A progress report: The Evolutionary Sequence of Young Radio Galaxies

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27th May 2015 | 5th workshop on CSS & GPS radio sources | Rimini, Italy
Context – AGN evolution

• AGN evolution
  • Relationship between AGN & normal galaxies not understood
  • Don’t yet understand evolution of young radio galaxies

• Some questions to address:
  • When do AGN first appear? What evolutionary path do they follow?
  • Does AGN evolution occur in a short burst or gradually within first few Gyr?
  • What are the properties of AGN & host throughout their evolution?
  • Are GPS/CSS sources the youngest radio galaxies?

• To pinpoint when AGN becomes active, and the timescales over which they evolve, we observe GPS/CSS sources
GPS/CSS sources – the youngest AGN?

• Jets grow with age
  • GPS → CSS → Large RGs

• Typical sizes:
  • GPS: < 1 kpc
  • CSS: 1 – 10s kpc

• Jet size excellent tool for dating RGs

$10^{11} M_\odot$ AGN w/ jet power $Q_{\text{tot}} = 10^{35.5} \text{ W}$

Ross Turner et al. (2015)
GPS/CSS sources – the youngest AGN?

• $v_m - \ell$ relation

• Studies mostly limited to Jy levels
  • Need depth, many frequencies and high res

• Hancock+ (2010) & Randall+ (2012) are among the faintest samples
  • Only goes down to a few mJy

\[
\log v_m = -0.21(\pm 0.05) - 0.65(\pm 0.05) \log \ell
\]
Goal – construct evolutionary sequence

- **Aim:** To construct an evolutionary sequence for the early stages of AGN, with a particular focus on faint GPS/CSS sources

- Place in evolutionary sequence not well understood

- We study very faint RGs from radio – X-rays over a large sample in order to detect meaningful tracers of their age (e.g. jet sizes, spectra, colours, etc)
Main age indicators

- Jet sizes
- Electron lifetimes / spectral age & index (based on break & turnover frequency)
- Separation of nuclei (binary AGN)?
- Colours & SED of host

Shabala+ (2011)

\[ (u - r) \]

\[ t_{age} \]

\[ Z = 0.2 Z_\odot \]
\[ Z = 3.0 Z_\odot \]

\[ \nu_{peak} = 1551.7 \]

SMC, 76

Data
Best power law fit to data.
Best single-homogeneous fit to data.

University of Western Sydney
Faint Sample: ATLAS
(The Australia Telescope Large Area Survey)

- Widest deep radio survey (Norris+ 2006; Franzen+ 2015)
  - 7 square degrees of CDFS and ELAIS-S1
  - r.m.s. (σ) of 15 μJy
- Overlaps with deep observations in:
  - X-ray – e.g. Chandra
  - Optical – e.g. AAT spectra (500 redshifts)
  - Infrared – e.g. Spitzer, VISTA, Herschel
- Data Release 3 (DR3; Franzen+ 2015)
  - > 5000 galaxies (about half AGN)
  - Redshifts for most sources with more coming

- First time this research will have taken place using such a faint sample of this size – will pave the way for ASKAP science
Mid-Strength Sample: SMC (Small Mag Cloud)

- Additional data set of radio-continuum mosaics compiled by merging a number of observations together at $\lambda = 20\text{cm}, 13\text{cm}, 6\text{cm}, 3\text{cm}$ by Wong+ (2011) & Crawford+ (2011)
- Many background sources (mostly AGN) – 1560 at 20 cm from Wong+ (2011)
- Great spectral coverage across shorter wavelengths from 3 cm – 36 cm
- Wider & shallower (0.4 – 0.8 mJy $\rightarrow$ complimentary to fainter AGN)
- Well-studied
  - Surveys from other bands include Spitzer, Chandra, XMM
  - Many spectroscopic redshifts (Kozlowski+ 2011/13) and RMIs (Mao+ 2008)
Selection Strategy

Find young AGN from Radio Data

Select subsample of unresolved* AGN with GPS/CSS spectrum

GMRT  MOST  ATCA

Observe at higher resolution (3/6 cm) & repeat process for VLBI

Range of [low to high redshift / small to large linear sizes / bright to faint] young AGN to construct our evolutionary sequence

*some resolved in SMC
Observations

High resolution ATCA (~1 arcsec) obs. the faintest GPS/CSS sample to date

Now we have significant spectral coverage:

• **ATLAS** – 8-13+ frequencies between 0.150 – 9 GHz (*MWA, GMRT, ASKAP, MOST, ATCA*)
• **SMC** – 5+ frequencies between 0.843 – 9 GHz (*MOST, ATCA*)

• **Sample**: 151 GPS/CSS sources (8 with VLBI) from several mas – several 10s arcsec (few 100s pc – several 10s kpc) PLUS handful of larger FR I/II
ATCA images of 143 ATLAS / SMC sources

- ELAIS-S1 & CDFS sources “complete” down to $\sim 100 \mu$Jy (5σ)
- So far met our goals of resolving
  $\sim$half sample & measuring spectra
- Interesting maps:
Obtain morphology & linear size – Aegean

- Using --island option in Aegean source finder
Obtain accurate spectrum – turnover / break

- 71 ATLAS sources & 72 SMC sources – thanks Joe!
Spectral Index maps

- 71 ATLAS sources & 72 SMC sources
- Spectral index maps (e.g. 5.5 GHz):
SMC mosaic of 72 pointings

Overcoming computational challenges:

~40,000 x 40,000 pixel image!
But mostly empty!
Fraction of GPS sources in SMC

- In the SMC, at mJy levels:

  Is fraction of GPS sources the same as in O’Dea (1998)?
  - i.e. ~10%

- Classifying spectra is hard, so some only tentative GPS
- Therefore large error on fraction
- Result:

  2.5-12.5% of mJy sky behind SMC consists of GPS sources
VLBI images of 8 most compact sources

- 8 of the most compact GPS/CSS sources from 1” 3/6 cm obs
- 3 are resolved, 2 not detected
- Ranging from approx. 0.3-2 kpc, $L_{20cm} = 10^{23-26}$ W/Hz
VLBI obs. – turnover-linear size relation

\[ x = \text{VLBI obs. w/ spec-z} \]
\[ x = \text{VLBI obs. w/ photo-z} \]
VLBI obs. – what can we do?

• Since we now have range of source sizes, we will be able to confirm or reject the young RG hypothesis using age indicators

• We will be able to separate AGN/SF

• We may catch some RGs being “born”
  • Measure (or place limits on) timescales

• We hope to detect some binary AGN
  • Few known – Only one generally accepted radio binary AGN w/ separation < 1 kpc (Rodriguez+ 2006)
  • Test hierarchical merging + gravitational waves
GPS mis-ID in ATLAS – one-sided RG??

- Blue = ATLAS DR3
  (10 arcsec @ 1.4 GHz)
- Red = ATCA
  (~1 arcsec @ 9 GHz)
- Background = Spitzer
  (~1.5 arcsec @ 3.6 um)
Infrared-Faint Radio Sources (IFRSs): dominated by GPS/CSS sources at high-z

- ~20% of IFRSs at 2 < z < 3 are GPS/CSS
- >50% at z > 3?

(Collier+2014 - 2014MNRAS.439..545C)
Infrared-Faint Radio Sources (IFRSs): dominated by GPS/CSS sources at high-z

- ~7 IFRSs / deg²
- Up to ~100,000 IFRSs across sky
  - Only ~200 HzRGs currently known
  - Large number of previously unseen RGs at $2 < z < 5$?
Conclusion

- We have observed the faintest GPS/CSS sample to date
- High-res. obs. have allowed us to resolve jets of many sources
- VLBI obs. have resolved the most compact (young?) sources and follow the $v_m - \ell$ relation
- mJy sky behind SMC consists of 2.5-12.5% GPS sources
- IFRSs are dominated by GPS/CSS sources at high-z
- Age from jets will be compared to a many other multi-\(\lambda\) age tracers
- We will place GPS/CSS sources into an evolutionary sequence
- We will help confirm / reject the young RG hypothesis
- We will discover the properties of faint GPS/CSS sources
Thank you

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Control freak moving the telescope:
Observations – preliminary radio spectra

Modelling the radio spectrum of GPS source 1718-649 (Tingay+ 2015):
Detecting the hosts of GPS/CSS sources

- 71 ATLAS sources & 72 SMC sources
- Comparing morphologies (radio contours on Spitzer 3.6 μm image):

Contour levels: 3,4,5,6,7σ

Contour levels: 5 - 17σ, in 1σ increments
Using accurate fluxes

\[ y = x \]
Using accurate fluxes

\[ y = x \]
VLBI images of 8 most compact sources

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Observations – goals

• Science goals
  1. Test hypothesis that GPS/CSS sources are the youngest radio galaxies
  2. Place GPS/CSS sources into evolutionary sequence with other young AGN
  3. Search for evidence of evolving accretion mode and its relationship to SF

• Observational Goals
  1. Resolve about half sample
     – Measure jet sizes
     – Observe small-scale morphology
     – Construct sub-sample for VLBI follow-up
  2. Measure radio spectra
  3. Select subset of unresolved sources for follow-up with VLBI
Multi-wavelength data

• Data:
  • Radio – MWA, GMRT, ASKAP, MOST, ATCA (150 MHz – 9 GHz)
    • Spectra index, turnover & break frequencies
    • Resolved features / morphologies
    • Measure jet sizes / separation of AGN nuclei
    • Polarimetry / RMs
  • IR / optical – Herschel, WISE, Spitzer, VIDEO, AAT, etc
    • Colours & photometry, SEDs & morphologies, spec-z
  • X-ray – Chandra
    • Temperature / emission type