SHEDDING LIGHT ON THE DARK SIDE OF GALAXY FORMATION: SUBMILLIMETRE SURVEYS THROUGH LENSING CLUSTERS

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Most new sub-mm/mm surveys, both deep and shallow, are being targeted at rich cluster fields. I explain why, comparing surveys that have exploited weak lensing by massive foreground clusters with those done in blank fields.

1 Historical perspective

Sub-mm/mm surveys have revolutionised our understanding of star formation in the early Universe through the discovery of a vast population of very luminous galaxies clarifying the relative importance of obscured and unobscured emission. Many are extremely red (a factor $\geq 100$ in flux between 1 and $2 \mu$m) and most are optically invisible, $BVRI > 26$, even to the Hubble Space Telescope.

The impact of sub-mm/mm surveys has been due to the commissioning of revolutionary bolometer cameras such as SCUBA on the James Clerk Maxwell Telescope and MAMBO at the Institut de Radioastronomie Millimétrique and the sensitivity of those devices to heavily extinguished galaxies – to ‘the optically dark side of galaxy formation’. SCUBA, in particular, has made a huge impact in cosmology through its ability to measure the bolometric output of $1 < z < 5$ dust-enshrouded galaxies (albeit with a resolution of only $14''$) whose energy distributions peak in the sub-mm band.

The foundations of sub-mm/mm cosmology are already in place, only a few years after the commissioning of SCUBA, and the community is moving rapidly to build on them, developing new telescopes and instrumentation (e.g. the Atacama Large Millimeter Array in Chile, the Large Millimeter Telescope in Mexico, and the next-generation of ground-based bolometer cameras, SCUBA-2 and BOLOCAM).

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Table 1: Published and ongoing sub-mm/mm surveys and their claimed areas and rms sensitivities.

| Survey name                                      | Wavelength\(^d\)/ FWHM of beam | Area \(/\text{arcmin}^2\) | Depth (rms) \(/\text{mJy beam}^{-1}\) |
|------------------------------------------------|----------------------------------|--------------------------|-------------------------------------|
| Completed:                                      |                                  |                          |                                     |
| SCUBA lens survey\(^3\)                        | 850µm/14''                      | 36\(^b\)                 | 1.7\(^b\)                           |
| Hawaii survey fields\(^4\)                     | 850µm/14''                      | 104\(^e\)                | 2.7\(^e\)                           |
| HDF\(^5\) (UK sub-mm survey consortium)        | 850µm/14''                      | 5.6                       | 0.5                                 |
| Hawaii HFF radio-selected survey\(^6\)        | 850µm/14''                      | 31                        | 2                                   |
| Canada-UK deep sub-mm survey\(^7\) (CUDSS)    | 850µm/20''                      | 92                        | 1.2                                 |
| Dutch lens survey\(^8\)                       | 850µm/14''                      | 50\(^b\)                 | ∼2\(^b,\!f\)                        |
| Canada HFF survey\(^9\)                       | 850µm/17''                      | 121                       | ∼3                                  |
| Canada lens survey\(^10\)                     | 850µm/14''                      | 42\(^b\)                 | ∼2\(^b\)                            |
| MAMBO survey\(^11\)                           | 1250µm/10''                     | 450\(^c\)                | 0.5\(^c\)                           |
| Ongoing:                                       |                                  |                          |                                     |
| 8mJy survey (UK sub-mm survey consortium)      | 850µm/14''                      | 240                       | 2.7                                 |
| High-z signpost survey\(^12\)                 | 850µm/14''                      | 78                        | 1                                   |
| UK shallow lens survey                         | 850µm/14''                      | 45\(^b\)                 | 2.5\(^b\)                           |
| A370/A2218 SCUBA lens surveys                  | 850µm/14''                      | 11\(^b\)                 | 0.5\(^b\)                           |
| A2218 MAMBO lens survey                       | 1250µm/10''                     | 20\(^b\)                 | 0.3\(^b\)                           |

\(^a\) Effective FWHM is 20'' after convolving with beam to achieve depth of 1.2 mJy beam\(^{-1}\) rms.
\(^b\) Divide values by ∼2.5 to calculate the effective source-plane area/depth/resolution.
\(^c\) Equivalent to ∼1.2 mJy beam\(^{-1}\) rms at 850 µm for \(z \sim 3\).
\(^d\) Note that 450-µm source counts have also been reported\(^12\).
\(^e\) Sub-area of 7.7 arcmin\(^2\) to 0.8 mJy beam\(^{-1}\) rms.
\(^f\) Two/two/four fields to 1.5/2/3 mJy beam\(^{-1}\) rms.

2 Sub-mm/mm surveys and the nature of sub-mm galaxies

The first generation of sub-mm/mm surveys, completed and ongoing, are listed in Table 1.

It is apparent that conventional blank fields have soaked up most of the time spent on cosmology surveys. Areas and rms depths range from the UKSSC 8-mJy survey’s 200 arcmin\(^2\)/2.7 mJy beam\(^{-1}\) to the UKSSC HDF\(^2\) survey’s 5.6 arcmin\(^2\)/0.5 mJy beam\(^{-1}\), and MAMBO has now completed its first deep 1250-µm survey\(^7\) (450 arcmin\(^2\)/0.5 mJy beam\(^{-1}\), FWHM 10'').

These blank-field surveys have been tremendously successful, determining the 850-µm source counts above 2 mJy and thereby resolving directly up to about half of the COBE background at 850 µm. The deepest map, of the HDF\(^2\), has also yielded a statistical detection of the sub-mm emission from Lyman-break galaxies\(^37\).

After initial uncertainty, there is now a growing consensus amongst the sub-mm/mm community that the sources uncovered by SCUBA (and now MAMBO) are massive, intensely star-forming galaxies at \(\bar{z} \sim 3\) (possibly slightly closer\(^35\)), resembling ultraluminous IRAS galaxies in some respects, usually with only a tiny fraction (<1%) of their luminosity released in the rest-frame UV\(^38\) (c.f.\(^34\)) so that many qualify as ‘extremely red objects’\(^17,\!41\) (EROs, \(R - K \gtrsim 6\)).

The road to this consensus has been paved by painstaking efforts to determine the nature of individual galaxies, largely through a process of trial and error, slowly determining the most efficient techniques for identifying near-IR or optical counterparts, investigating basic properties and, in pitifully few cases, measuring redshifts\(^29,\!30\).
To date, deep imaging in the radio and near-IR bands have been far and away the most effective techniques, pinpointing counterparts (see Figures 1 and 2 and their captions) and facilitating spectroscopic follow up. This has culminated in several CO detections that suggest molecular gas masses consistent with the formation of elliptical galaxies.

Radio flux measurements or limits at 1.4 GHz have also provided a plausible redshift distribution based on new photometric techniques. Other techniques – mm interferometry, for example – have been less successful at elucidating what we know of the SCUBA galaxy population, but clearly hold promise for the future, particularly for very bright sources (>8 mJy at 850 µm) found in the field, through cluster lenses or near luminous radio galaxies. There are hopes that broad-band spectral devices may be able to determine spectroscopic redshifts using CO transitions, regardless of the availability of plausible optical/IR counterparts, though the technical challenges are immense.

The current samples of sub-mm/mm galaxies contain a small but significant fraction of active galactic nuclei (AGN), though deep, hard-X-ray imaging has so far failed to uncover the large, heavily obscured AGN population that some had suspected from the earliest follow-up work and from theoretical arguments.

The problem of confusion – lifting and separating with a lens

Had the galaxies discovered in sub-mm surveys been only fractionally fainter or less numerous, a second, more sensitive generation of bolometer cameras would have been required to discover them. Early surveys would collectively have uncovered only a couple of sources – the first, an obvious AGN (SMM J02399−0136) and the second, a puzzle with no optical or near-IR counterpart (HDF850.1). Who can say what conclusions might have been reached and how future surveys, e.g. with FIRST, may have suffered?

We have been fortunate, then, that first-generation bolometer arrays were sufficiently sensitive to enable rapid progress in sub-mm cosmology. We have been less fortunate regarding source confusion: few would have predicted that SCUBA would reach its effective confusion limit within a few months of being commissioned. The deepest direct counts are already at the confusion limit, suggesting that further progress in constraining the intensity of the sub-mm background and the nature of the faint sub-mm population requires an innovative approach.

To probe below the confusion limit using the existing sub-mm/mm cameras requires the use of the natural magnifying glasses that provide the raison d’être for this conference: gravitational lenses. Massive clusters provide a magnified (although distorted) image of a small region of the background sky; thus both the effective resolution and sensitivity of the survey are increased, as measured on the background sky. This enables surveys to probe faint flux densities without suffering confusion, albeit at the price of a distorted view.

With an accurate cluster mass model, the distortion can be corrected. The first lens survey illustrated the advantages of this approach for the counts. About 100% of the COBE 850-µm background was resolved down to 0.5 mJy. Follow-up observations also benefitted from achromatic gravitational amplification: not only was the effective depth of the sub-mm maps increased, but the counterparts at all other wavelengths were similarly amplified. This allows useful follow-up observations to be obtained in several hours or tens of hours using the current generation of telescopes and instrumentation: it is no coincidence that of the ∼100 known sub-mm galaxies, only a handful have reliable spectroscopic redshifts and all of these were discovered through cluster lenses.

Another advantage of using clusters is that extraordinarily deep images – X-ray, optical, IR and radio – exist or are scheduled for these fields. The HDF is the only blank field that is equally blessed. Abell 851, 1835 and 2218 (and many other cluster fields) have superb HST images and near-IR data; Abell 370, 851 and 2125 have 1.4-GHz maps with <10-µJy beam−1 noise levels.
Figure 1: An illustration of the detection and further investigation of sub-mm galaxies in the Abell 1835 cluster field. Top left: 850-µm map (field diameter ∼ 150′′); top right: 450-µm map. Sources are labelled on the 850-µm image. Below these are a true-colour $UBI$ image (lower left) and a 1.4-GHz map from the VLA (lower right), both ∼ 370′′ across. The sub-mm sources are easily detected in the very deep radio map (red circles), with far better positional accuracy than afforded by SCUBA. Twenty other radio sources seen in the VLA image can be used to co-align the radio/optical (or radio/near-IR) coordinate frames, yielding counterpart positions accurate to 0.1′′. Note that the radio image shown here represents only 6% of the VLA’s primary beam area at 1.4 GHz.
Figure 2: $K$-band images of regions around the $z = 3.8$ radio galaxy, 4C 41.17, where there is an order-of-magnitude over-density of sub-mm sources\textsuperscript{31}. 850-$\mu$m data are shown as contours. Red circles (solid lines) denote EROs ($R - K > \sim 6$). Two EROs are probably associated with the blended sub-mm galaxy, HzRG850.2. For the other sub-mm galaxies (HzRG850.1, 4C 41.17), green circles (dashed lines) denote the likeliest counterparts (faint and red, in the case of HzRG850.1, though a bona fide ERO could also be responsible for the sub-mm emission).

4 Future plans and concluding remarks

Following on from the success of the earliest sub-mm cluster survey\textsuperscript{8,10}, groups in the UK, Holland and Hawaii are currently undertaking more surveys with SCUBA and MAMBO that exploit cluster lenses. The latest of these will combine a long integration (equal to that obtained on the HDF) with amplification by the cores of amongst the most massive, well-constrained cluster lenses known, A 370 and A 2218.

At modest amplifications ($A \sim 2–5$), it should be possible to detect the optically-identified arclet population; probing fainter, it is likely that a new, largely unexplored class of lensed feature may appear: multiply-imaged pairs, recognised in the first $HST$ cluster images.

These appear in the optical/near-IR as symmetric images with typical separations of 5–10\arcsec (i.e. within a single SCUBA or MAMBO beam) and can be simply and successfully modelled as highly magnified images ($A \sim 10–100$) of very faint, compact sources which lie close to a critical line. In a well-constrained lens such as A 2218, their location in the cluster, combined with the positions and separation of any radio/IR/optical counterparts, can give the source redshift and amplification to high precision. The area of the source plane in which pairs are formed can also be estimated from the lens models, allowing their rate of occurrence to be converted into an estimate of the surface density of extremely faint (tens of $\mu$Jy) sub-mm/mm background sources, with the bonus of crude redshift information.

Using the superb recent $HST$ imaging of A 2218, at least 4 highly magnified pairs have been identified (from a source population with a comparable surface density to that expected for the very faint sub-mm/mm population, $\sim 10$ arcmin\textsuperscript{-2}) suggesting that the cluster amplification cross-section is high and that the chance of finding such systems is good. Failure to detect any of these highly magnified sources using SCUBA and MAMBO would indicate convergence of the source counts and can be used to impose strong limits on the surface density of very faint sources and the total intensity in resolved sources in the sub-mm background.
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