PROCEEDINGS OF SCIENCE

The e-MERGE Legacy Survey

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The e-MERGE Consortium

The e-MERLIN Galaxy Evolution Survey (e-MERGE) is an ambitious multi-tiered legacy survey to exploit the unique combination of very high sensitivity and spatial resolution to study the formation and evolution of star-forming galaxies and AGN out to redshifts of z > 5. These observations will provide a powerful, obscuration-independent tool for measuring the massive star formation and AGN activity in high-redshift galaxies, hence tracing the development of the stellar populations and the black hole growth in the first massive galaxies.

With a resolution of 50-200 mas in C- and L-Bands, corresponding to < 0.5-1.5kpc at z > 1, e-MERLIN gives us our first truly reliable view of the distribution of star-formation within typical galaxies at the epoch where the bulk of the stars in the present-day Universe were being formed. In a previous study (Muxlow et al. 2005) it was shown that high angular resolution imaging of the distant radio source population with MERLIN is able to separate radio emission from AGN and star-forming regions. Thus in the deep e-MERGE Tier 1 observations of a 30 arc minute field centred on GOODS-N, combination EVN + e-MERLIN + JVLA imaging will disentangle the relative contributions of AGN and star-formation - an essential step given the apparently simultaneous growth of the black holes and stellar populations in galaxies. With the central region of the Tier 1 field ultimately reaching sub-µJy noise levels, e-MERGE will image several thousand star-forming galaxies, and statistically characterize the nature of the sub-µJy radio population - which are the target objects for the SKA.

Initial results from e-MERLIN, JVA, and EVN on e-MERGE Tier 1 region are presented here.

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1. Introduction

Astronomers have discovered and use many tracers of star-formation. Amongst these are UV radiation which is directly radiated by the rare but bright, high-mass O- and B-type stars which have recently been formed in regions of intense star-formation. Dust in such regions readily absorbs the UV radiation and re-radiates the energy in the Infra-Red bands. Both are good estimators of star-formation rate, but whilst star-forming regions are essentially transparent to IR radiation, the UV is subject to significant extinction, particularly at high redshift, which needs to substantial correction before an accurate star-formation rate can be derived.

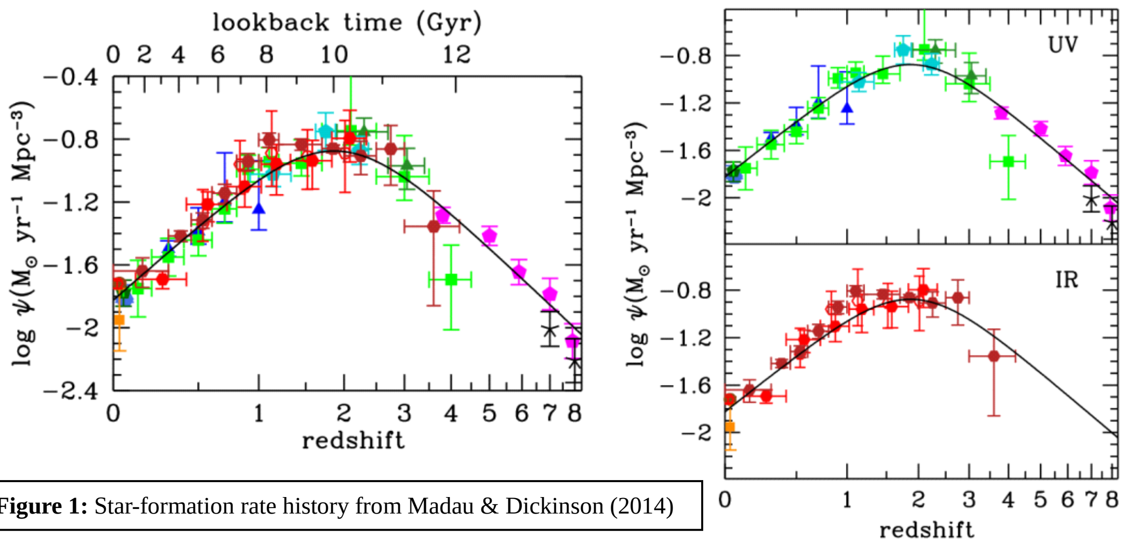


Figure 1: Star-formation rate history from Madau & Dickinson (2014)

Madau and Dickinson (2014) have derived a detailed star-formation history for the Universe from published samples of multi-band data. Figure 1 (left) shows the evolution of star-formation rate density with redshift as published by Madau and Dickinson. This rises to a peak around a redshift of two and then decreases at higher redshifts. The far-UV and IR contributions to this study are shown in Figure 1 (right), and it can be seen that the UV data from Bouwens et al (2012) [purple], and Schenker et al. (2013) [black], are critical in constraining the star-formation rate density models at high redshift. Although corrected to account for extinction, the total amount of star-formation missed from UV surveys at such high redshifts remains uncertain.

The high-mass O- and B-type stars end their brief lives in supernova explosions, and radio synchrotron emission from the supernova remnants which are formed is another excellent tracer of optically-obscured star-formation activity. The radio emission is extinction free, however it is important that any contribution from AGN activity be removed before a star-formation rate can be accurately calculated for such galaxies. This requires spectral information and high angular resolution.

2. Initial Deep Radio Field Study

The original deep MERLIN+VLA study of faint radio sources in GOODS-N. (Muxlow et al., 2005) covered a 10’×10’ L-Band field centred on GOODS-N with 92 faint radio source with flux densities >40μJy. The field was observed between 1996 and 1998 and postage-stamp images of each source showed that high resolution imaging can morphologically distinguish radio emission from AGN & star-forming systems. Below ~70µJy at 1.4GHz the radio source population becomes dominated by star-forming galaxies (~70%), typically at z<1.5.

Following the initial study, the data were re-analyzed with enhanced imaging software and a 15’ diameter contiguous combination image was made and 178 sources with flux densities >5σ (beam corrected) were mapped in detail, 90% complete to 20µJy (Wrigley et al., in preparation).

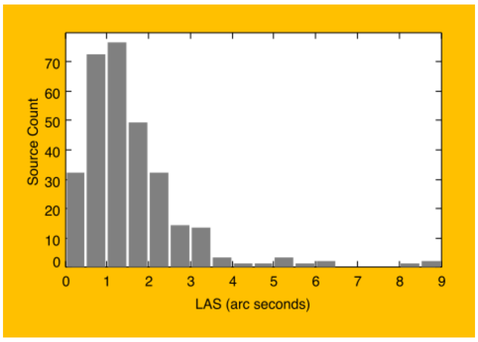


Figure 2: LAS distribution of 25µJy sample

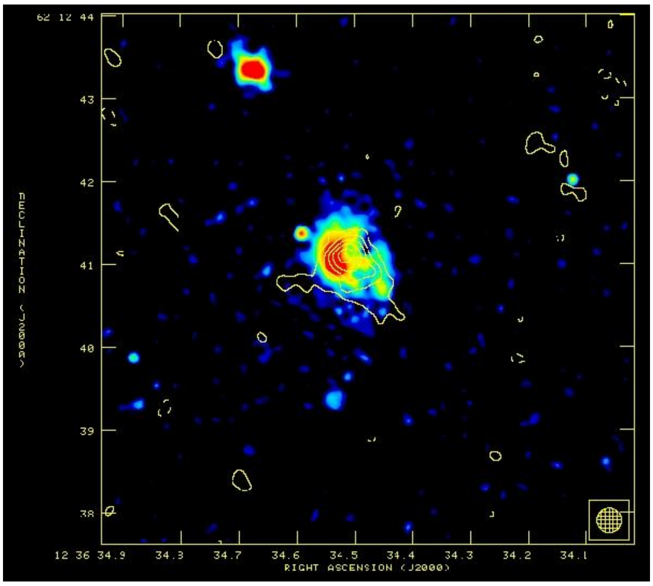


Figure 3: J123634+621241, z=1.219 starburst
False colour: HST WFPC2 Contours: Radio
CI=10µJy/beam. 1σ =3.3µJy/beam

The peak of the angular size distribution is ~1.2 arc seconds and is dominated by star-forming galaxies which possess a steep radio spectrum and are extended on galactic scales. Most AGN systems have flatter radio spectra and are small core-jet systems. The tail of the distribution to large angular sizes is associated with the few classical lobed AGN structures found.

3. The e-MERlin Galaxy Evolution (e-MERGE) Survey

e-MERGE is a tiered e-MERLIN, JVLA, and EVN Legacy to fully sample the AGN & star-forming galaxy radio luminosity functions to z~5. The consortium contains over 60 CO-Is from 9 countries. 3 tiered regions are proposed, Tiers 0 and 1 have been approved for e-MERLIN Legacy time, Tier 2 will likely follow via PATT-allocated time or by combination with the existing SuperCLASS Legacy programme. Tier 0 is a single deep L-Band pointing on a strong lensing cluster, A2218 (z=0.18). Tier 1 is an ultra-deep study of the GOODS-N region at both L- and C-Band. The Tier PIs and allocated e-MERLIN time is as shown below

Tier 0: Ian Smail [Durham], Tier 1: Tom Muxlow [Manchester] (Deep-narrow – 0.2 sq°)
Tier 2: Ian McHardy [Southampton] (via PATT or SuperCLASS) (Shallow-wide – 2.0 sq°)

Tier 0: 180hrs e-Merlin (L-band) + JVLA-A
Tier 1: 360hrs e-Merlin+40hrs JVA-A (L-band)+380hrs e-Merlin+ JVLA-A/B/C (C-band) mosaic

Tier 1: L-band: Single pointing centre including 76m Lovell telescope. Central 12 arc minute field 1σ ~ 500nJy/beam (with JVLA) + outer 30 arc minute field 1σ ~ 1µJy/beam

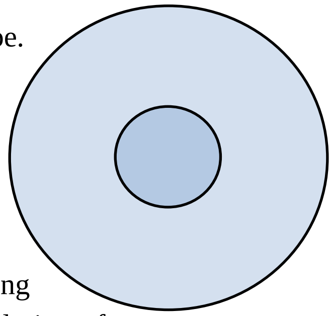
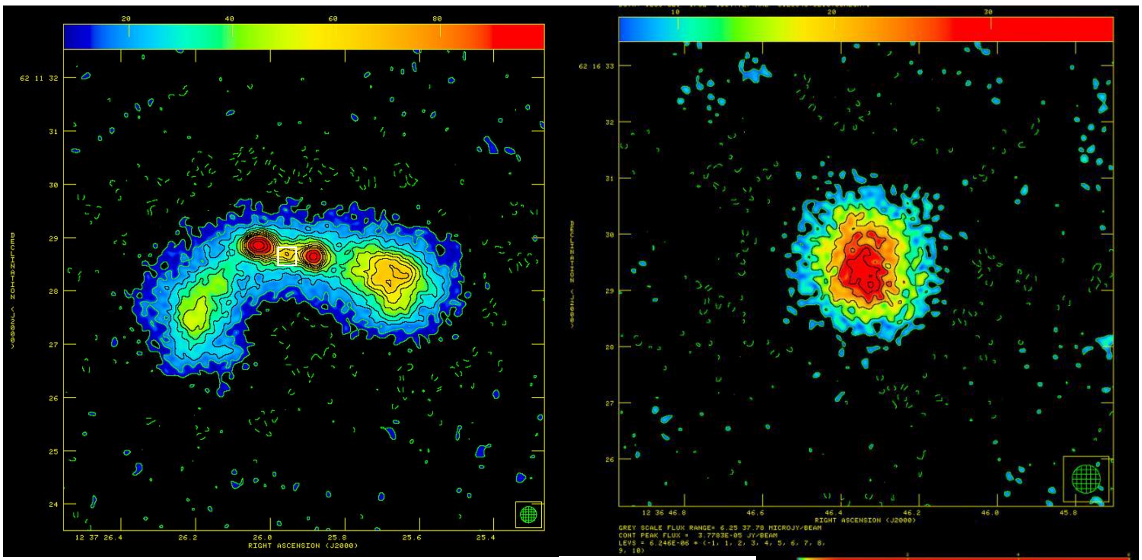


Figure 4: Tier 1 area coverage: Inner ultra-deep 12' diameter field + surrounding 30' diameter annulus

The ultra-deep central field will also be imaged with the EVN at L-Band with a deep 72-hr integration. Additionally the central field will be imaged at C-Band with a 7-pointing mosaic. The e-MERLIN combination images will have an angular resolution of ~300mas at L-Band and ~40mas at C-Band. The EVN image will have an angular resolution of ~4mas. Within the central field, *e*-MERLIN will image ~580 starbursts and ~270 AGN with an angular resolution of ~200 mas, complete to ~3µJy (>10 times deeper than the Muxlow et al. 2005 study). In the surrounding 800 square arc minutes, e-MERLIN will image ~2500 star-forming galaxies and ~1200 AGN brighter than ~6µJy. In total e-MERLIN will image >5000 faint radio sources in 0.2 square degree field centred on GOODS-N.

Tier 1 JVLA data at L- and C-Band have been taken and fully reduced. e-MERLIN L-Band data will be taken in Q1 and 2 2015 with the C-Band data following in Q3 2015 after the 2GHz bandwidth upgrades have been completed. Observations for the EVN L-Band data have been started. Around 40 hrs of e-MERLIN L-Band test data have been taken (~10% of e-MERGE allocation) and initial L-Band combination images with the JVLA have been made. Examples from the inner 12' field are shown in Figure 5 for an AGN and star-forming systems.



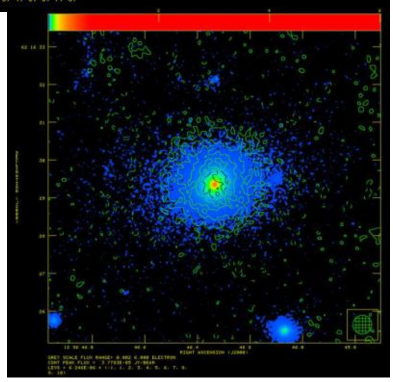


Figure 5: e-MERLIN+JVLA L-Band combination images – beam 0.3"
Left: AGN Wide-angled tail radio galaxy – total 5.3mJy CI 7.5µJy/bm. White square marks the position of I=22.9 galaxy at z=1.2653
Right: (Upper) Extended steep-spectrum starburst galaxy with possible embedded AGN– total 393µJy. CI=6.2µJy/bm. Star-formation rate ~200 M⊙/yr (0.1-100M⊙) assuming a Salpeter IMF.
Right: (Lower) Radio image contoured over HST ACS image in false colour showing a I=19.8 face-on galaxy at z=0.5032 with BL nuclear emission. Radio emission covers the face of the galaxy.

In the star-forming galaxy shown in Figure 5, the radio emission extends over the whole of the optical extent of the face-on galaxy, but shows no evidence for any compact AGN radio component even though AGN activity is inferred since the bright optical nucleus emits broad-line emission.

3.1 e-MERGE Tier Combination

The Tier 0 deep L-Band study of the strong lensing cluster A2218 (Figure 6) will image ~50 amplified sources with intrinsic L-Band fluxes at faint as 300nJy and may include star-forming galaxies with SFR ~200M⊙/year to z~5.

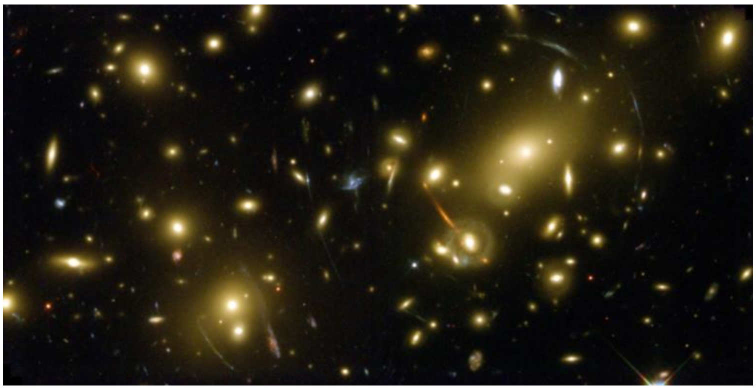


Figure 6: HST WFPC2 image of gravitational lensing cluster Abell 2218

In combination with Tier 1 ultra-deep L-Band imaging, the e-MERGE programme will characterise the µJy and sub-µJy radio source population which is the target population for the SKA in future ultra-deep high redshift star-formation studies.

Figure 7 shows the rest-frame 1.4GHz luminosity of the star-forming galaxies in GOODS-N as imaged in the original Muxlow et al. (2005) study for those starburst galaxies with measured redshifts complete to 40µJy plotted against redshift. The sub-set of starbursts which were also sub-mm sources are marked as filled stars and those containing embedded AGN are marked with open triangles. 3 individual starburst systems are also marked for comparison purposes – M82, Arp220, and HDF850.1, the brightest sub-mm sources in the HDF-N field (a sub-set of GOODS-N).

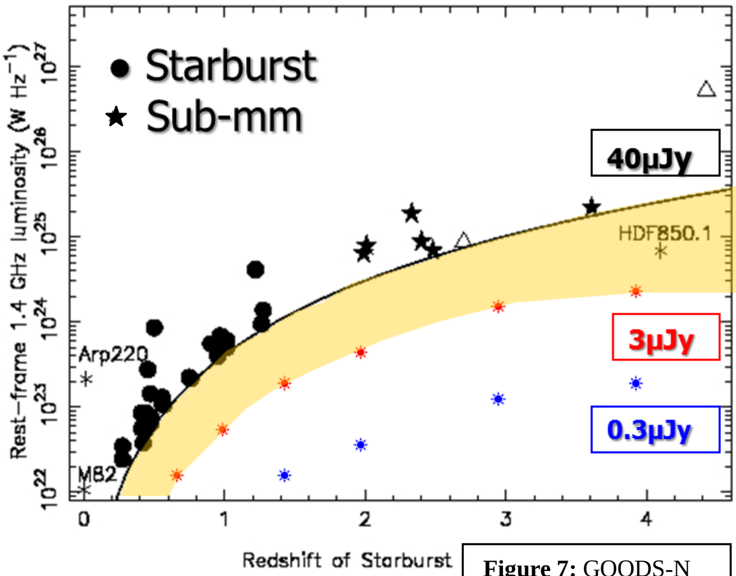


Figure 7: GOODS-N Starburst luminosities

Tier 1 will extend the direct imaging of star-forming galaxies complete to 3µJy in the central ultra-deep 12’ field (hatched in yellow in Figure 7). Tier 0 direct imaging of ~50 star-forming galaxies amplified by gravitational lensing will extend the study to around 0.3µJy, supplemented by several thousand systems sampled statistically from stacked imaging within Tier 1. Such studies, together with the several thousand star-forming systems imaged directly in the Tier 1 30’ field and the wide-shallow Tier 2 study, will constrain the star-formation rate density distribution above the established peak at z~2 and show the nature of the fall in rate density at high redshift using an extinction-free star-formation rate indicator for the first time.

3.2 AGN-Star-formation Feedback

The role of AGN feedback in star-formation activity will be investigated within the central 12' Tier 1 field with high angular resolution (~40mas) e-MERLIN+JVLA imaging at C-Band and ~4mas L-Band imaging with the EVN. Existing L-Band studies with MERLIN, VLA, and EVN (Muxlow et al., 2005 and Chi et al., 2013) have confirmed the presence of embedded AGN in some high-redshift sub-mm starburst systems. e-MERGE will extend this investigation to lower luminosity star-forming systems.

One example of a high-redshift (z=4.424) sub-mm star-forming system with an imbedded AGN is shown in Figure 8 where Muxlow et al., (2005) find a compact AGN core and short one-sided jet lying within an extended star-forming region. Chi et al., (2013) confirm the AGN and inner jet structure with the EVN.

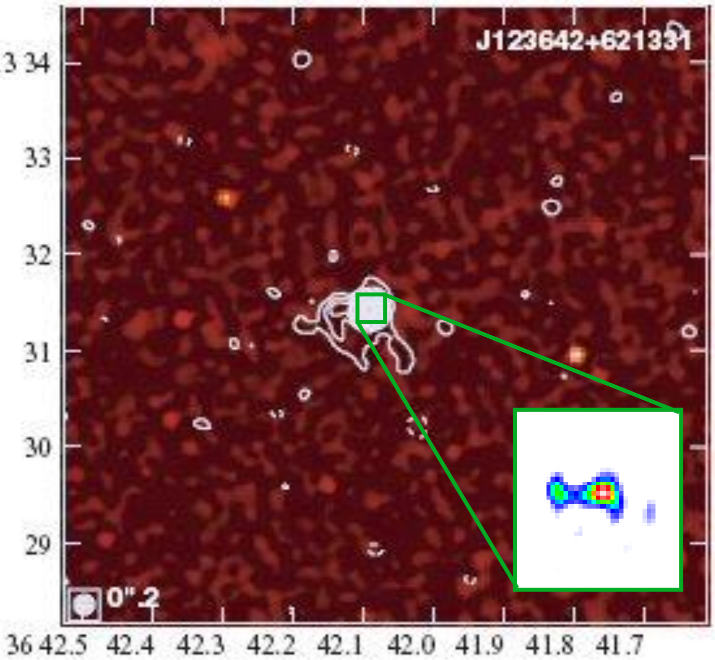


Figure 8: L-Band image of z=4.424 sub-mm starburst from Muxlow et al. (2005). Insert: EVN image from Chi et al. (2013) showing inner core and jet.

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