Star-formation and AGN feedback across cosmic time

High-resolution imaging of the μJy radio source population

e-MERGE – Latest results and planned releases...

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Ian Smail, Ian McHardy, Nick Wrigley, Jack Radcliffe, Alasdair Thompson, Daria Guidetti, & the e-MERGE Consortium

e-MERLIN & JBO:
A radio astronomy facility for the SKA era
JBO 16th September 2016
Best fit SMBH accretion history from X-rays \([\text{red curve (Shankar et al. 2009); green shading (Aird et al. 2010)}]\) and infrared \((\text{blue shading (Delvecchio et al. 2014)})\) data. Co-moving rates of SMBH accretion scaled up by 3,300 to facilitate visual comparison.

Star-formation and black hole growth are co-evolving and closely linked at all redshifts.

Need to study the evolution and interactions in both populations:

- Role of AGN in S-F – AGN feedback required to account for observed (bright end) galaxy luminosity function
- AGN can trigger as well as quench S-F – study feedback from embedded AGN in S-F galaxies
- S-F rate turn over at \(z>2\) is still problematical – needs to be confirmed by extinction-free S-F tracers
- Need to separate AGN-jet activity from S-F emission to accurately measure S-F rate in the radio band
The µJy radio source population

Differential radio source counts show an upturn below flux densities of ~1mJy

→ A new population of starburst systems

Padovani et al, & others, show AGN population evolves, R-Q AGN dominating over radio-loud AGNs < 100µJy

R-Q AGN properties? Similar to R-Loud AGN but fainter? Starbursts with faint embedded AGN? Need high resolution, high sensitivity radio imaging to separate AGN-jet from S-F emission...
The e-MERlin Galaxy Evolution survey
A tiered e-Merlin + JVLA + EVN Legacy proposal

Tier 0 – Normal galaxies out to $z \sim 5$  
  Deep imaging around clusters to utilise amplification by lensing*  
  [Ian Smail – Durham]

Tier 1 – Deep survey of $\mu$Jy radio sources  
  Deep imaging of the $\mu$Jy radio sources in GOODS-N*  
  [Tom Muxlow – Manchester]

  * – e-MERLIN Legacy programme

Tier 2 – Shallow-wide survey over $\sim 2$ square degrees  
  May piggyback on another survey ?  
  [Ian McHardy – Southampton]

→ full sampling of AGN & S-F galaxy radio luminosity function to $z \sim 5$

Tier 0 – Observations to follow Tier 1  
  [2017→]

Tier 1 – L-Band:  
  [Complete, 25% e-M data reduced]
  C-Band:  
  [e-M 2016/7→, JVLA complete]

  L: Single pointing centre – Central $12' \ 1\sigma \sim 500nJy/beam$ Outer $30' \ 1\sigma \sim 1\mu Jy/beam$
  C: Mosaic covering central $12'$ field $1\sigma \sim 700nJy/beam$

  In full $30'$ field $\sim 1500$ AGN and $\sim 3100$ S-F galaxies complete to $\sim 6\sigma$
Tier 1: New Ultra-Deep Study of GOODS-N

→ Interim data release with ~25% e-MERLIN of data processed....

Initial (2016) detailed investigation of several >300 SF galaxies and AGN in central region
L-Band e-MERLIN/JVLA + EG078 (EVN) + C-Band JVLA mosaic 1σ~1.5μJy/bm
L-Band image 1σ ≤ 2μJy/bm
+EG078 EVN deep wide-field 1σ~3μJy/bm
→ Talk by Jack Radcliffe

In progress:
Final assembly/calibration of
e-MERLIN (~110 hrs), JVLA, EVN
datasets for initial combination imaging
(+archival dataset from Muxlow et al (2005)

Wide-field imaging test with WS CLEAN in progress with e-MERLIN+JVLA L-Band data

Some recent images from e-MERLIN + archival VLA+MERLIN data 1σ~2.5μJy/bm
Tier 1: New Ultra-Deep Study of GOODS-N

High angular resolution imaging together with spectral properties can separate populations within the µJy radio source population

Radio-loud AGN: Very few classical double structures found. Nearly all are small core-jet structures

J123652+621444 MERLIN+VLA Flat spectrum core + jet
Compact cores confirmed by deep VLBI imaging
Tier 1: New Ultra-Deep Study of GOODS-N

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**Classical Star-forming Galaxies:** Radio emission from central region of $10^{10}$ M$_\odot$ dust obscured irregular galaxy at $z=0.422$ – No compact emission detected

\[ L_{1.4} = 3.8 \times 10^{22} \text{ W/Hz} \Rightarrow \text{Star-formation rate} \ 15 \ M_\odot/\text{yr} \]

(0.1-100 M$_\odot$ assuming Salpeter IMF)

Extended ($\alpha>0.35$) starburst ($S_{1.4} = 45 \mu\text{Jy}$)

S-F rate for M82 $\sim 3 \ M_\odot/\text{yr}$

cf J123708+621056 $\sim 15 \ M_\odot/\text{yr}$

$\Rightarrow \sim x5$ more luminous

<100µJy population dominated by sfgs typically at $z<1.5$
Tier 1: New Ultra-Deep Study of GOODS-N

Steep-spectrum ($\alpha=0.74$) starburst (Total 230$\mu$Jy) – ISO detection

$\rightarrow$ Star-formation rate $\sim$960 $M_\odot$/yr

Merging Scd sub-mm galaxy with tidal tail
- Radio emission follows merger & extends towards tail (cf ‘Antennae’)
Tier 1: New Ultra-Deep Study of GOODS-N

Ultra-luminous Starburst

**e-MERLIN**

J123634+621241

- Radio emission follows merger & extends towards tail (cf 'Antennae')

S-F rate for Antennae 60+ M☉/yr

\( \text{cf } J123634+621241 \sim 960 \text{ M}_\odot/\text{yr} \)

\( \rightarrow \times 10 \) more luminous

Peak 25μJy/bm

1σ 2.5μJy/bm

- VLA cm Continuum

ESO

Radio contoured

CI = 7μJy/bm

ESO
Tier 1: New Ultra-Deep Study of GOODS-N

Extended (0.7") steep spectrum ($\alpha>0.71$) starburst ($S_{1.4} = 49\mu$Jy) – No compact emission (VLBI)
No detectable emission in visible bands. Faint very red object detected in F160W (1.6µm IR)

ISO detection $\Rightarrow$ dust obscured starburst at $z\sim3$ 1.3mm SMA detection $\Rightarrow$ S-F rate $\sim2000$ M$_{\odot}$/yr
Hard Chandra X-rays $\Rightarrow$ obscured QSO at $z=2.7$ $\Rightarrow$ Embedded R-Q AGN?
Tier 1: New Ultra-Deep Study of GOODS-N

Central field contains 43 identified SMGs

Median radio continuum LAS Lockman Hole $z=1$-$3$ sub-mm sources $\sim0.65''$ (Biggs & Ivison, 2008)

ALMA 1100$\mu$m dust continuum for $z>3$ SMGs are $\sim2\times$ smaller (Ikarishi+ 2015)

– Talk by Alasdair Thomson
Tier 1: New Ultra-Deep Study of GOODS-N

Radio-Quiet AGN

HST ACS

$I = 20.8^{\text{mag}}$ galaxy $z = 0.5032$

$I = 25.3^{\text{mag}}$ galaxy $z = 0.76$

$I = 23.8^{\text{mag}}$ galaxy $z = 0.79$

New Ultra-Deep Study of GOODS-N

$\sigma \sim 2.75$ $\mu$Jy/bm

Peak $38$ $\mu$Jy/bm

New Image HST ACS $I = 20.8^{\text{mag}}$ galaxy $z = 0.5032$

$e$-MERLIN $J123646+621629$

$1\sigma = 2.5$ $\mu$Jy/bm

Peak $35$ $\mu$Jy/bm

Radio-Quiet AGN

$SFG$

$AGN$

radio-quiet AGN

radio-loud AGN
**Tier 1: New Ultra-Deep Study of GOODS-N**

**Radio-Quiet AGN**

Extended steep-spectrum ($\alpha > 1.62$) starburst ($S_{1.4} = 393\mu$Jy).

- Ring of star-formation – interacting galaxies? (e.g. Arp147)
- Radio emission extends across face of massive spheroidal galaxy
- Star-formation rate $\sim 200 \, M_\odot/yr$

No evidence for galaxy interactions

Bright galaxy core shows BL emission $\rightarrow$ Optical AGN activity

AGN or nuclear starburst? – C-Band/VLBI non-detection – NOT AGN
Tier 1: New Ultra-Deep Study of GOODS-N

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e-MERLIn
J123646+621629

Peak 35$\mu$Jy/bm
$1\sigma$ 2.5$\mu$Jy/bm

HST ACS

I=20.8$^{mag}$ galaxy z=0.5032

I=25.3$^{mag}$ galaxy z=0.76

I=23.8$^{mag}$ galaxy z=0.79

e-MERGE will provide very deep high angular resolution images of radio-quiet AGN systems – little is known about the detailed radio properties for this population

Arp147
**Tier 1: New Ultra-Deep Study of GOODS-N**

Extended steep-spectrum ($\alpha=0.67$) starburst (?) ($S_{1.4} = 130\mu\text{Jy}$). Sub-mm source GN17

Radio emission associated with $I=25^{\text{mag}}$ disturbed galaxy at $z=1.76$ $\rightarrow$ S-F rate $\sim670\ M_\odot/\text{yr}$

Brightest radio emission aligned over optical nucleus. LAS $\sim2''$
Tier 1: New Ultra-Deep Study of GOODS-N

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Strong Spitzer 3.6µm detection → Luminous starburst

Sub-mm starburst

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Extended steep-spectrum ($\alpha=0.67$) starburst (?) ($S_{1.4} = 130\mu Jy$). *Sub-mm source GN17*

Radio emission associated with $I=25^{\text{mag}}$ disturbed galaxy at $z=1.76$  \(\Rightarrow\) S-F rate $\sim 670 \, M_\odot/\text{yr}$

Brightest radio emission aligned over optical nucleus.  \(\text{LAS} \sim 2''\) - large for a $z=1.76$ SMM source!

Strong Spitzer 3.6µm detection  \(\Rightarrow\) Luminous starburst

Chandra X-ray consistent with star-formation – but radio emission looks like jet triggering....

Laird et al (2010)

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**Jet-induced starburst following a major galaxy interaction triggering AGN activity which has now subsided?**
Results for 248 detected sources within central 12′ field from ~90 hrs of data
Assign probabilities of emission being due to AGN or star-formation from measured radio structures and spectral properties...

Size evolution of S-F galaxies in radio and optical

Lindroos et al (in prep)

Sized from uv-stacking for ~1000 S-F galaxies with masses $10^{10} - 10^{11} \, M_\odot$ in central 12′ field using archival MERLIN+VLA data from Muxlow+ 2005.

Sizes derived from model fitting to binned uv data

Red area indicates $1\sigma$ uncertainties in the fitted model

Sizes measured for star-forming galaxies at a stellar mass of $5 \times 10^{10} M_\odot$
Tier 0: Imaging sub-µJy galaxies

A single L-Band pointing on a strong lensing cluster A2218 (z=0.18).

Expect ~50 amplified sources with intrinsic fluxes as faint as 300nJy

Measure faint radio counts

May include SF galaxies with SFR~200M☉/yr to z~5
Tier 0: Imaging sub-µJy galaxies

A single L-Band pointing on a strong lensing cluster A2218 (z=0.18).

Characterise the µJy & sub-µJy radio source population

→ The target population for the SKA in future high redshift SF studies
→ Sub-arcsec resolution separates SF and AGN
→ 100-200mas resolution required to study feedback in µJy sources
→ Will help constrain turn-over region in Madau plot in z=2 - 5 region

Measure faint radio counts

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