Spectroscopic redshifts for ATLAS, the EMU pathfinder

Minnie Yuan Mao
NRAO
Outline

- EMU – Ray’s talk earlier today
- ATLAS
- Getting spectroscopic redshifts for ATLAS
- Things we wouldn’t have been able to do without SPECTROSCOPIC redshifts
  - Cluster
  - Statistical redshift training…
Outline

• EMU – Ray’s talk earlier today
• ATLAS
• Getting spectroscopic redshifts for ATLAS
• Things we wouldn’t have been able to do without SPECTROSCOPIC redshifts
  – Cluster
  – Statistical redshift training…
• TAIPAN x EMU
  – Radio galaxy environments
  – Confirming RLF result
  – Robustify statistical redshifts for the low z end?
EMU:
Evolutionary Map of the Universe

• How have galaxies formed and evolved with cosmic time? (Norris et al. 2011)
• PI:
  – Ray Norris (CSIRO-ATNF)
• Project Scientists:
  – Andrew Hopkins (AAO)
  – Nick Seymour (CSIRO-ATNF)
EMU: Quick Look

- Frequency Range: 1130 – 1430 MHz
- Sensitivity: 10 uJy/beam
- Resolution: 10 arcsec FWHM
- Area: Entire sky south of +30 dec
- Instantaneous FOV: 30 sq deg
EMU: Quick Look

- Total integration time: ~1.5 years
- Number of Sources: ~70 million

- We need redshift information to study the evolution of these 70 million radio sources!
Enter ATLAS
ATLAS: Australia Telescope Large Area Survey

• How have galaxies formed and evolved with cosmic time? (Norris et al. 2006, Middelberg et al. 2008)

• PIs:
  – Ray Norris (CSIRO-ATNF)
  – Enno Middelberg (Bochum)
ATLAS: Quick Look

- Frequency: 1.4 GHz (pre-CABB)
- Sensitivity: 10 uJy/beam (Data Release 1: 30 uJy/beam)
- Resolution: 10 arcsec FWHM
- Area: 7 square degrees over 2 fields
ATLAS: Quick Look

- Total integration time: ~2000 hours
- Number of Sources: ~16000 (current 2000)

- We need redshift information to study the evolution of these 16000 (2000) radio sources!
ATLAS

- **Australia Telescope Large Area Survey**
- Uses the Australia Telescope Compact Array in Narrabri, NSW
- ATLAS aims to produce the widest deep radio survey
  - Wide = 7 square degrees
  - Deep = ~10 μJy rms at 1.4 GHz
- ATLAS comprises two fields so as to mitigate cosmic variance
  - CDFS – Chandra Deep Field South
  - ELAIS-S1 – European Large Area ISO Survey-South 1

These fields were chosen as they have deep optical, infrared and X-ray data.

~2000 radio sources so far (~30 µJy rms), expect ~16000 when we get down to a rms of 10 µJy
ATLAS publications

- Norris et al., 2006, AJ, 132, 2409
  Deep ATLAS Radio Observations of the Chandra Deep Field-South/Spitzer Wide-Area Infrared Extragalactic Field
  Very long baseline interferometry detection of an Infrared-Faint Radio Source
- Middelberg et al., 2008, AJ, 135, 1276
  Deep Australia Telescope Large Area Survey Radio Observations of the European Large Area ISO Survey S1/Spitzer Wide-Area Infrared Extragalactic Field
  The first VLBI image of an infrared-faint radio source
  Evidence for Infrared-faint Radio Sources as z > 1 Radio-loud Active Galactic Nuclei
  Wide-angle tail galaxies in ATLAS
  The radio properties of infrared-faint radio sources
  Deep Spitzer Observations of Infrared-Faint Radio Sources: High-redshift Radio-Loud AGN?
  Wide-field VLBA Observations of the Chandra Deep Field South
  ATLAS: Spectroscopic Catalogue and Radio Luminosity Functions
Cosmic Evolution of Radio Sources in ATLAS

• We have a sample of radio sources at 1.4 GHz above 150 µJy (5 x rms) over 7 square degrees

• We need to know their distances so that we can determine if and how they have evolved with redshift!

• The aim of my PhD thesis was to study the evolution of radio sources by obtaining spectroscopic redshifts for the ATLAS sources
AAT
Anglo-Australian Telescope
The Dream

- Spend 8 nights observing on the AAT. Target all ATLAS sources.
- Reduce data and obtain redshifts for all ATLAS sources.
- Do science with a sample that is now complete in radio and optical data.
- Obtain PhD! 😊
First Impression of AAT
It didn’t get much better...
The Reality

- Spend 8 nights observing cloud/rain/fog at the AAT
- Apply for telescope time the following year (meanwhile, study WATs for a year)
- Spend 8 nights observing cloud/rain/fog at the AAT
- Apply for telescope time the following year (meanwhile, go to Caltech for 6 months and spend remaining time writing up paper)
- Spend 8 nights observing cloud/rain/fog at the AAT
- Decide that having 23% of sources with redshifts is good enough
- Spend the next year understanding the selection biases of dataset!
AAOmega on the AAT

- 8 nights in Dec 2007
- 8 nights in Dec 2008
- 8 nights in Dec 2010 for a complementary project

- AAOmega was used in multi-object mode & nod+shuffle mode
- Total observing time: 31.3 h
- Seeing: 1.2 – 3 arcsec
## Observations

<table>
<thead>
<tr>
<th>Observation</th>
<th>Plate</th>
<th>Exposure</th>
<th>Obs. date</th>
<th>Dichroic</th>
<th>Seeing</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDFS A bright</td>
<td>1</td>
<td>3 × 1200(^1)</td>
<td>20071202</td>
<td>5700Å</td>
<td>2.4</td>
</tr>
<tr>
<td>CDFS A bright</td>
<td>0</td>
<td>4 × 1200</td>
<td>20071204</td>
<td>5700Å</td>
<td></td>
</tr>
<tr>
<td>CDFS B bright</td>
<td>1</td>
<td>4 × 1200</td>
<td>20071204</td>
<td>5700Å</td>
<td></td>
</tr>
<tr>
<td>CDFS A med</td>
<td>0</td>
<td>4 × 1800</td>
<td>20071207</td>
<td>5700Å</td>
<td>1.9-2.5</td>
</tr>
<tr>
<td>CDFS B med</td>
<td>1</td>
<td>2 × 1200</td>
<td>20071205</td>
<td>5700Å</td>
<td>1.8-2.3</td>
</tr>
<tr>
<td>CDFS A ns</td>
<td>1</td>
<td>1 × 1500</td>
<td>20071206</td>
<td>5700Å</td>
<td>1.4</td>
</tr>
<tr>
<td>CDFS A ns</td>
<td>1</td>
<td>13 × 2400</td>
<td>20071206,07,08</td>
<td>5700Å</td>
<td>1.2-3</td>
</tr>
<tr>
<td>CDFS A ns</td>
<td>0</td>
<td>5 × 2400</td>
<td>20071208</td>
<td>5700Å</td>
<td>1.2 - 1.7</td>
</tr>
<tr>
<td>CDFS B ns</td>
<td>0</td>
<td>1 × 1500(^2)</td>
<td>20071205</td>
<td>5700Å</td>
<td>2.3</td>
</tr>
<tr>
<td>CDFS A 2010</td>
<td>1</td>
<td>6 × 2400</td>
<td>20101206</td>
<td>5700Å</td>
<td></td>
</tr>
<tr>
<td>CDFS B 2010</td>
<td>1</td>
<td>2100+1500</td>
<td>20101207</td>
<td>5700Å</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observation</th>
<th>Plate</th>
<th>Exposure</th>
<th>Obs. date</th>
<th>Dichroic</th>
<th>Seeing</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELAIS bright</td>
<td>0</td>
<td>7 × 1200</td>
<td>20071205</td>
<td>5700Å</td>
<td>1.8</td>
</tr>
<tr>
<td>ELAIS bright</td>
<td>0</td>
<td>4 × 1800</td>
<td>20081221,22</td>
<td>6700Å</td>
<td>1.6-1.7</td>
</tr>
<tr>
<td>ELAIS bright</td>
<td>1</td>
<td>4 × 1800(^3)</td>
<td>20081224,25,26</td>
<td>6700Å</td>
<td>1.6-2.4</td>
</tr>
<tr>
<td>ELAIS 2010</td>
<td>0</td>
<td>1270+1770</td>
<td>20101208</td>
<td>5700Å</td>
<td>1.4 - 1.6</td>
</tr>
</tbody>
</table>
Data

- We observed a total of 1120/2018 ATLAS sources, of which 466 had quality spectra.
- We also observed a total of 1080 24um excess sources, of which 697 had quality spectra. The 24um excess sources are currently being studied in the context of sources that deviate off of the FRC (Norris et al. in prep).

\[ \sim 80\% \text{ complete at } R=20 \]
Spectroscopic redshifts are hard!
ATLAS: Spec $z$ vs. Phot $z$

- ATLAS: Australia Telescope Large Area Survey (Norris et al. 2006, Middelberg et al. 2008)
- Photo-$z$ from Rowan-Robinson et al. (2008)
- 5 optical bands and 2 IR bands
- Broad agreement but basically a scatter plot at $z>1$
Mao et al. (2010)
Redshift Distribution

There are a total of 309 sources with spectroscopic redshifts within a degree of S1189

- Peak at z~0.22!
- 42 galaxies in 3 ‘peak’ bins
- Significant to 7σ
- Velocity dispersion 870 km/s
- Similar to rich, local Universe clusters undergoing mergers (e.g. A3667, A3376)
- Inset shows 3 ‘peak’ bins
- The distribution in the inset is not Gaussian and shows substructure, consistent with merging systems
Spectroscopic vs. Photometric

- Binsize $z=0.05$
- Photometric redshifts from Rowan-Robinson (2008)
- Spectroscopic redshifts from our AAOmega observations
Spectroscopic vs. Photometric

- Binsize $z=0.05$
- Photometric redshifts from Rowan-Robinson (2008)
- Spectroscopic redshifts from our AAOmega observations
Spectroscopic vs. Photometric

- Binsize $z=0.025$
- Photometric redshifts from Rowan-Robinson (2008)
- Spectroscopic redshifts from our AAOmega observations
Spectroscopic vs. Photometric

- Binsize $z=0.025$
- Photometric redshifts from Rowan-Robinson (2008)
- Spectroscopic redshifts from our AAOmega observations
Redshift distribution

- 466 with spectroscopic redshifts
- 142 SF
- 282 AGN
- 10 stars
- 32 unclassified
  - i.e. Has enough spectral features to redshift, but unable to classify
A quick look at statistical redshifts

- We compared our spectral classifications with mid-infrared colour-colour diagrams similar to using the SWIRE data from Spitzer (e.g. Lacy et al. 2004, Richards et al. 2006).
A quick look at statistical redshifts

Mean $z \sim 0.2$

Mean $z \sim 0.4$

“Lacy Wedge”
Mean $z \sim 0.6$
Far-infrared Radio Correlation

Mean $z \sim 0.7$

Mean $z \sim 0.7$

Mean $z \sim 0.37$

Mean $z \sim 0.37$
What can TAIPAN do for EMU?

• Mainly already covered in Ray’s talk this morning

• Two specific things I care about
  – The environments of radio galaxies
    • WATs
    • Giant radio galaxies
  – The local radio luminosity function
Radio Luminosity Functions

- Radio Luminosity Function → RLF
- Used the spectroscopic classifications to construct RLF for both star-forming (SF) galaxies and AGN
RLF for SF galaxies

- Separated SF RLF into two redshift bins
  - $0 < z < 0.2$
  - $0.2 < z < 0.5$
- Results consistent with pure luminosity evolution
- Agrees well with previous work by Afonso et al. (2005)
RLF for AGN

- Separated AGN RLF into three redshift bins
  - $0 < z < 0.2$
  - $0.2 < z < 0.4$
  - $0.4 < z < 0.8$

- Results inconsistent with previous work by Mauch and Sadler (2007)
• Results consistent with previous work by Padovani et al. (2011) and Smolcic et al. (2009)
• Attribute the inconsistency to the Mauch & Sadler work to deeper radio data and different selections…
Summary

- ATLAS is an ideal testbed for EMU
- Spectroscopic redshifts are necessary for studying galaxy cluster kinematics and the environments of galaxies
- Spectroscopic redshifts may be used to train statistical redshifts
- TAIPAN will enable us to
  - Study the environments of radio galaxies
  - Probe the local RLF with a much higher degree of accuracy than previous studies!
Radio Luminosity Functions

- Sensitivity of \(~0.15\text{mJy}\)
- Cf Mauch & Sadler (2007): \(~2.8\text{mJy}\)
- We can probe the luminosity function for low-luminosity (~10\(^{23.5}\) W/Hz) out to z ~ 0.6!

Current flux limit of ATLAS(150\(\mu\)Jy)
ECDFS: Spec z vs. Phot z

- Phot-z from MUSYC survey (Cardomone et al. 2010) and COMBO-17 (Wolf et al. 2004)
- COMBO-17 uses 17 bands to derive phot-zs
- MUSYC uses 32 bands to derive photo-zs
- These are among the best photometric surveys conducted to date!
- Good agreement but still basically a scatter plot at $z > 1$
- (The mean $z$ of EMU sources will be $z \sim 1$ for SF sources and $z \sim 1.9$ for AGNs)
ATLAS Spectroscopy

- We have obtained 466 new spectroscopic redshifts in the CDFS and ELAIS-S1 fields.
- These data enable us to study the cosmic evolution of radio sources in ATLAS.
- These data also have important legacy value for the next generation of deep surveys…