An ALMA Survey of Submillimetre Galaxies in the Extended Chandra Deep Field South: First Results

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Sensitive ALMA submillimetre maps of a sample of 122 870 μm selected submillimetre sources from our survey of the Extended Chandra Deep Field South are presented. The combination of sensitivity and resolution of ALMA allows us to precisely pinpoint the submillimetre emission from these galaxies to an accuracy of < 0.3 arcseconds. In two ALMA submillimetre galaxies (SMGs) we serendipitously detect bright [C II] 157.4 μm emission, yielding redshifts of 4.4. This blind detection rate within the 7.5 GHz bandpass of ALMA is consistent with the previously derived photometric redshift distribution of SMGs and suggests a modest, but not dominant (< 25 %), tail of 870 μm selected SMGs at $z > 4$.

Background

A significant fraction of the obscured star formation at redshift $z > 1$ arises from the most luminous galaxies: ultraluminous infrared galaxies (ULIRGs) with bolometric luminosities of > 10^{12}–10^{13} $L_{\odot}$ and implied star formation rates (SFR) of > 100–1000 $M_{\odot}$/yr. Their very low space densities means ULIRGs are a negligible element of the star-forming population at $z \sim 0$, contributing < 1 % of the total SFR density. However, the situation at high redshift is very different: the first deep, single-dish bolometer surveys in the 870 μm atmospheric window uncovered a significant population of dusty starbursts (e.g., Smail et al., 1997), with SFRs > 1000 $M_{\odot}$/yr. These galaxies are some of the brightest sources in the submillimetre waveband and so are frequently called submillimetre galaxies.

This 870 μm high-redshift population may host up to half of the star formation occurring at $z \sim 2$ (Chapman et al., 2005; Wardlow et al., 2011) and may be linked to the formation of massive local elliptical galaxies (Genzel et al., 2003; Swinbank et al., 2006). Moreover, the highest-redshift SMGs ($z > 4$), have also been linked to the formation epoch of massive, "red and dead" galaxies at $z \sim 2$ which are now being found in large numbers (e.g., Whitaker et al., 2012). The progenitors of these $z \sim 2$ red and dead galaxies must have formed the bulk of their stellar populations at $z > 4$ and the necessary SFRs ~ 100–1000 $M_{\odot}$/yr correspond to the bright submillimetre galaxy population. If true, then SMGs are a key evolutionary stage for the evolution of massive galaxies at all epochs, and so determining their true redshift distribution and contribution to the star formation density are basic parameters that are needed to constrain galaxy formation models (Baugh et al., 2005). Indeed, since they lie on the rapidly diminishing, exponential tail of the mass function, massive galaxies at all epochs can provide strong tests of galaxy formation models as they are often the most challenging systems for galaxy formation models to reproduce.

However, measuring the redshifts for a complete and unbiased sample of SMGs is not trivial: the poor resolution of single-dish submillimetre telescopes, ~ 18 arcseconds, means that there are many possible counterparts responsible for submillimetre emission. SMGs have therefore to be identified through correlations between their submillimetre emission and that in other wavebands where higher spatial resolution is available, usually the radio and/or mid-infrared (e.g., Ivison et al., 2007). These identifications are probabilistic as they rely on empirical correlations that have both significant scatter and which may evolve with redshift. In submillimetre surveys, typically 30–50 % of SMGs lack robust counterparts in the radio or mid-infrared and these may represent either an unidentified tail of high-redshift SMGs, or galaxies whose submillimetre emission is relatively bright compared to the radio/mid-infrared. The latter includes SMGs with colder than average dust temperatures, which may include the isolated, gas-rich disc galaxies. Thus these biased identifications may miss precisely those SMGs that are critical for testing the models.

To circumvent this problem requires identifying the submillimetre emission directly using submillimetre interferometers, but until recently their sensitivity has been too low to locate large numbers of SMGs (Smolčić et al., 2012). However, with the commissioning of the Atacama Large Millimeter/submillimeter Array (ALMA), we can now construct the large samples of precisely located SMGs needed to unambiguously study their properties and test galaxy formation models.

The ALMA LESS (aLESS) survey

We have recently undertaken an ALMA Cycle 0 study of the 126 submillimetre sources from the 870 µm LABOCA survey of the Extended Chandra Deep Field South (the LESS survey of Weiss et al., 2009) conducted with the Large APEX Bolometer Camera (LABOCA) on the Atacama Pathfinder Experiment Telescope (APEX). Despite the short integration time per source (~ 2 min), our ALMA maps are typically ~ 3 times deeper (σ_{870} ~ 0.4 mJy) than the original LABOCA survey and critically the angular resolution is more than an order of magnitude higher, with a full width at half maximum (FWHM) of 1.4 arcseconds.

This combination of sensitivity and resolution precisely locates the SMGs directly (see examples in Figure 1), pinpointing the source(s) responsible for the submillimetre emission (to within < 0.3 arcseconds), without recourse to statistical radio/mid-infrared associations. Whilst a large number of the radio and/or mid-infrared counterparts from previous statistical associations are confirmed, in a significant number of instances the previous counterparts have been shown not to be SMGs. Our ALMA maps turn up new counterparts to previously unidentified submillimetre sources, as well as multiple SMG counterparts to LABOCA sources in a number of cases (Hodge et al., 2012). For the first time, this ALMA study provides us with a unique and unbiased sample of SMGs with direct identifications from the submillimetre with which we can study the multi-wavelength properties in an unbiased manner (Simpson et al., 2012; Smail et al., 2012). Animations of these ALMA observations of the Extended Chandra Deep Field South can be viewed[1].

We use the sources detected in these maps to derive the first reliable counts of faint SMGs free from the effects of confusion. These counts agree broadly with those derived from lower resolution single-dish surveys, demonstrating that the bulk of the submillimetre sources are not caused by the blending of emission from several, significantly fainter sources (Karim et al., 2012) However, we find an exception: all of the brightest submillimetre sources in the LESS sample (with $S_{870\,\mu m}$ > 10 mJy) actually consist of emission from multi-ple SMGs, each with 870 µm fluxes of 3–4 mJy, significantly steepening the 870 µm counts above ~ 8 mJy (Karim et al., 2012).

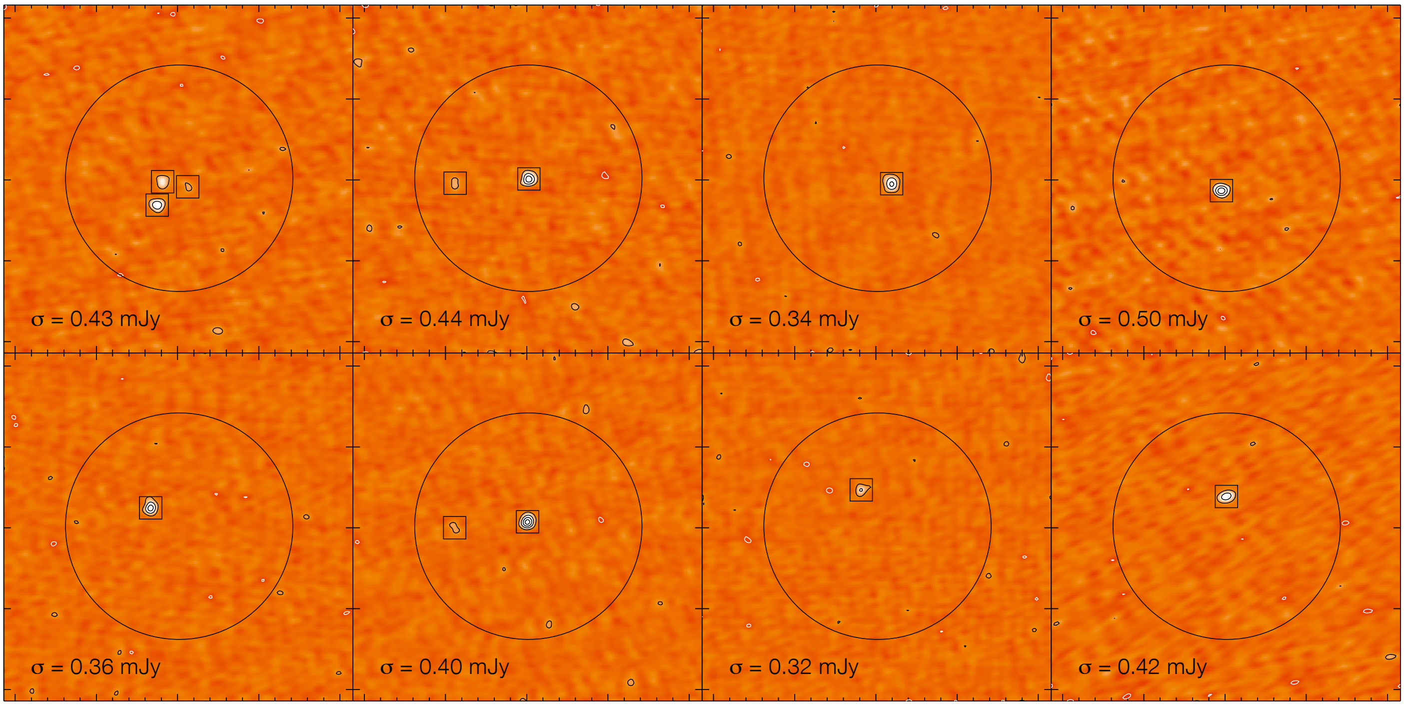

Figure 1. Examples of 345 GHz (870 µm) ALMA maps of eight of the SMGs in our ALMA LESS sample. In each map we identify all of the SMGs (with signal-to-noise > 4σ) by large squares. The contours on each map start at 4σ and are incremented by 2σ (and the 1σ value is given in the bottom left corner of each panel). We also show the primary beam (circle). Each map is 40 arcseconds across. The ALMA data unambiguously locates the SMG counterpart(s) to a precision of < 0.3 arcseconds and to flux limits of ~ 1.5 mJy.

The highest redshift SMGs

As an initial step in our analysis of the ALMA data of the LESS SMGs, we also exploited the frequency coverage of our observations to search for emission lines in the datacubes. In two SMGs, aLESS61.1 and aLESS65.1 we identify the redshifted [C II] 157.4 µm emission line, indicating redshifts of 4.419 and 4.445 respectively (see Figure 2 and Swinbank et al., 2012). Both of these SMGs are very faint at all other wavelengths: both have radio (1.4 GHz) 3σ upper limits of < 25 mJy and are blank in the Herschel maps at 250, 350 and 500 µm; i.e. they are so-called 870 µm peakers. Although based on only two sources, the blind detection rate of [C II] in the 7.5 GHz (Δz = 0.12) bandpass of ALMA is consistent with the previously derived photometric redshift distribution of SMGs (Wardlow et al., 2011) and suggests a modest, but not dominant, (< 25 %) tail of 870 µm selected SMGs at $z > 4$.

Since the [C II] emission line is the dominant cooling line within the interstellar medium (the [C II] emission line can comprise ~ 1 % of the total bolometric luminosity of a galaxy), we can use the data to investigate the properties of the interstellar medium (ISM) in the galaxies. In local luminous-infrared galaxies, the ratio of $L_{[C\,II]}/L_{FIR}$ is approximately constant at ~ 1 %, but decreases to < 0.1 % in local ULIRGs (Figure 3, left). However, the [C II] detections in high-redshift ULIRGs and active galactic nuclei (AGNs) have shown that the [C II] emission can be as bright as in local, low luminosity galaxies. This has been interpreted as due to the lower ionisation field arising from more widely distributed star formation activity within these systems, in contrast to the compact nuclear star formation seen in low-redshift ULIRGs. From our ALMA observations, the ratio of $L_{[C\,II]}/L_{FIR}$ in these SMGs is also much higher than seen for similar far-infrared luminous galaxies in the local Universe (Figure 3, left). We attribute this to the more extended gas reservoirs in these high-redshift ULIRGs. In aLESS65.1 the [C II] emission shows extended emission on > 3 kpc scales.

We also use the volume probed by our ALMA survey to investigate the bright end of the [C II] luminosity function (Figure 3, right). Our ALMA observations cover the [C II] emission over a redshift range of $\Delta z = 0.12$ at $z = 4.4$ (a co-moving volume of 2.9×10^5 Mpc^3). Finding two galaxies in this volume with bright [C II] emission indicates an increase > 1000 times in the number density of luminous [C II] emitters from $z \sim 0$–4.4 (Figure 3). This is equivalent to a [C II] luminosity evolution of a factor ~ 3–4 times between $z = 0$ and 4.4, consistent with the evolution in the far-infrared luminosity function over the same redshift range.

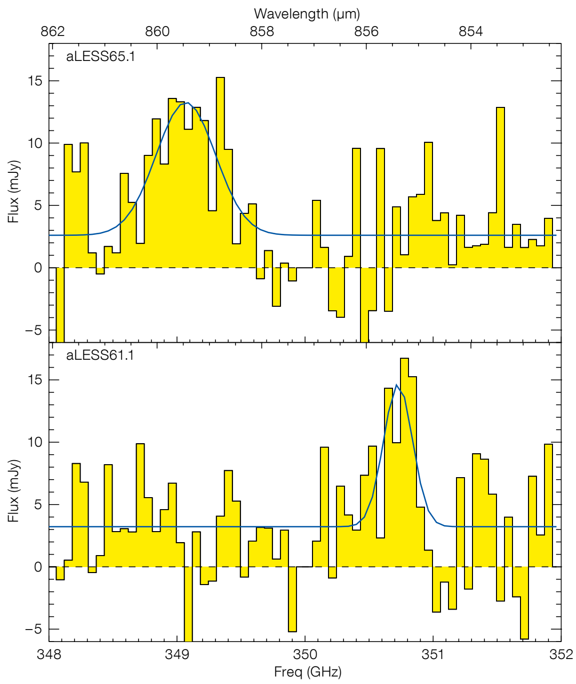

Figure 2. ALMA spectra of aLESS65.1 and aLESS61.1, extracted at the position of the peak submillimetre emission from the SMGs. From the spectra, we identify the [C II] 157.4 µm emission lines in the upper sideband which we attribute to [C II] emission at $z = 4.419$ and $z = 4.445$ for aLESS61.1 and aLESS65.1, respectively.

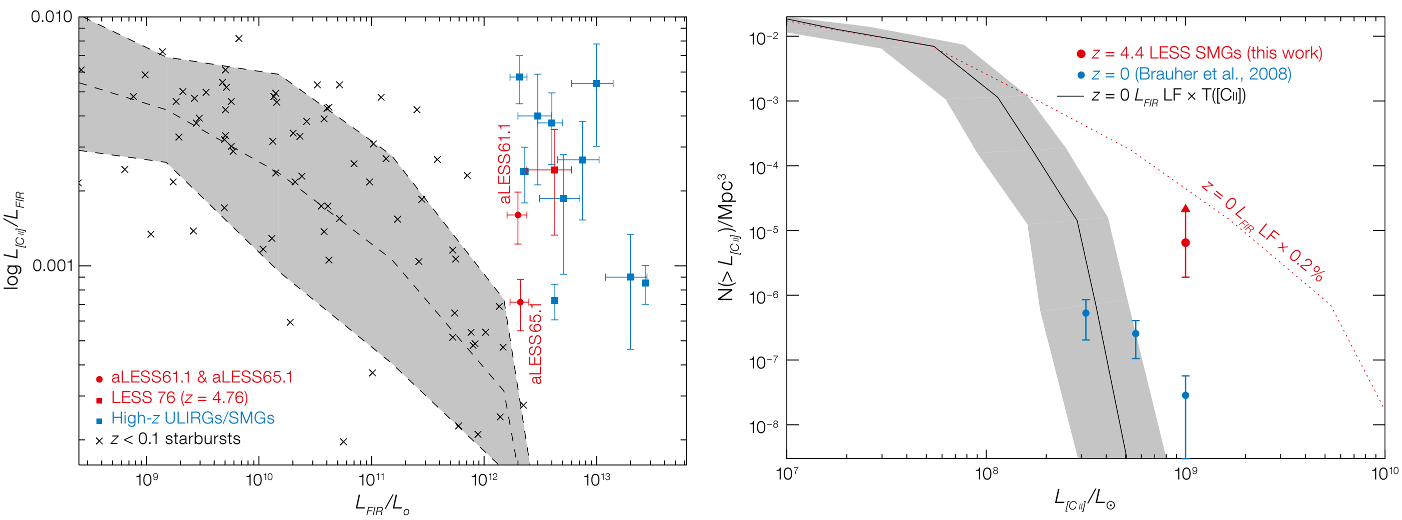

Figure 3. Left: The ratio of the [C II] to far-infrared luminosity ($L_{[C\,II]}/L_{FIR}$) as a function of the far-infrared luminosity for aLESS61.1 and aLESS65.1 compared to local star-forming galaxies and ULIRGs. This figure shows that the ratio of $L_{[C\,II]}/L_{FIR}$ for high-redshift ULIRGs is a factor ~ 10 times higher given their far-infrared luminosities compared to those at $z \sim 0$. Right: The [C II] luminosity function at $z = 4.4$ from our survey compared to $z = 0$. For the $z = 4.4$ luminosity function, we assume that all of the [C II] emitting galaxies in the $\Delta z = 0.12$ volume covered by our observations were detected and so these calculations yield only a lower limit on the volume density of high-redshift [C II].

Prospects

These early results show that ALMA can trivially identify large samples of SMGs in short exposure times, measure blind redshifts through the detection of fine structure lines and spatially resolve the dust and gas within the galaxies on ~ kpc scales. Constructing large and unbiased samples of SMGs with ALMA in a single well-studied field are crucial to investigate the unbiased redshift distribution and the nature of these galaxies. Topics such as the triggering mechanisms for their immense starburst activity, their stellar and gas masses and dynamics can be addressed, and hence the evolution of a population which have been proposed as the formation epoch of today's massive galaxies — the luminous ellipticals.

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Links

[1] Fly-through animations of the ALMA observations: http://astro.dur.ac.uk/~ams/ALMAmovie/

ESO/B. Tafreshi (twanight.org)

A recent image showing some of the growing number of ALMA antennas on Chajnantor pointing towards the Milky Way. See Picture of the Week 28 May 2012.