The Discovery of Submillimeter Galaxies

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Abstract. I briefly describe some results about luminous distant dusty galaxies obtained in the 5 years since sensitive two-dimensional bolometer array cameras became available. The key requirements for making additional progress in understanding the properties of these galaxies are discussed, especially the potential role of photometric redshifts based on radio, submillimeter (submm) and far-infrared (IR) continuum observations.

1. Introduction

In 1997 the SCUBA camera was commissioned at the 15-m JCMT in Hawaii, providing 2.5-arcmin-wide images at wavelengths of 450 and 850 µm with resolutions of 7 and 15" respectively. The MAMBO 1.25-mm camera at the 30-m IRAM telescope provides a similar capability (see Dannerbauer et al. 2002), while the 350-µm SHARC-II and 1.1-mm BOLOCAM cameras being commissioned at the 10-m Caltech Submillimeter Observatory (CSO) should provide significantly enhanced performance within a year. In the future, BOLOCAM is expected to observe from the 50-m mm-wave GTM/LMT telescope under construction in Mexico, a larger-format 8×8-arcmin² camera SCUBA-II is being designed in the UK, and developments of MAMBO are planned for APEX – a new 12-m telescope at the 5000-m ALMA site in Chile. APEX will join the 10-m-class Japanese ASTE submm telescope at the ALMA site for which a large bolometer camera is being designed.

SCUBA was the first submm camera able to survey fields large enough to detect the redshifted thermal dust emission from previously unknown galaxies (Smail, Ivison & Blain 1997). The peak of the emission from galaxies, typically at 60–200 µm in their restframe, corresponding to a range of dust temperatures between about 60 and 20 K, is redshifted into SCUBA’s observing bands. The steep submm Rayleigh–Jeans slope of the dust emission ensures that distant galaxies with similar bolometric luminosities and spectral energy distributions (SEDs) would produce similar flux densities at all redshifts from z ≃ 0.5 to z ~ 5, assuming the same spectral energy distribution (SED). The detectability of galaxies does depend on the details of the SED, in general being greater for cooler temperatures at a fixed luminosity and redshift (see Blain et al. 2002).

More than 300 high-z submm galaxies (SMGs) have now been detected by SCUBA and MAMBO, while BOLOCAM (Glenn et al. 1998) could detect new examples at a rate of order 1 per hour. Various types of surveys have been made: in narrow fields to exploit the gravitational lensing effect of clusters of galaxies...
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(Smail et al. 2002; Chapman et al. 2002a; Cowie, Barger & Kneib 2002); in the Hubble Deep Field (Hughes et al. 1998); and in wider shallower surveys (Eales et al. 1999; Borys et al. 2002; Scott et al. 2002) covering a total of about 0.25 deg$^2$.

These SMGs are responsible for a significant fraction of the star-formation/AGN activity at $z > 1$ (Blain et al. 1999a). It is vital to understand their individual properties if we are to understand the formation of galaxies as a whole. Their inferred space density is similar to that of giant Elliptical galaxies in the local Universe, and it has been suggested that they are high-$z$ formation events of these rare galaxies (Eales et al. 1999), presumably in the most massive dark-matter halos with the lowest specific angular momenta. It is more likely that they reflect a more common, short-lived phase involving the formation of galactic bulges in perhaps episodic mergers (Blain et al. 1999b). The test of these ideas is to measure the redshifts, clustering properties and mass distribution of a representative sample of SMGs.

2. Finding redshifts and studying astrophysics

The coarse ($\sim$15$''$) resolution of submm images ensures that there are many possible faint optical counterparts to the detected galaxy. Hence, while some SMGs have bright optical counterparts (Ivison et al. 1998, 2000), most remain unidentified at optical wavelengths. Final confirmation of a correct identification in both position and redshift is provided by detecting (sub)mm-wave CO molecular line emission with a suspected redshift in the narrow spectral window of existing (sub)mm-wave spectrographs (Frayer et al. 1998, 1999).

Mm-wave continuum interferometer images of the fields have reduced positional uncertainties to $\sim$1 arcsec for several SMGs (Downes et al. 1999; Frayer et al. 2000; Dannerbauer et al. 2002), but are very expensive in observing time. Deep near-IR imaging to $K > 22$ tends to reveal plausible red counterparts for many SMGs (Smail et al. 1999; Frayer et al. 2003) by their $J - K$ and $I - K$ colors. Deep optical/near-IR spectroscopy of these galaxies can then be attempted to find redshifts. The most efficient technique for determining redshifts, however, appears to be to exploit very deep radio images. For reasonable SEDs, SMGs with 850-µm flux densities of about 5–10 mJy (with luminosities $\sim 10^{13} L_\odot$) should be detectable in $\sim 10 \mu$Jy RMS 1.4-GHz VLA images out to $z \approx 3$, if they lie on the far-IR–radio correlation observed for local galaxies (Condon 1992): (see Barger, Cowie & Richards (2000) and Chapman et al. (2001, 2002b). The wide field ($0.25 \text{deg}^2$) and accurate sub-arcsec astrometry of VLA images, coupled with the low surface density of the faintest radio sources as compared with optically-selected galaxies yield accurate positions for a large fraction ($\sim 70\%$) of the SMGs brighter than 5 mJy at 850 µm. This provides an opportunity for efficient multi-object optical spectroscopy. In March 2002, about 25 spectra were obtained using the Keck-LRIS spectrograph (Chapman et al. 2003). These will be subject to CO molecular line spectroscopy to confirm the identifications and to study both their gas masses (via velocity dispersions) and excitation conditions (via line–line and line–continuum ratios), using mm-wave interferometers in the 2002-2003 Northern winter. Only a handful of reliable redshifts were available for SMGs in 2001: now it is likely that a luminosity function of these radio-selected SMGs should be available in 2003.
3. Photometric redshifts

The key target of investigating the SMGs is now to find their physical properties, especially their masses. However, just obtaining a reasonably complete redshift distribution is important for fixing their form of evolution and ensuring their fractional contribution to the energy emission of all galaxies is correctly accounted for (Eales et al. 1999; Blain et al. 1999a).

As redshift surveys were generally unsuccessful until (Chapman et al. 2003), photometric techniques have been proposed to provide redshift information (Eales et al. 1999; Hughes et al. 1998, 2002). The key information available is radio (Carilli & Yun 1999), submm and mid-/far-infrared photometry, typically from VLA, SCUBA and ISO respectively. The IRAS survey is not sufficiently deep to detect SMGs; ISO data is deeper, but covers only a small area and is only useful for the closest (Soucail et al. 1999) or brightest examples (Ivison et al. 1998). The SIRTF space telescope will be ideal for finding far-IR SEDs.

Fitting a thermal spectrum to a galaxy at uncertain redshift leads to an unavoidable degeneracy between the inferred dust temperature $T$ and redshift $z$. The peak wavelength of the SED is determined in the observer's frame, but this is shifted in exactly the same way by either a fractional increase in $T$ or a corresponding fractional decrease in $(1 + z)$. This makes any far-IR/submm-based photometric redshift only as accurate as the knowledge of the temperature (Blain, Barnard & Chapman 2003), and not to $\Delta z \simeq 0.5$ as claimed by Hughes et al. (2002). Despite non-thermal radio emission being due to an entirely different process, the submm–radio properties of galaxies on the far-IR–radio correlation conspire to produce a similar $T–(1 + z)$ degeneracy if $T < 60$ K (Blain 1999). If a reliable link exists between dust temperature and luminosity, then it is possible to break this degeneracy; however, the accuracy of the result is then determined by the scatter in the LT relation, which is likely to be at least 30%, implying at least this great an uncertainty in redshift (Blain et al. 2003).

The addition of K-band near-IR data (Dannerbauer et al. 2002) could also help, but first the intrinsic scatter in the ratio between the K-band and far-IR luminosity of the galaxies must be known. Based on observations of fairly complete samples of SMGs (Ivison et al. 1998; Frayer et al. 2003), the K-band magnitudes are certainly scattered by as much as $\Delta K \sim 2$ mag. Spectroscopic redshifts remain essential for accurate study of SMGs.

4. Spectroscopic mm-wave redshifts

Correct identifications of SMGs via either samples of faint radio galaxies that feed targets to multi-object spectrographs or deep near-IR imaging and spectroscopy, must be confirmed and verified using mm-wave interferometers or single-antenna telescopes to detect CO molecular rotational line emission at integer multiples of 115 GHz in the galaxy’s rest frame.

There are other possibilities for obtaining spectroscopic redshifts, especially the direct detection of molecular or atomic fine-structure spectral lines at mid-/far-IR and submm wavelengths. The key is to obtain wide-band spectral coverage at these wavelengths, in order to allow searches for redshifts. At present,
mm-wave spectrographs cover a total frequency range of only $\Delta \nu/\nu \simeq 0.05$, and so a redshift must be known to well within 5% before confirmation can be made.

Powerful correlators for the 100-m GBT will allow searches for CO(1-0) lines (rest frequency 115 GHz) from high-redshift galaxies in the 22 & 44-GHz radio bands. At shorter submm wavelengths new very stable 230/345-GHz spectral line receivers at the CSO will have $\sim 10$ GHz bandwidths (Rice et al. in prep.). Dispersive techniques may allow very-wideband, low-resolution spectrographs at millimeter or far-infrared wavelengths. These include the ZSPEC and WaFIRS waveguide/grating concepts for space-borne and ground-based applications (Bradford et al. in prep).

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