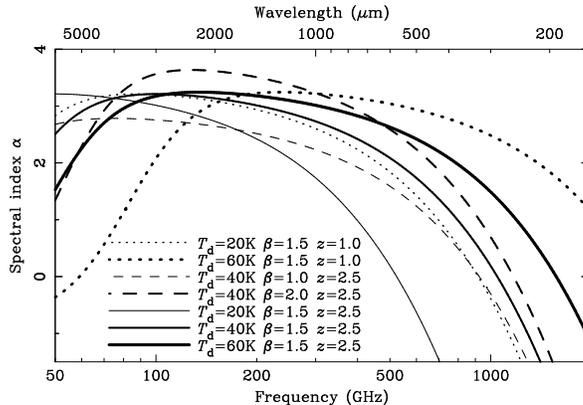
Figure 3.   The spectral index α ($f_\nu \propto \nu^\alpha$) as a function of frequency for different SEDs, defined by temperature $T_{\rm d}$, emissivity index β and redshift. ALMA and redshift machines can both determine the continuum spectral index in a single tuning. The index can be used as a redshift indicator, subject to the quantity $T/(1+z)$ being determined accurately, as for submm/mm colors. The change in spectral index with redshift–temperature is more dramatic at shorter submm wavelengths.

5.   The Role of ALMA

ALMA will be capable of imaging any galaxy detected at long wavelengths in a matter of minutes to hours, and is almost immune to confusion noise. Hence, obtaining a spectrum from ALMA with an 8 GHz bandwidth will allow a CO line to be detected in about 25% of tunings on a chosen target at $z \sim 2.5$ (CO ladder separation of $115/(1+z) = 33$ GHz). ALMA can thus likely find redshifts for even the most difficult cases after four adjacent tunings, and can do it even more easily for higher redshifts: at reionization ($z = 6.7$), adjacent CO lines are separated by just 15 GHz.

5.1.   Line-to-Continuum Ratio

By determining the equivalent width (EW) of the CO line, either ALMA or a z-machine can assign a likely transition to a single line (Blain 2000): owing to the redshifting of the peak of the underlying continuum emission, the CO EW should decrease systematically as J increases. After detecting one line, this estimate of J obtained from the EW should thus enable a direct search using ALMA, choosing the frequency tuned to detect an expected confirming CO line with a known J value in an available band.

6.   Summary

1. The capability of continuum detectors at mm/submm wavelengths is becoming dramatically greater. SCUBA-2 nears reality, while several new concepts are being demonstrated for multiplexing detectors and filling large focal planes with them. A large-aperture, wide-field submm-wave

telescope like CCAT would be the ideal platform for them: able to overcome confusion noise and probe a large fraction of the SED for accurate determination of luminosity.

2. The capabilities of ALMA and next-generation optical spectrographs are sufficiently powerful that spectroscopy of galaxies detected in the submm should be viable, with WFMOS finding redshifts for over 1000 candidates per hour, and ALMA studying the astrophysics of many tens per hour. Hence, multiwaveband followup is definitely going to remain important.

3. Redshift machines will provide valuable astrophysical information for exciting difficult cases in the period before ALMA is in service. Line to continuum ratios and luminosity-temperature constraints can be exploited to help interpret the results.

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Discussion

Scoville: How deep does the survey have to go before there are multiple sources per ALMA beam and ALMA becomes efficient for followup?

Blain: At $350\,\mu$m the ALMA primary beam is of order $15''$. This requires a source density of order $20 \times 3600 \simeq 7 \times 10^4$ per square degree. The depth at which this surface density is reached is likely to be about 0.2 mJy, about ten times deeper than existing survey results.

Ekers: What range of depth and area will be possible with CCAT?

Blain: Everywhere from Sloan-sized regions to the depths of existing surveys, to the confusion limit over the deepest fields like GOODS, extending the fields out to COSMOS-sized representative volumes at high redshifts.

Yun: With a large number of sources identified by future surveys, what is the prospect for doing follow-up studies?

Blain: Excellent, but in a partial sense, with subsets and subsamples taking the lead, along with concerted campaigns in the best studied fields like GOODS, where ALMA will be taking us extremely deep.

Gawiser: I recognize the importance of your second bullet that optical/NIR MOS is inefficient at sky density $\leq \sim 5$ arcmin^{-2}, but I think you're being a bit pessimistic. Lyman break galaxies have about 1.5 arcmin^{-2} and MOS has been quite effective for them. For lower sky densities, surveys can put multiple science target categories on a single mask (as we've done for MUSYC) and take advantage of wide-field spectrographs like Magellan+IMACS or VLT+VIMOS.

Blain: I agree, noting the twiddle before 5 arcmin^{-2}. I expect the safest place to make the surveys will include substantial extant spectral data, like EGS, GOODS, COSMOS, etc.