The LABOCA Survey of the Extended Chandra Deep Field South (LESS)

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We present the latest results from the LABOCA Extended Chandra Deep Field South (ECDFS) Submillimetre Survey (LESS), a joint 300-hour ESO–MPG survey of the 30 × 30 arcminute ECDFS field using the LABOCA camera on the 12-metre APEX telescope. This survey provides an important new waveband for comparison to previous studies of galaxies and active galactic nuclei (AGN) in the ECDFS, and one which is particularly sensitive to obscured starburst galaxies out to very high redshifts ($z < 8$). We highlight the identification in the LESS map of the highest redshift submillimetre galaxy currently known, as well as high significance statistical detections of a variety of star-forming galaxies and AGN, their clustering and evolution with redshift within the ECDFS.

One of the most significant findings of the IRAS survey was the identification of a population of ultraluminous infrared galaxies (ULIRGs, galaxies with far-infrared luminosities $> 10^{12}\ L_{\odot}$ or star formation rates of $> 100\ M_{\odot}\ \mathrm{yr}^{-1}$) that emit the bulk of their bolometric luminosity at far-infrared wavelengths (Sanders & Mirabel, 1996). Surveys in the submillimetre and millimetre wavebands over the past decade (with the SCUBA camera on the James Clerk Maxwell Telescope at 870 µm or MAMBO on the IRAM 30-metre telescope at 1.2 mm) have shown that ULIRGs are much more common at high redshift compared to the local Universe (e.g., Smail et al., 1997; Coppin et al., 2006; Austermann et al., 2009), with indications from the first redshift surveys of an increase by a factor of 1000 out to $z \sim 2$ in the comoving volume density of luminous submillimetre galaxies (SMGs; Chapman et al., 2005). Therefore luminous obscured galaxies at high redshift could dominate the total bolometric emission from galaxies at those epochs. Such intense star formation would potentially build up significant stellar masses in a relatively short period of time and is thus capable of forming massive, evolved galaxies at high redshifts (e.g., Swinbank et al., 2006).

Surveys of the high redshift Universe in the submillimetre waveband are of particular interest due to the positive K correction from the dust spectrum in this waveband (Blain & Longair, 1993). Hence a source with a fixed far-infrared luminosity yields an almost constant flux density irrespective of redshift across $1 < z < 8$ — providing an efficient tool to survey for ULIRGs in the distant Universe. However, such submillimetre surveys have been hampered by the limited fields of view of the cameras, which have resulted in small survey areas and limited statistics of the detected sources. This situation has only very recently improved with the advent of the new Large APEX Bolometer Camera (LABOCA; Siringo et al., 2007; 2009) on the 12-metre APEX telescope (Figure 1), which features an impressive instantaneous 11.4-arcminute-diameter field of view providing a new opportunity for panoramic submillimetre surveys. Such surveys also benefit from APEX's location at one of the best astronomical sites worldwide: the ALMA high site at Llano de Chajnantor in Chile.

The LABOCA ECDFS Submillimetre Survey

LABOCA on APEX provided the opportunity to undertake the first sensitive and uniform panoramic survey of the extragalactic sky at 870 µm. This survey targeted the 2-Ms Chandra Deep Field South (CDFS; Luo et al., 2008) and the region immediately surrounding it (the Extended CDFS or ECDFS; Lehmer et al., 2005). This field has very low far-infrared backgrounds and good ALMA visibility and hence has become one of the pre-eminent fields for cosmological survey science. The ECDFS has been one of the prime targets for ESO's observatories over the past decade and hence a wealth of observations has been built up, pro-

Figure 1. The APEX telescope on Chajnantor. The LABOCA camera on APEX was used to obtain a deep map at 870 µm of the Extended Chandra Deep Field South for the LESS project. The wide field of view of LABOCA and the excellent site for the APEX telescope make this the most powerful facility for panoramic submillimetre surveys in the southern hemisphere.

viding a rich archive for the analysis of each additional dataset. As a result, the ECDFS is unique in the southern hemisphere in the combination of area, depth and spatial resolution of its multiwavelength coverage from X-rays through optical, near- and mid-infrared to the radio regime (e.g., Lehmer et al., 2005; Gawiser et al., 2006; Wolf et al., 2008; Caldwell et al., 2008). This field has also recently been observed in the far-infrared by the BLAST balloon experiment (Devlin et al., 2009) and will be one of the deepest fields observed by the Herschel Space Observatory. The ECDFS was thus a natural choice for the first large extragalactic survey to be undertaken with the new LABOCA camera on the APEX telescope.

Even though LABOCA's mapping speed dwarfs that of previous cameras at similar wavelengths, a complete survey of the ECDFS was still a major effort: a number of groups within ESO and the Max-Planck-Gesellschaft (MPG) communities proposed a joint public legacy survey of the ECDFS to the ESO and MPG time allocation committees. The LABOCA ECDFS submillimetre survey (LESS) covers the full 30 × 30 arcminute extent of the ECDFS. The completed LESS survey used a total of 310 hours of observing time and covers the full ECDFS with a uniform noise level of $\sigma_{870\,\mu m} \sim 1.2$ mJy beam^{-1} (Figure 2). LESS is thus the largest contiguous deep submillimetre survey undertaken to date. A total of 126 SMGs have been detected in this field. Due to the positive K correction in the submillimetre waveband this deep map is sensitive enough to detect individual starburst galaxies with star formation rates of $\sim 500\ M_{\odot}\ \mathrm{yr}^{-1}$ at $z < 8$. Moreover, the wide area and depth provide the largest reliable sample of SMGs in a single field yet obtained and provides a unique opportunity to tackle key questions about this enigmatic population.

Weiss et al. (2009) show that the differential source counts in the full field are well described by a power law with a very steep slope, $dN/dS \sim S^{\alpha}$ with $\alpha = -3.2$, similar to the results from previous surveys (e.g., Coppin et al., 2006). The ECDFS is known to have underdensities of various high redshift source populations (e.g., optically bright AGN and massive *K*-band selected galaxies) and

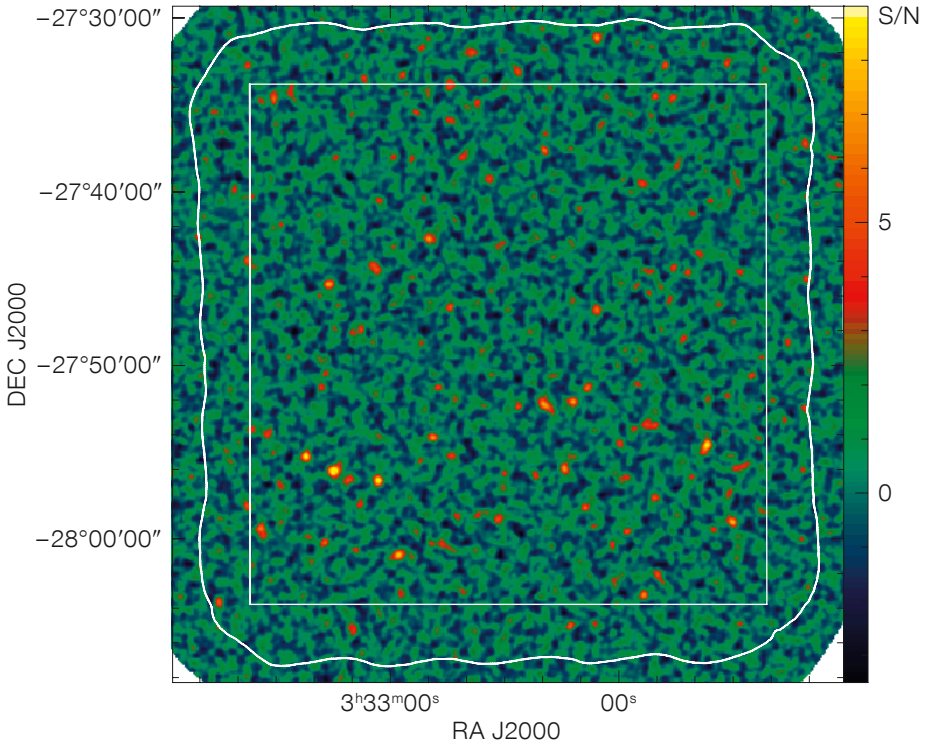

Figure 2. The submillimetre map of the ECDFS from the LESS project (Weiss et al., 2009) shown as a signal-to-noise map to highlight the uniformity of the coverage achieved by LABOCA and to give a visual impression of the distribution of the most significant sources. The white box shows the full 30 × 30 arcminutes of the ECDFS for which Hubble Space Telescope imaging and a large amount of supporting multiwavelength data exists. The white contour shows the 1.6 mJy beam^{-1} noise level which was used to define the field size for the source catalogue, yielding a search area of 1260 arcminutes^2.

indeed we find that the ECDFS exhibits a similar deficit of bright SMGs relative to previously studied blank fields, although the numbers of fainter SMGs, that dominate the extragalactic background light (EBL), are comparable to previous estimates. We have also taken advantage of our large contiguous field of view to investigate the clustering of SMGs in the ECDFS and find evidence for strong clustering on angular scales < 1 arcminute (~ 0.5 Mpc at the relevant redshifts) for the first time. Assuming a power law dependence for the correlation function and a typical redshift distribution for the SMGs we derive a spatial correlation length of $13 \pm 6\ h^{-1}$ Mpc. This strong clustering demonstrates that SMGs are a highly biased population in the early Universe and thus are likely to relate to the formation phase of massive galaxies.

The most distant submillimetre galaxy

To understand the physical processes driving the intense activity within the SMG population we need to identify counterparts to these sources at other wavelengths. Unfortunately the relatively coarse resolution of LABOCA — 19 arcseconds FWHM — along with the modest signal-to-noise of many of the detections and the expected high redshifts and dusty nature of the counterparts, all conspire to make the identifications challenging. At present the most efficient and reliable technique to locate the source of the submillimetre emission precisely is to exploit the close relation between radio and far-infrared emission from star-forming regions and hence use the higher spatial resolution of deep interferometric radio maps to identify counterparts to SMGs (Ivison et al., 2002). One of the first sources to be identified from the LESS map using this technique turned out to be the highest redshift SMG known to date: LESSJ033229.4 (see Figure 3). The submillimetre emission is identified with a radio counterpart for which archival optical spectroscopy gave a redshift of $z = 4.76$. Analysis of the spectral energy distribution of this galaxy shows that the bolometric emission is dominated by

a starburst with a star formation rate of ~ 1000 $M_{\odot}$ yr^{-1}, although a moderate luminosity AGN is also present in this galaxy. This mix of starburst and obscured AGN signatures is also characteristic of the bulk of SMGs at z ~ 2 and suggests that star formation and black hole growth may also be strongly linked in this population at z ~ 5.

Starbursts and growing black holes

An intimate link between AGN activity and luminous obscured starbursts is also suggested by the analysis of the sub-millimetre emission from the 900 X-ray sources across the CDFS and ECDFS using the LESS map (Lutz et al., 2009). The total sample is detected at > 10σ significance, but more intriguingly we find distinct behaviour which suggests that there are two modes of AGN-star formation coexisting. For the bulk of the population, the X-ray properties of the AGN are only weakly coupled to their hosts, which have relatively modest star formation. In these systems, the period of moderately luminous AGN activity may not highlight a major evolutionary transition of the galaxy. The hints of more intense star formation and a more pronounced difference in star formation rates between unobscured and obscured AGN in our sample at the highest X-ray luminosities suggests that these luminous AGN may follow an evolutionary path, where obscured AGN activity and intense star formation are closely linked, possibly via a single physical process such as merging.

Submillimetre emission from "normal" galaxies

Most recently, we have employed the LESS map and the extensive multiwavelength observations available for the ECDFS to investigate the star formation activity in high redshift galaxy populations which are individually below the detection limit of our map. We achieve this through a stacking analysis of the submillimetre map using a sample of 8266 near-infrared selected (K_{Vega} ≤ 20 mag) galaxies, including 893 BzK galaxies (selected in *B-z v. z-K* colour space), 1253 extremely red objects (EROs) and

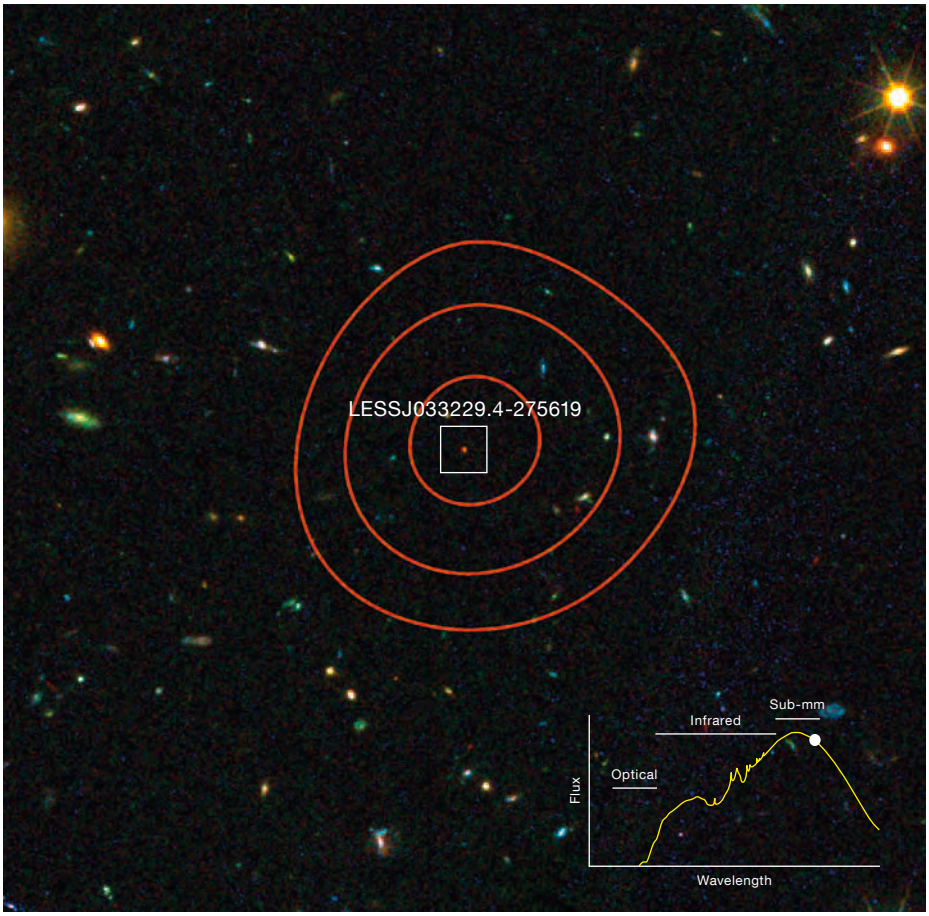

Figure 3. An early discovery from the LESS project was the highest redshift submillimetre galaxy (SMG) currently known (Coppin et al., 2009). The spectroscopic redshift, z = 4.76, for this galaxy was derived from some of the extensive archival observations available in the Extended Chandra Deep Field South. This system contains both a luminous, but dust-obscured, starburst and an actively fuelled supermassive black hole, underlining the strong link between black hole and galaxy growth in the SMG population. The best-fit spectral energy distribution demonstrates that most of the energy in this system escapes in the restframe far-infrared (the observed submillimetre band).

737 distant red galaxies (DRGs), all drawn from the Multi-wavelength Survey by Yale–Chile (MUSYC; Gawiser et al. 2006). In this way we obtain very strong statistical (10–20σ detection) constraints on the submillimetre emission from these different populations (Figure 4). For the BzK, ERO and DRG subsamples, which overlap to some degree and are all likely to be at z ~ 1–2, this implies an average far-IR luminosity of ~ 2–6 × 10^{11} $L_{\odot}$ and star formation rates of ~ 40–100 $M_{\odot}$ yr^{-1}. Splitting the BzK galaxies up into the photometrically-defined star-forming (sBzK) and passive (pBzK) subsets, the former is significantly detected while the latter is not (Figure 4), thus confirming that the sBzK/pBzK criteria do isolate obscured, star-forming and relatively passive galaxies. By mapping the stacked 870-μm signal across the *B-z v. z-K* diagram we suggest that the subset of sBzK galaxies which are also EROs are responsible for > 80 % of the submillimetre emission from the entire sBzK population. In total we estimate that galaxies with K ≤ 20 mag contribute ~ 15 % of the 870-μm EBL, most of this arising below the detection limit of our submillimetre map. To study the evolution of this activity we further divide the K ≤ 20 mag sample based on photometric redshift and derive the contributions to the EBL. We find a decline in the average submillimetre flux (and therefore IR luminosity and star-formation rate) by a factor ~ 2–3 times from z ~ 2 to z ~ 0. This suggests that the cosmic star formation history traced by far-infrared emission also exhibits a significant decline at z < 1, as indicated by UV tracers.

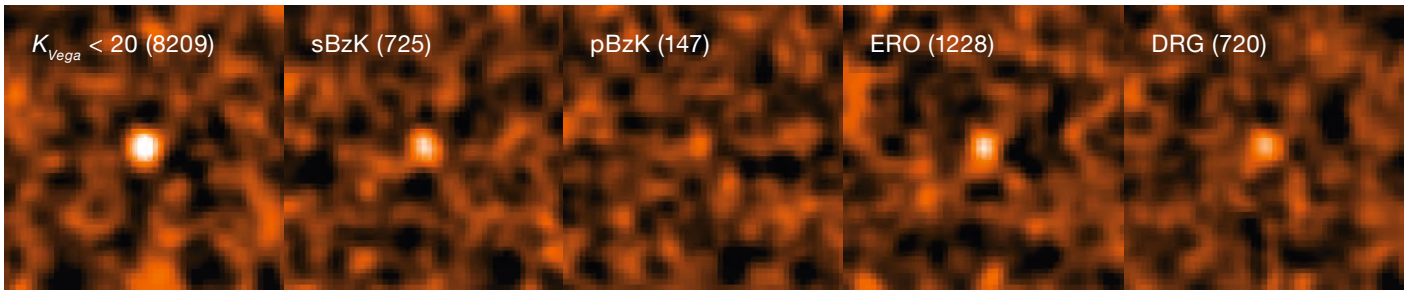

Figure 4. A demonstration of the science that can be derived from combining the LESS map with the rich multiwavelength archive in the Extended Chandra Deep Field South. These images show the average submillimetre emission from different photometrically-defined populations of faint, high redshift galaxies derived by stacking the emission at the positions of hundreds to thousands (number in brackets) of galaxies (Greve et al., 2009). From left to right they show the stacked emission from a simple magnitude-limited sample, the emission from star-forming BzK galaxies, from passive BzK galaxies, from Extremely Red Objects (EROs) and from Distant Red Galaxies (DRGs).

The future

This work has only just begun on exploiting the LABOCA map of the ECDFS, which will be released to the community through the ESO archive simultaneous with the publication of Weiss et al. (2009). Highlights of the ongoing work on the LESS project include a detailed comparison of the BLAST far-infrared maps of this region to the LABOCA submillimetre map. One goal of this comparison (and future work with Herschel) is to identify "drop-out" sources which are visible to LABOCA, but faint in the far-infrared and could conceivably be at very high redshifts, $z > 5$. The major element of our ongoing studies is a 200-hour VLT Large Programme that was awarded to obtain spectroscopic redshifts for the SMGs identified by LESS (as well as far-infrared targets selected from the Spitzer FIDEL survey). We therefore expect that APEX's contribution to studies of the ECDFS will continue to produce new and exciting science for a considerable period to come.

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Links

* More information about the survey, including the full list of co-investigators, is available at http://www.astro.dur.ac.uk/~irs/LESS.

Colour composite displaying the triggered star formation in the shell surrounding the HII region RCW 120, formed by combining submillimetre and optical images. The APEX LABOCA 870-μm emission from cold dust is visible as the blue clouds surrounding the core of ionised gas in red (image from the SuperCOSMOS H-alpha survey). See ESO Press Photo 40/08 for further details.