Star-formation Across Cosmic Time: Initial Results from the e-MERGE Study of the μJy Radio Source Population

SPARCs VII – The Precursors Awaken

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Perth 20th July 2017
The e-MERGE Survey (e-MERLIN+JVLA)

**Tier 1:** *Deep high resolution imaging of the μJy radio sources in GOODS-N*

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<th>EMU:</th>
<th>10” resolution over ~30k deg²  →  ~70M galaxies</th>
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<td>e-MERGE:</td>
<td>200mas resolution over ~0.2 deg²  →  ~5000 galaxies</td>
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~200mas – detailed investigation of SF activity / AGN feedback

L-Band imaging of 30’ field (200mas)
C-Band mosaic of the inner 12’ field (50mas)

L-Band – Central 12’ 1σ ~500nJy/bm Outer 30’ annulus 1σ ~1μJy/bm

In full 30’ field ~1500 AGN and ~3100 S-F galaxies complete to local ~6σ [2019]

**Q3 2017 → First consortium data and image release [DR-1]:**

- **L-Band:** JVLA 30’ field, beam~2”, 1σ~1.8μJy/bm
  + e-MERLIN(130hrs)+JVLA 12’ field, beam ~200mas, 1σ~1.5μJy/bm *Soon!!*
- **C-Band:** JVLA mosaic of 12’, beam ~500mas, 1σ~3μJy/bm
  [+EVN L-Band12’ field (72-hrs), beam ~5mas, 1σ~3μJy/bm] ✓ 30%

→ Detailed investigation of >500 SF galaxies and AGN in 12’ field

**Interim L-Band images from 12’ field (90hrs e-MERLIN) 1σ~2.5μJy/bm**
Central 12 Arcminute Field

JVLA L-Band image of the central 9' of GOODS-N. Full image to 30', 38 hrs, BW 1GHz, 1σ~1.8μJy/bm

≈600 detections in the inner 12' field to 5x local noise level. Complete to 9μJy

Few classical AGN double structures seen – confined to the mJy sources
Radio-loud AGN: Nearly all are small core-jet structures

J123652+621444 MERLIN+VLA Flat spectrum core + jet
Compact cores confirmed by deep VLBI imaging

Relative proportion of source types with 1.4GHz flux density
Star-forming Galaxies

Star-forming Galaxies: Extended radio emission across star-forming region

Typical example – J123708+621056 – steep-spectrum starburst ($S_{1.5} = 45\mu$Jy)

Emission across central region of $10^{10} \, M_\odot$ dust-obscured irregular galaxy at $z=0.422$

$L_{1.4} = 3.8 \times 10^{22} \, W/Hz \rightarrow$ S-F rate 20 $M_\odot$/yr

$\sim 5 \times$ linear size of M82

Radio population dominated by S-F galaxies below $S_{1.4} \sim 100 \mu$Jy
Nuclear Activity within Star-forming Galaxies

SFGs with z>0.5:
Tend to contain centrally condensed nuclear starbursts + extended star-formation
Many found in galaxies with AGN only visible in other wavebands

$10^{11}\, M_\odot$ Seyfert-2 galaxy
z=0.5186

Steep-spectrum ($\alpha<-0.56$) starburst extended along galaxy major axis with nuclear radio emission ($S_{1.5} = 76\, \mu Jy$).

$L_{1.4} = 1.7 \times 10^{23} \, \text{W/Hz}$
$\rightarrow$ S-F rate 88 $M_\odot$/yr

AGN or nuclear starburst?
Resolved by e-MERLIN ($\sim 370\, \text{mas}$), no VLBI detection to 8$\mu$Jy $\rightarrow$ Nuclear starburst
Need deep 5.5GHz e-MERLIN (+EVN 1.4GHz) to image in detail (Beam 5$\rightarrow$50mas)
Initial Results From Interim Images: – From Nick Wrigley’s PhD Work

Sample of 248 detected sources within central 12’ field from ~90 hrs of data.
Assign probabilities of being AGN or SF from radio structures and spectral properties...

**Machine-learning** (SVM – Support Vector Machine)

- **AGN core-jets**
- **Star-forming galaxies**
- **AGN classical doubles**
- **Complex mergers**

**Differential Source Counts:**

Derived from all 248 sources with class assigned by machine learning algorithm (SVM)

26 AGN & 80 SFGs with spectroscopic redshifts
The proportion of SFGs with nuclear starbursts are seen to increase with redshift. At high redshifts the proportion with nuclear starburst is approximately 70%. Malmquist bias since SFGs containing nuclear starbursts are more luminous systems – although some extended only SFGs are still found in high redshift systems.
Imaging SFG Radio Structures
Strongly dependent on spectral properties....

SMMJ123635.6+621424
I=23.3\textsuperscript{mag} Seyfert-2 galaxy z=2.015

Comparison of GOODS-N SFG radio structures seen by e-MERGE at 1.5GHz and the JVLA at 10GHz

Eric Murphy+ 2017
JVLA A+C-array
8-12GHz
23hrs (A) +
1.5hrs (C)
Beam 0.22"
1\sigma = 572nJy/bm
e-MERLIN+JVLA L-Band
– shows nuclear starburst + fainter emission extending across face of Seyfert-2 galaxy

36µJy nuclear starburst
EVN non-detection
Fitted size 250x160mas
@ PA+165°

SF ~ equally distributed between nuclear and extended components

Steep-spectrum (α<-0.87)
sub-mm source.
(Total $S_{1.5} = 88 µJy$).

$S_{850} = 5.5$ mJy. Radio + IR flux densities $\rightarrow$ S-F rate $\sim 1500 M_\odot/yr$
e-MERLIN+JVLA L-Band
– shows nuclear starburst + fainter emission extending across face of Seyfert-2 galaxy

Displays a bright ring of SF and a SF nucleus – though nuclear UV is heavily obscured

SMMJ123635.6+621424
$I=23.3^{\text{mag}}$ Seyfert-2 galaxy $z=2.015$

Anna Cibinel (Sussex) – private communication – multiband star-formation mapping
e-MERLIN+JVLA L-Band
- shows nuclear starburst + fainter emission extending across face of Seyfert-2 galaxy

At 10GHz the JVLA only detects the nuclear starburst – none of the radio emission from the ring of star-formation is detected (even with $1\sigma=572\text{nJy/bm}$!)

Extended 1.5GHz structure overlies SF ring

Displays a bright ring of SF and a SF nucleus – though nuclear UV is heavily obscured

Eric Murphy+ 2017
JVLA 10GHz
Beam 0.22"

X-band fitted size
380x270mas
$S_{10\text{GHz}} = 12\mu\text{Jy}$

Anna Cibinel (Sussex) – private communication – multiband star-formation mapping
Matched Resolution Imaging of SFGs at 1.5 GHz and 10 GHz...

JVLA 10 GHz v e-MERLIN 1.5 GHz (Beam~200 mas)

For 15 sources common to both e-Merge and Murphy+ 2017:

JVLA LAS at 10 GHz are up to an order of magnitude smaller than e-MERGE at 1.5 GHz (Median ~170 mas)

- also significantly smaller than 3 GHz sizes of 115 SMGs in COSMOS (median FWHM ~0.54")

Miettinen+ 2017
Matched Resolution Imaging of SFGs at 1.5 GHz and 10GHz...

JVLA 10GHz v e-MERLIN 1.5GHz (Beam~200mas)

Merging Scd sub-mm galaxy with tidal tail - High redshift version of the ‘Antennae’

JVLA at 10GHz detects only the central nuclear starbursts / merging cores in star-forming galaxies - and the inner core-jet structures in AGN systems
Matched Resolution Imaging of SFGs at 1.5 GHz and 10 GHz...

JVLA 10 GHz v e-MERLIN 1.5 GHz (Beam~200 mas)

Unusual merging system with star-formation + nuclear starburst (No VLBI detection)

$S_{1.5\,\text{GHz}} = 130\,\mu\text{Jy} \quad S_{10\,\text{GHz}} = 8 \,\mu\text{Jy}$

10 GHz: JVLA detects nuclear starburst (LAS~180 mas)

For 32 reliably detected sources in Murphy+ (2017) median FWHM~170 mas → near peak of SFR density

SF occurs in compact regions within galaxies.

1.5 GHz: Confirms that many systems at z~2 have compact nuclear starbursts – but these are embedded within lower surface brightness steep spectrum emission from additional extended areas of SF

- and the inner core-jet structures in AGN systems
Some Concluding Thoughts...

- Most radio-loud AGN are simple core-jets.
- Classical extended starbursts dominate at $z<0.5$
- At higher redshifts star-formation in intense nuclear starbursts appears to be common – but extended star-formation is also present
- Some nuclear starbursts contain AGN visible in other wavebands – Are these young systems where the AGN activity has not yet quenched SF?
- Is the evolution of nuclear starburst SFGs and AGN related? Is there a common recent trigger?
- Need deep C-Band e-MERLIN+JVLA (50mas beam) + full depth L-Band EVN (5mas beam) to confirm the nature of these nuclear starbursts
- At higher redshifts, high-frequency imaging is insensitive to steep spectrum emission from extended regions of SF & may detect only nuclear starbursts – very deep images will be required to recover the extended structure!!
- Extended starburst regions may contain substantial SF

→ Fuller analysis to follow from DR-1 release with better images on ~500 sources