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

Ian Smail[1]
Fabian Walter[2]

For the ALESS consortium

[1] Institute of Computational Cosmology, Durham University, United Kingdom
[2] Max-Planck-Institut für Astronomie, Heidelberg, Germany

The ALESS survey is an ALMA Cycle 0 study of ~ 100 luminous high-redshift ultraluminous infrared galaxies in the Extended Chandra Deep Field South (ECDFS), one of the best-studied cosmological deep fields accessible from the southern hemisphere. These galaxies were originally selected based on their bright emission in the submillimetre continuum (so-called submillimetre galaxies, or SMGs) through observations using the APEX bolometer camera LABOCA. Compared to the single-dish LABOCA data, the interferometric ALMA data provide a positional accuracy that is nearly two orders of magnitude higher. The ALMA data thus enable galaxy identifications that were previously impossible, and so remove many of the biases inherent in previous studies of SMGs to give us our first unbiased view of a large sample of this important galaxy population.

The submillimetre is an ideal wavelength regime to search for luminous, but dust-obscured, sources which may represent the most active phase of galaxy formation. Submillimetre surveys most commonly use the atmospheric windows at ~ 870 μm or ~ 1200 μm. These wavebands benefit from the positive *K*-correction produced by the dust spectrum which means that a source with a fixed far-infrared luminosity has an almost constant measured flux density from redshifts $z \sim 1$–8 (i.e., lookback times of ~ 7 to 13 Gyr). Thus a deep submillimetre survey provides an effectively volume-limited sample of the most luminous far-infrared sources out to the highest redshifts.

Over the past ~ 15 years sensitive surveys of the submillimetre sky with bolometer cameras on single-dish telescopes have uncovered an abundant population of ultraluminous infrared sources (with infrared luminosity $L_{IR} > 10^{12}\ L_{\odot}$, corresponding to star formation rates of $> 100\ M_{\odot}\ \mathrm{yr}^{-1}$). These appear to be dusty starburst events occurring in massive galaxies out to the highest redshifts, $z > 5$ (e.g., Walter et al., 2012). Unfortunately, the study of these sources has been hampered by two factors: firstly, the resolution of these single-dish maps is poor, typically ~ 10–30 arcseconds, making it difficult to precisely locate the submillimetre sources; secondly, given their high redshifts and dusty nature, the SMGs are typically very faint in the optical/near-infrared passbands, making it hard to derive their properties (e.g., redshifts, stellar masses, morphologies, etc). In addition, the surface densities of these sources is 1 per 10 square arcminute at a flux density $S_{870\,\mu m} \sim 5$ mJy, so they are too rare to find in large numbers in blank-field searches with submillimetre interferometers, which instead have to rely on targets detected by the single-dish surveys.

Prelude: LESS — The LABOCA ECDFS Submillimetre Survey

In 2004 we began discussing with ESO a proposal to undertake a survey for submillimetre galaxies in the 150 square arcminute GOODS-South field using the planned Large APEX Bolometer Camera (LABOCA) on the new 12-metre Atacama Pathfinder Explorer (APEX) telescope sited at Chajnantor. The main aim of this proposal was to provide a large sample of SMGs in a field ideally placed for study with ESO's facilities, in particular the long-awaited Atacama Large Millimeter/submillimeter Array (ALMA).

By 2007 this proposal had evolved into a public legacy survey of the whole of the 0.5 by 0.5 degree ECDFS. The completed LABOCA ECDFS submillimetre survey (LESS) took 310 hours of observing time to map the full ECDFS to a uniform noise level of $\sigma_{870\,\mu m} \sim 1.2$ mJy beam^{-1} and was published in Weiß et al. (2009). At the time LESS was the largest contiguous deep submillimetre survey undertaken and detected a total of 126 SMGs above a significance level of 3.7σ (with an expectation of no more than five false detections). As discussed above, due to the positive *K*-correction in the submillimetre waveband, the LESS survey should detect all dusty starbursts within the ECDFS with star formation rates of $> 500\ M_{\odot}\ \mathrm{yr}^{-1}$ out to $z \sim 8$.

With ALMA Early Science not yet scheduled in 2009, we used the traditional probabilistic identification techniques (e.g., Ivison et al., 2002) to locate likely counterparts — the individual SMGs — to the LESS submillimetre sources. These approaches rely on proxy tracers, such as radio or mid-infrared brightness, of the luminous submillimetre emission or near/mid-infrared colours, as indicators of extreme dust reddening (Biggs et al., 2011). In this manner we identified probable counterparts to around 60 % of the submillimetre sources (Biggs et al., 2011; Wardlow et al., 2011). With these precisely located counterparts, we could then exploit the wealth of archival multi-wavelength data in the ECDFS to study the active galactic nuclei (AGN) content of SMGs (Lutz et al., 2010), their redshift distribution and stellar masses (Wardlow et al., 2011) and clustering (Hickox et al., 2012), as well as the multiwavelength properties of one of the highest-redshift submillimetre galaxies known (Coppin et al., 2009) and more normal galaxies in the field (Greve et al., 2009). Moreover, combining this submillimetre sample with shorter-wavelength observations from the Balloon-borne Large Aperture Submillimeter Telescope (BLAST) experiment, it was also possible to get a first insight into the restframe far-infrared emission of the SMG population (e.g., Ivison et al., 2010) prior to the launch of Herschel (Magnelli et al., 2011).

MORE from LESS: ALESS — an ALMA study of LESS SMGs

Early Science observations with ALMA (Cycle 0) were advertised in mid-2011 and 5.4 hours were awarded to our consortium to obtain 870 μm continuum maps of all 126 submillimetre sources from LESS (ALMA project #2011.1.00294.S). These short 120 s exposures were intended to yield maps with $\sigma_{870\,\mu m} \sim 0.4$ mJy beam^{-1}, around three times deeper than the LABOCA map, but with a beam of ~ 1.5 arcseconds, compared to ~ 18 arcseconds for APEX, sufficient to unambiguously identify the SMGs responsible for the emission detected by LABOCA. Moreover, the ALMA primary beam matches the LABOCA map resolution, ensuring that the SMGs contributing to the emission in the LESS map should fall within the ALMA field of view. Finally, one key feature of the ALMA study was that it would observe the LESS sources in the same waveband as the original LABOCA survey, removing any ambiguity when comparing fluxes between the two studies. As will be seen, this was a critical choice.

The ALMA observations were undertaken in October and November 2011 and released to the consortium in late February 2012. As shared risk observations the data were of variable quality, but after removing maps with noise levels significantly higher than our goal ($\sigma_{870\,\mu m}$ > 0.6 mJy beam^{-1}) or very elliptical beams (axial ratios > 2), we were left with 88 good quality maps from the 122 that were delivered.

Hodge et al. (2013) catalogued the SMGs detected in these maps and presented a MAIN catalogue comprising 99 ALMA-detected SMGs with detection significances of > 3.5σ (with a false detection rate < 1 %) and lying within the primary beam area in our best maps. There are a further 32 SMGs, detected at > 4σ either outside of the ALMA primary beam in the best maps, or within primary beams in the lower quality maps, which we provided in a supplementary catalogue, but do not use in our analysis.

The fundamental characteristics of an unbiased sample of SMGs

One of the first results from ALESS was the incidence of multiple SMGs within a single submillimetre source (Karim et al., 2013; Hodge et al., 2013). This was not entirely unexpected, given earlier known examples (e.g., Smolcic et al., 2012). However, the surprise was that all of the LESS submillimetre sources brighter than ~ 10 mJy broke into several components (see Figure 1 for examples), with the result that there are no individual SMGs brighter than 9 mJy in the ALESS catalogue. Due to the modest depth of the ALESS maps, it is not clear whether this blending bias is limited to the brightest submillimetre sources or occurs at all flux limits.

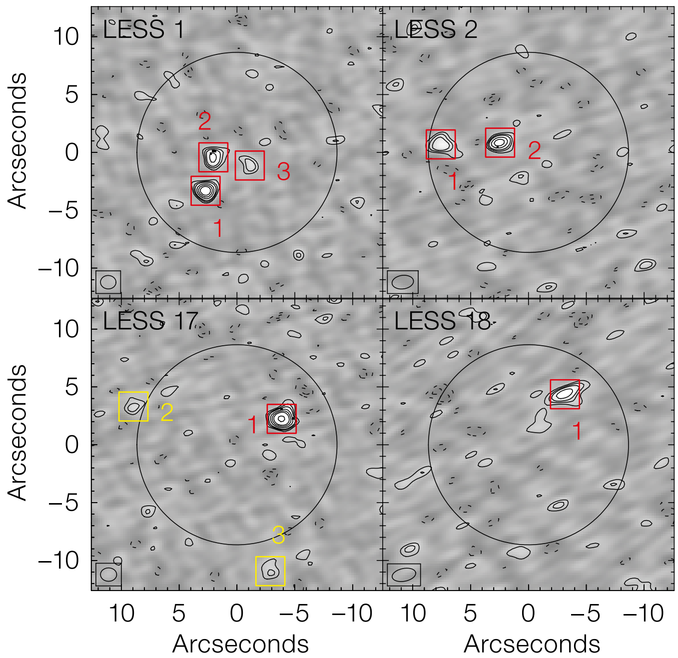

Figure 1. Examples of ALMA 870 μm maps (from Hodge et al., 2013) of submillimetre sources from the LESS survey. Some single-dish sources fragment into several SMGs when observed with ALMA at 1.6-arcsecond resolution. The circle shows the ALMA primary beam (comparable to the LABOCA map resolution) and contours start at ± 2σ, with increments of 1σ. Main and supplementary catalogue sources are indicated by red and yellow boxes respectively, with the ALMA beam at lower left.

However, Hodge et al. (2013) also found a surprisingly high fraction (~ 20%) of good quality ALMA maps which are blank, i.e., maps where LABOCA detected a source but there is nothing above 3.5σ seen by ALMA. As the two datasets were taken in the same waveband, the most likely explanation for this is that multiplicity is also an issue for fainter submillimetre sources as well. This is supported by the detection of these ALMA-blank submillimetre sources in Herschel Spectral and Photometric Imaging Receiver (SPIRE) far-infrared maps (Swinbank et al., 2014), confirming their reality as submillimetre sources, and by the discovery of excess populations of z ~ 2–3 galaxies, observed by the Infrared Array Camera (IRAC) on board the Spitzer Space Telescope, in these maps. These z ~ 2–3 galaxies exhibit enhanced 870 μm emission as shown by stacking analysis (Decarli et al., 2014; Simpson et al., 2014).

ALESS can transform our understanding of the SMG population, providing a unique sample of 99 SMGs with the precise positions necessary to investigate their fundamental properties. Hence in Figure 2 we show the apparent magnitude and flux distributions of the SMGs in the V, K, 3.6 μm and 1.4 GHz bands (Simpson et al., 2014). These distributions demonstrate increasing detection rates from V to K to 3.6 μm, reflecting the typically red colours of the SMGs.

However, Figure 2 also shows that more than half of the SMGs are undetected in the radio waveband above a limit of ~ 20 μJy. This highlights the incompleteness in previous studies which had to rely on radio (or mid-infrared) observations to attempt to statistically associate counterparts with submillimetre sources. These studies typically correctly identified at most half of the SMGs (Hodge et al., 2013). In contrast, our ALMA study allows us to robustly determine the true properties of the SMG population, including the mysterious ~ 10% fraction which are undetected at any wavelength other than the submillimetre (Simpson et al., 2014).

Figure 3 shows the composite restframe spectral energy distribution (SED) of the SMGs in the optical–radio wavebands (Swinbank et al., 2014; see also Simpson et al., 2014). From this plot, we see that a typical ALESS SMG has a far-infrared luminosity of $L_{IR} = 3 \times 10^{12}\,L_\odot$, corresponding to a star formation rate (SFR) of 300 $M_\odot$ yr^{-1}. As expected this star formation activity is dust-reddened, with an apparent A_V ~ 2 mag for the detectable restframe near-infrared continuum light.

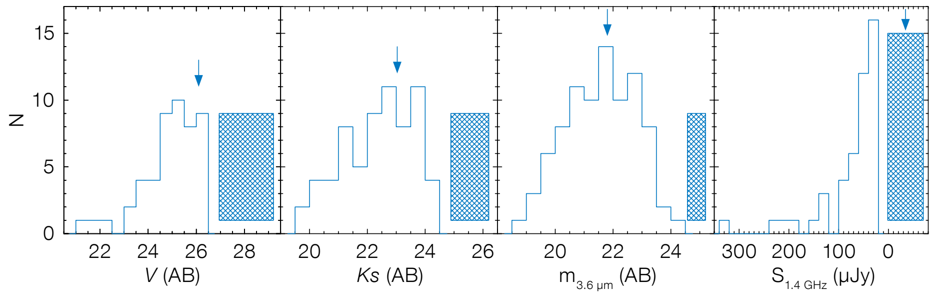

Figure 2. (Above) The V, Ks, IRAC 3.6 μm and 1.4 GHz brightness distributions for ALESS SMGs from Simpson et al. (2014). The checked region shows the undetected sources and the arrows the medians (including the non-detections): $V = 26.1 \pm 0.2$, $Ks = 23.0 \pm 0.3$ and $m_{3.6\,\mu m} = 21.8 \pm 0.2$ mag. The radio data reaches a 3σ depth of 19.5 μJy, but only detects 45 % of the SMGs, so their median flux must be < 19.5 μJy.

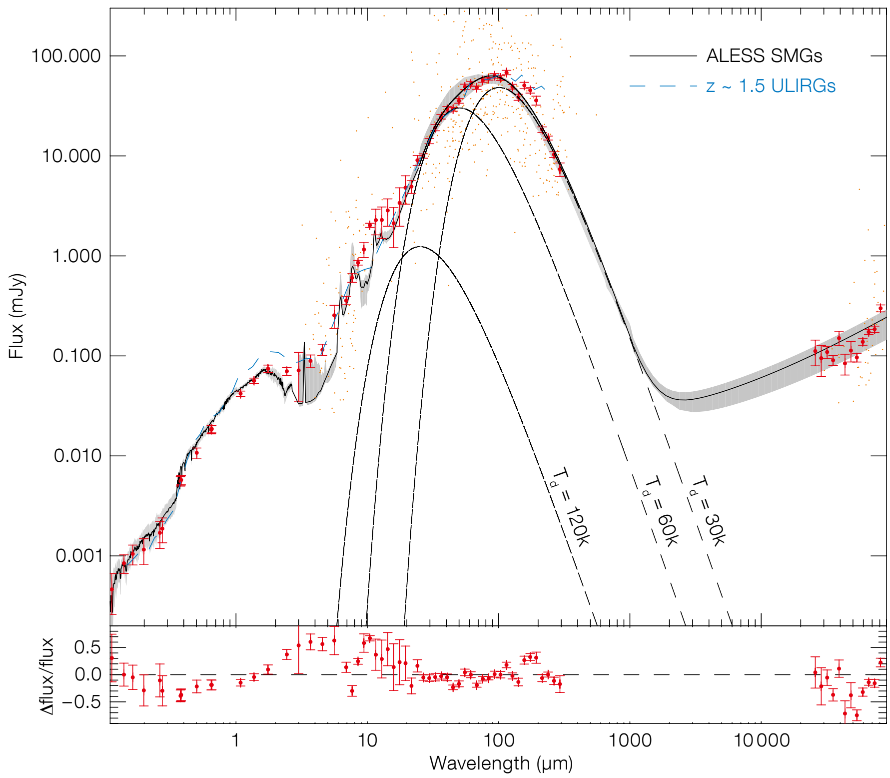

Figure 3. (Below) The composite SED of SMGs from Swinbank et al. (2014). The large red points denote the bootstrap median and the solid curve shows the best-fitting SED, with the 1σ uncertainty indicated by the shaded region, with the residuals shown in the lower panel. The dashed curve shows the composite SED derived for $z \sim 1.5$ U/LIRGs from Lee et al. (2013). The black curves show a three-component grey-body dust SED fit with $T_d \sim 30$, 60 and 120 K components.

Estimates of the stellar mass from the near-infrared luminosity indicate $M_* \sim 8 \times 10^{10}\, M_\odot$ (Simpson et al., 2014), but with significant systematic uncertainties. Similarly the submillimetre luminosity yields a dust mass of $M_d \sim 4 \times 10^8\, M_\odot$, which implies a typical gas mass of $M_g \sim 4 \times 10^{10}\, M_\odot$. Combining these we obtain a total baryonic mass of an SMG of $M \sim 10^{11}\, M_\odot$ and a gas mass fraction of ~ 40 %, underlining the massive and gas-rich nature of these galaxies (Swinbank et al., 2014).

Starbursts and growing black holes

The precise positions of the SMGs from ALMA also allow us to investigate their AGN content by combining these data with the excellent Chandra X-ray coverage in the ECDFS. In Wang et al. (2013) we estimate that at most 20 % of SMGs are likely to host luminous AGN ($L_X > 8 \times 10^{42}$ erg s^{-1}), with the majority of these showing moderate/high absorption ($N_H > 10^{23}$ cm^{-2}).

This analysis uncovered a submillimetre continuum source lying within 1 arcsecond of a $z = 1.3$ X-ray luminous (but unobscured) quasi-stellar object (QSO; see Figure 4). Submillimetre-bright X-ray QSOs are of particular interest as they may represent a transition phase in galaxy evolution between starburst progenitors and passive descendants. However, in this particular case subsequent spectroscopic follow-up of the ALESS sample (Danielson et al., in prep) has shown that the submillimetre emission is actually from a background SMG at $z = 2.4$, which is being weakly lensed by the foreground QSO host. This system demonstrates the critical importance of precise submillimetre positions for the correct identification of SMGs.

Wang et al. (2013) also exploited the precise ALMA positions, by stacking the X-ray flux at the position of the 49 individually undetected SMGs in the field (Figure 5). These stacks reach an equivalent on-source exposure time of 10 Ms and they detect soft-band X-ray emission at 5.4σ significance. The corresponding average SMG luminosity is $L_X \sim 1 \times 10^{42}$ erg s^{-1}, consistent with the X-ray emission expected from star formation, given the SMG's star formation rates (Wang et al., 2013); as such there is no evidence for luminous activity associated with an active galactic nucleus in the bulk of the SMGs.

The evolution of high-redshift ULIRGs

Simpson et al. (2014) used the extensive archival photometry in the ECDFS (e.g., Figures 2 and 3) to determine photometric redshifts for the ALESS SMGs. Their analysis included a statistical correction for the 20 % of the ALESS sample for which reliable photometric redshifts could not be derived due to the SMG being detected in < 4 photometric bands (most frequently just the IRAC mid-infrared bands, see Figures 1 and 2). These faint SMGs are expected to include the highest-redshift examples of the popula-

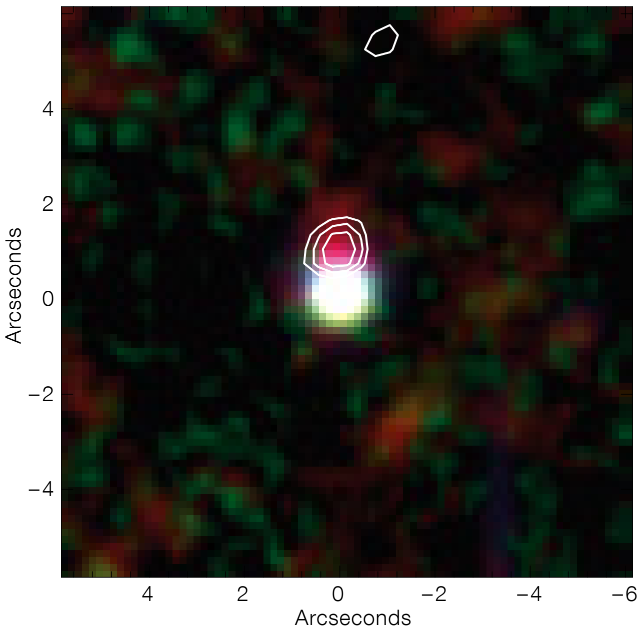

Figure 4. A *VJK* image of ALESS66.1 overlaid with ALMA contours (starting at 3σ in increments of 1σ). The submillimetre position lies within 1 arcsecond from an X-ray detected z = 1.3 QSO which was initially identified as the counterpart (Wang et al., 2013). However the faint red source visible under the ALMA emission is a background z ~ 2.5 SMG, weakly lensed by the foreground QSO (Danielson et al., in prep.).

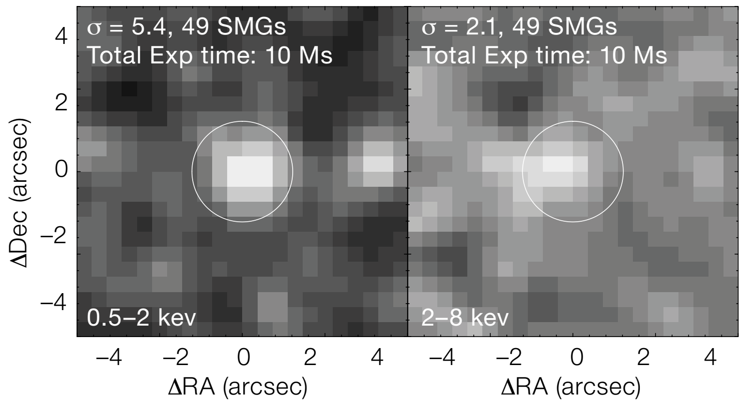

Figure 5. The stacked X-ray emission in the 0.5–2 keV and 2–8 keV bands for the 49 individually X-ray-undetected SMGs from Wang et al. (2013). The stacks have an equivalent cumulative integration of 10 Ms. The measured X-ray luminosities and their X-ray colours are consistent with that expected purely from on going star formation.

tion and Simpson et al. (2014) were able to place a firm limit of ~ 20 % of SMGs at z > 4 (see Figure 6).

Simpson et al. (2014) find that the redshift distribution of ALESS SMGs is strongly peaked with a median z ~ 2.3, as seen by previous studies (e.g., Chapman et al., 2005; Wardlow et al., 2011). Plotted as a function of lookback time, the distribution is well described by a Gaussian with peak activity occurring at a lookback time of 11.1 Gyr and a duration of the activity of 1.1 Gyr (full width at half maximum [FWHM]). The ALESS SMGs show a clear and strong peak at z ~ 2, rather than previous claims of a flat redshift distribution for SMGs between z ~ 2–6. This peaked distribution suggests that the evolution of SMGs can be described simply by the combination of the growth of dark matter and the variation in molecular gas mass fraction with time (Hickox et al., 2012).

Next, assuming a simple model with no additional star formation beyond the current burst and no subsequent merging, Simpson et al. (2014) used the redshifts and near-infrared luminosities of the SMGs to predict the properties of their

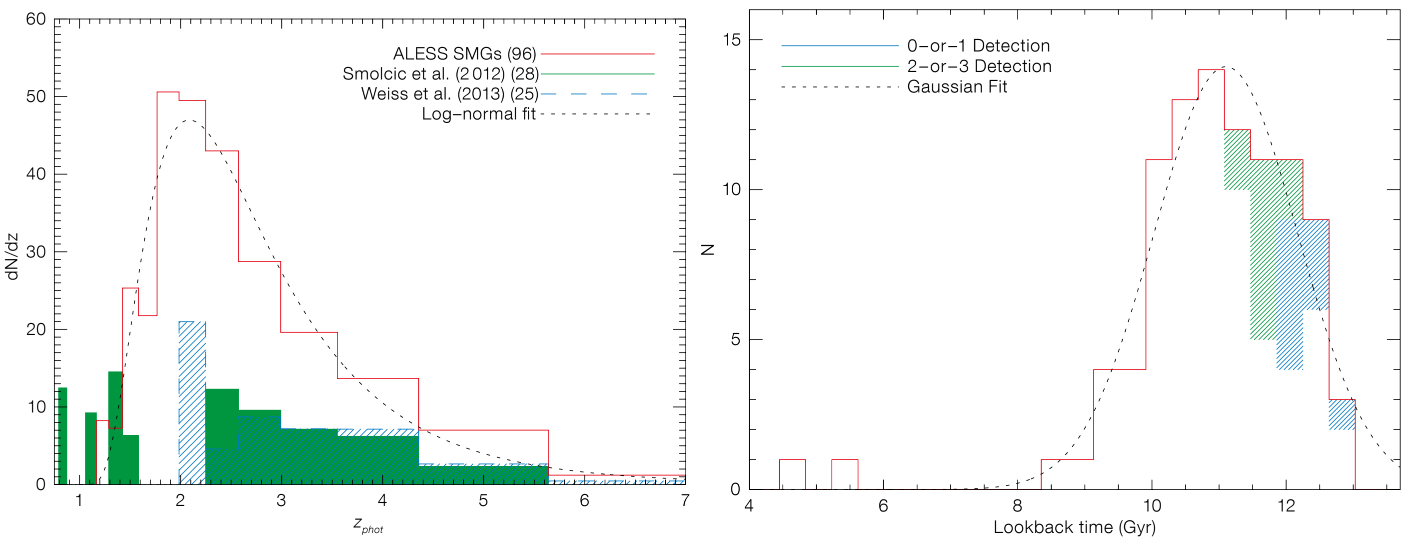

Figure 6. Left: The redshift distribution of the ALESS SMGs, binned uniformly in time. This is well represented by a log–normal distribution (see Simpson et al., 2014). For comparison we show the redshift distribution from Smolcic et al. (2012) and Weiß et al. (2013), including a correction for lensing probability as a function of redshift from that work. Right: The distribution of ALESS SMGs as a function of time. The distribution is well fit by a Gaussian centred at 11.10 ± 0.05 Gyr (equivalent to z = 2.6 ± 0.1), with a width of 1.07 ± 0.05 Gyr.

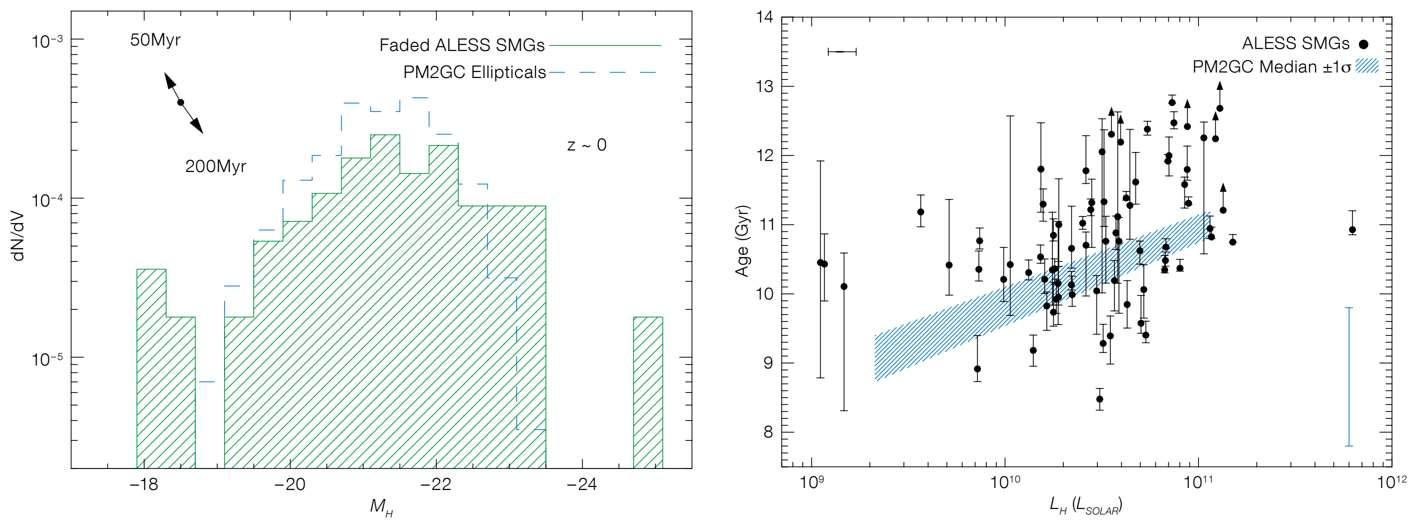

Figure 7. Left: The predicted z ~ 0 absolute H-band magnitudes of ALESS SMGs from Simpson et al. (2014), assuming a simple star formation history with a 100 Myr duration burst. The vectors indicate the effect of adopting either a 50 Myr or 200 Myr burst. Right: A comparison of the mass-weighted ages of local elliptical galaxies to the lookback age of the ALESS SMGs (from Simpson et al., 2014). The error bar (bottom right) shows the error in the mass-weighted age from the spectrophotometric modelling.

present-day descendants. Figure 7 (left) compares the faded restframe H-band luminosities of the SMGs (assuming a 100-Myr burst duration) to that of a volume-limited sample of morphologically classified elliptical galaxies at z ~ 0 from the Padova Millenium 2 Galaxy and Group Catalogue (PM2GC; Calvi et al., 2013). Simpson et al. found good agreement between the faded SMGs and local ellipticals, in terms of both typical luminosities and space densities. Moreover, by comparing the mass-weighted ages of the z ~ 0 ellipticals to the lookback times of the ALESS SMGs, they also found broad agreement in the expected ages (shown in Figure 7, right). Despite the large systematic uncertainty, Simpson et al. were able to conclude that the local ellipticals have ages which are in broad agreement with the ALESS SMGs, consistent with a simple evolutionary model where SMGs are the progenitors of local, giant elliptical galaxies.

Summary

Even during Early Science operations, ALMA has demonstrated its world-leading capabilities for advancing our knowledge of dust-obscured activity in the distant Universe.

The ALESS survey has yielded the first statistically reliable sample of SMGs with robust identifications. The properties of these galaxies are documented in: Hodge et al. (2013), catalogue paper; Karim et al. (2013), number counts; Swinbank et al. (2012), serendipitous [C II] emitters; Wang et al. (2013), X-ray properties; Swinbank et al. (2014), far-infrared properties; Simpson et al. (2014), photometric redshift analysis; Thomson et al. (2014), radio spectral properties; and Decarli et al. (2014), submillimetre stacking of less active populations.

Forthcoming papers will discuss the Hubble Space Telescope morphologies of ALESS SMGs (Chen et al., 2014), an SED analysis using the MAGPHYS code (da Cunha et al.,2014) and the spectroscopic survey of the ALESS SMGs (Danielson et al., in prep.).

More information about the survey, including the full list of ALESS co-investigators, is available[1].

Acknowledgements

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Links

[1] ALESS web page: http://www.astro.dur.ac.uk/~irs/LESS