Large AGN Surveys With VLBI

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Outline

• Science motivations and applications for VLBI

• Large VLBI Surveys from Earth and Space: past and present

• Investigating radio and γ-ray properties of powerful AGN jets with MOJAVE and Fermi
Why VLBI?

1. Ultrahigh angular resolution (sub-milliarcsecond scale).

2. Precise (microarcsecond scale) positional accuracy for astrometry.

1 million factor zoom-in views of γ-ray-loud AGNs (MOJAVE program)

Maser proper motions in HII region G24 (L. Moscadelli)
Limitations of VLBI

- **Too much resolution**
  - Sensitivity limits require target sources to be very compact ($T_b > 10^6$ K)

- **Not enough resolution**
  - Many target sources are too compact (!)

- **Interferometric coverage can be sparse**
  - Limited image fidelity, lack of short spacings

- **Very limited field of view ($\leq 1$ arcsec$^2$)**
  - but multiple correlation sky positions possible
Early VLBI Surveys

• Limited by availability of ad-hoc antenna arrays, small recording bandwidth, correlator capabilities

• Strategy was to identify and observe suitable targets from single-dish catalogs (bright, flat spectrum)

• **VLBI surveys are an excellent filter for finding AGN**

  – Complete sample of 64 AGN with:
    
    $5 \text{ GHz flux density} > 1.3 \text{ Jy}, \quad \delta > +35^\circ, \quad |b| > 10^\circ$

  - Roughly 75% were compact enough for VLBI observations
  - Extensive follow-up studies at other wavelengths and resolution scales
Pearson-Readhead Survey

2352+495: Young Radio Jets

3C 84: Radio Galaxy

3C 380: Radio Quasar

Owsianik et al.

Walker et al.

VSOP program

- Three main morphological classes of radio AGN jets
- Observed jet emission strongly affected by relativistic beaming
- Flat-spectrum AGN tend to be more compact
Caltech-Jodrell Bank Surveys

- **CJ1**: lowered the PR survey flux density limit to 0.7 Jy at 5 GHz
- **CJF** (flat-spectrum survey; Taylor et al. 1996)
  - complete sample w.r.t flux density and spectral flatness (293 AGN)
- **Jet kinematics**: (Britzen et al. 2008)
  - 3 to 5 VLBI epochs per source at 5 GHz;
  - superluminal speeds up to 30c
  - some inward motions seen
  - speeds positively correlated with radio luminosity

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<th>Frequency(MHz)</th>
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<td>Flux lower limit @5 GHz</td>
<td>350 mJy</td>
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<td>Galactic latitude</td>
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<td># Quasars</td>
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<td># Radio galaxies</td>
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<td># Unclassified</td>
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<tr>
<td># Total</td>
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Karouzos et al. 2012
Large VLBI AGN Surveys: Modern Era

**1994:** Advent of VLBA greatly facilitates large monitoring programs, polarimetry, & multi-frequency studies

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<th>Survey</th>
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<th>Flux Lim. (Jy)</th>
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<td>S. Lee et al. 2008</td>
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Large VLBI Surveys (> 80 AGN)

Font size proportional to \((N_{src})^{1/4}\)

Boxed = Multiepoch monitoring  Red = Full polarization
Geodetic VLBI Surveys

- Large database of VLBI 2 and 8 GHz observations made of several hundred AGN for calibration of International Celestial Reference Frame (ICRF)

- The **Radio Fundamental Catalog** is a compendium of VLBI data on nearly 10,000 objects (nearly all AGN) at 2, 5, 8 and 22 GHz: [astrogeo.org/rfc/](http://astrogeo.org/rfc/)

- Virtually every cm-wave VLBI source above ~150 mJy is now catalogued

- Catalog is overwhelmingly dominated by AGN

Petrov et al. 2011
mJIVE-20

- 20cm VLBA survey of FIRST survey sources
- Short pointings during VLBA filler time yields peak flux density and approximate $T_b$
- Exploits multiple-phase center capability of VLBA software correlator
  ~100 sources/sq. deg./hour
- ~4300 VLBI detections so far in the range 1 to 100 mJy

Deller & Middelberg 2014
mJIVE-20: Preliminary Findings

1. Fainter FIRST sources show higher likelihood of VLBI detection

   • If more luminous jets have higher Lorentz factors, de-boosting effect of VLBI core luminosity is higher for arbitrary jet orientations.

   • Slower, less luminous jets less affected by orientation, so their ratio of VLBI core to total (FIRST) flux density is higher.

2. Stellar/point like SDSS sources show much higher VLBI detection likelihood than either galaxies or sources with no SDSS counterpart.

   • VLBI detection likelihood trend w.r.t. FIRST flux density (point 1) is even stronger in galaxies and no-SDSS-counterpart sources.

Deller & Middelberg 2014
VLBA Imaging and Polarimetry Survey (VIPS)

- 1127 flat-spectrum AGN imaged at 5 & 15 GHz in SDSS northern cap
  - all CLASS survey sources with 8 GHz VLA flux density > 85 mJy

- Major results:
  - No trend between optical magnitude and 5 GHz flux density
  - 37% of AGNs had detectable linear polarization, ranging from 1% - 20%, (typically 5%)
  - B field near core is typically aligned with the jet, and becomes more ordered downstream
  - Discovery of binary black hole candidate 4C +37.11: contains two flat spectrum cores separated by 7 pc

Rodriguez et al. 2006
Space VLBI Surveys

USA (1986-88)
2.2 Earth Diam.
~20 AGN at 2 & 15 GHz

3 Earth Diam.
~200 AGN at 1 and 5 GHz

Russia (2011-present)
30 Earth Diam.
0.3, 1.6, 5, & 22 GHz
Surveying >200 AGN
**Why Space-VLBI?**

A Gaussian region of FWHM diameter at a (radio) wavelength $\lambda$ has an equivalent blackbody temperature Kelvin.

The maximum resolving power of an interferometer is

Therefore,

$$\left(\ldots\right)$$ Kelvin

But hardly any AGN have flux densities $S > 10$ Jy, therefore

→ **With Earth-based VLBI we can only directly measure AGN brightness temperatures below $\approx 10^{12}$ K**
56% of AGN have $T_b > 10^{12}$ K (30% in observer frame)

Detected AGN up to $T_b = 4 \times 10^{12}$ K

TDRSS Survey
Linfield et al. 1990

VSOP AGN Survey
Dodson et al. 2008

$T_b / 10^{12}$ K

Log 10 [$T_b / K$]
Radioastron AGN Survey (Kovalev et al.)

• Key science program to measure $T_b$ in jet cores selected from a list of 240 AGN with correlated 8 GHz flux density exceeding 0.6 Jy at longest ground-based baselines

• Successfully detected fringes to more than 30 AGN at projected baselines 5-23 Earth diameters at 1.6 and 5 GHz.

• Fringes also found at 22 GHz over baseline lengths between 2.5 and 8 Earth diameters for at least 10 AGN

• Target detection rates as of Jan. 2014:
  1.6 GHz: 75%,  5 GHz: 70%,  22 GHz: 30%

$\Rightarrow$ All of these detections give $10^{12} \text{ K} < T_b < 10^{14} \text{ K}$

$\Rightarrow$ 22GHz 3C 273 fringe detection at 8.1 $D_E$ is the highest directly achieved angular resolution in the history of astronomy (27 µas)
MOJAVE Collaboration

- M. Lister (P.I.), J. Richards (Purdue)
- T. Arshakian (Byurakan Observatory, Armenia)
- M. and H. Aller (Michigan)
- M. Cohen, T. Hovatta, A. Readhead (Caltech)
- N. Gehrels (NASA-GSFC)
- D. Homan (Denison)
- M. Kadler (U. Wurzburg, Germany)
- K. Kellermann (NRAO)
- Y. Kovalev (ASC Lebedev, Russia)
- A. Lobanov, T. Savolainen, J. A. Zensus (MPIfR, Germany)
- A. Pushkarev (Crimean Observatory, Ukraine)
- E. Ros (Valencia, Spain)
- G. Tosti (INFN Perugia, Italy)

The MOJAVE Program is supported under NASA Fermi Grant 11-Fermi11-0019
MOJAVE Studies of AGN Jets

- Linear (I) and circular (II) polarization
- Kiloparsec radio (III, Kharb et al. 2010) and X-ray (Hogan et al. 2011)
- Parent population and luminosity function (IV)
- Faraday rotation measure (VII) and spectral index maps (XI)
- Nuclear opacity and magnetic fields (IX)
- Morphology and compactness (I, V, Homan et al. 2005)
- Kinematics (V, VI, VII, X)
- Optical properties (Torrealba et al. 2012, ; Arshakian et al. 2010)

Roman numerals refer to MOJAVE paper series, full list at http://www.cv.nrao.edu/2cmsgroup/publications.html
I. Jet Speeds

- Speed distribution:
  - peaked at low values
  - only 2 jets with $\beta_{\text{app}} > 30$
  - high $\Gamma$ jets are very rare in blazar parent population

- Lorentz factors of the most luminous/powerful jets range up to ~40
  - weaker jets have Lorentz factors of a few

- 98% of motions are outward from core

- Speeds of features increase down the jet

Lister et al., 2009, AJ, 138, 1874
2. Jet Accelerations

- Moving features have complex curved trajectories and are usually accelerating (70% are non-ballistic)

- Close to the base of the jet, accelerations are more common than decelerations
  - jet flow is still being organized on scales of tens of light years from the black hole

Homan et al. 2009
3. Energized Jet Channels

- Newly ejected jet features move out on successively different trajectories
- At any given time, only a portion of the (conical) jet is energized/visible
Fermi Meets Jansky: The AGN radio/$\gamma$-ray connection
Synchrotron Peak Location

Mk 421:
High-spectral
peaked jet

Fermi 2\textsuperscript{nd} LAT AGN Catalog

- Fermi is an excellent AGN survey instrument:
  - jet flux only, no contamination from host galaxy

- Quasars are all low-spectral peaked

- IC scattering of broad line region photons quenches high energy electron population

- Highest spectral peaked (HSP) jets are the less powerful BL Lac class (no broad line region)

Radio vs. $\gamma$-ray flux correlation

![Graph showing the correlation between log gamma-ray energy flux and log 8 GHz Flux Density [Jy].](image)
1. All of the fastest known jets have been detected in $\gamma$-rays
2. Highest spectral peaked blazars have small range of apparent speed
Relativistic Beaming Levels

- Radio core compactness (brightness temperature) strongly increases with beaming and jet activity level.

- Lower radio compactness and variability of HSP radio cores is indicative of lower relativistic beaming factors.

Lister et al. 2011
The Doppler Beaming Crisis for HSPs

- Extreme variability of TeV $\gamma$-rays imply very small emission regions.

- $\gamma$-rays cannot escape unless very high beaming factors are invoked.

- Possible explanations:
  - Fast spine / slow sheath structure (e.g., Tavecchio et al. 2008)
  - Misaligned ‘mini-jets’ (Giannios et al. 2010)
  - Fast leading edges of intermittent outflows (Lyutikov & Lister 2010)
Summary

• Large VLBI surveys are responsible for much of our current understanding of relativistic outflows in active galaxies

• Dedicated arrays such as the VLBA are indispensable for probing the time evolution of jets and their overall characteristics via the study of large samples

• VLBI data have complemented many other AGN surveys such as SDSS, FIRST and Fermi.

• Continuous advances in VLBI data recording and correlator technology offer significant opportunities for new studies of AGN populations