The Black Hole – Jet Connection

Study of Active Galactic Nuclei using global mm-/submm-VLBI

T.P. Krichbaum
(on behalf of the European mm-VLBI team)

Max-Planck-Institut für Radioastronomie
Bonn, Germany

tkrichbaum@mpifr.de
people involved in the European 1mm VLBI effort:


**IRAM:** M. Bremer, P. Cox, C. Kramer, S. Sanchez, K. Schuster, M. Torres, et al.

**OSO:** M. Lindqvist, I. Marti-Vidal, H. Olofsson, et al.

**INAF:** G. Tuccari


in collaboration with:

**US-EHT:** S. Doeleman et al. (Haystack + SMA/JCMT + Carma)

**SMTO:** L. Ziurys, P. Strittmatter, et al.

science:

**Boston:** A. Marscher, S. Jorstad, et al.
1mm-VLBI: Sources detected in early days with PV-PdB

1994-1995:
early detection of ~
10 mm-bright sources
at 215 GHz on the
PV-PdB baseline

1mm VLBI looks
promising and is
doable or many AGN!

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Greve et al.
Krichbaum et al.
First transatlantic detections with VLBI at 230 GHz in 2003:

(PV – PdB – HHT baselines):

short baselines: \( \text{SNR} \leq 25 \)
long baseline: \( \text{SNR} = 6 – 7 \)

Two Blazars detected at 6.4 GHz:

3C454.3 and 0716+714

for 3C454.3 (\( z = 0.859 \))
\[ \nu' = 428 \text{ GHz (in source rest frame)} \]
\[ 0 \leq 16 \mu \text{as} = 0.1 \text{ pc} = 1050 R_s^9 \]

SSA: \( B \leq 1 \text{ G} \rightarrow \gamma > 600 \)

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Krichbaum et al. 2004
Unified Scheme:

depending on viewing angle: jet brightness and jet-to-counter jet ratio changes

polarisation properties vary

spectral lines (absorption/emission) become visible

depending on BH mass, spin and luminosity:

different AGN classes such as FRI/FRII RGs, QSOs, BLLACs

magnetic field, accretion rate and angular momentum distribution:

radio loud / radio quiet (jet/no-jet) ??
Detection of the counter-jet of Cygnus A at 43 and 86 GHz

43 GHz  2007.807  Global VLBI

\begin{align*}
\text{gap between jet and counter jet at 43 GHz:} & \approx 0.5 \text{ mas} \sim 2200 \text{ } R_\odot \\
\text{at 86 GHz:} & \leq 0.2 \text{ mas} \leq 880 \text{ } R_\odot
\end{align*}

86 GHz  2005.791  GMVA

\begin{align*}
\text{beam:} & \quad 140 \times 56 \mu \text{as} \\
& \quad 0.15 \times 0.06 \text{ pc}
\end{align*}

Krichbaum et al. 2008

Bach et al. 2009
The spectral index distribution on sub-mas scales

- Inverted spectrum on counter-jet side

- Sketch from Jones et al. 2000

- Cygnus A: spectral index gradient along jet
  (Feb. - Oct 2005, 43/86 GHz, S - mas/alpha)

- Jet

- Counter-jet

Krichbaum et al. 2008

- 43 GHz

- 86 GHz
Intrinsic Jet-to-Counterjet Ratio determined from 3mm-VLBI

Parameters of torus:
inner edge: 0.3 mas
(0.3 pc)
outer edge: 4-5 mas
(4-5 pc)

$R_{86 \text{ GHz}} = 1.32 \pm 0.12$

Krichbaum et al. 2008
cm- and mm- absorption line spectra of NGC 1052

broad absorption profiles at mm-wavelength ($\Delta v = 300-400$ km/s)

Liszt & Lucas 2004
The size of a synchrotron self-absorbed emission region

SSA:

$$\theta_{\text{min}} \geq \sqrt{\frac{1.22 \cdot S}{\nu^2}} \cdot \frac{1}{T_B^{\text{max}}}$$

for $T_B^{\text{max}} \leq 10^{12} \text{ K} \cdot \delta$

$$\rightarrow \theta_{\text{min}} \geq 10 - 20 \mu\text{as} \cdot \delta^{-0.5}$$

accurate size measurements allow to test the relativistic jet model and the physical details of the (non-thermal) radiation mechanism (eg. equipartition conditions, jet speed, viewing angle, etc ...)
Angular and Spatial Resolution of mm-VLBI

for nearby sources, these scales correspond to 1 – 100 Schwarzschild radii, depending on distance and black hole mass!

→ mm-VLBI can directly image (!) the vicinity of SMBHs (Event Horizon, BH-Shadow, GR-theory)!

→ best candidates: Sgr A* (10 μas = 1 Rs⁹) and M 87 (Cen A is far south, M81 & NGC4258 are weak)

→ need sensitive mm-telescopes (i.e. ALMA) to image the emission around Black Holes in AGN

→ need a full global VLBI array for sensitivity and resolution.
Angular Resolution

Millimetre VLBI provides the highest angular resolution in Astronomy!
The Global Millimeter VLBI Array (GMVA)

Imaging with ~40 μas resolution at 86 GHz

Baseline Sensitivity
in Europe:
30 – 300 mJy
in US:
100 – 300 mJy
transatlantic:
50 – 300 mJy
Array:
1 – 3 mJy / hr
(assume 7σ, 100sec, 512 Mbps)

- Europe: Effelsberg (100m), Pico Veleta (30m), Plateau de Bure (35m), Onsala (20m), Metsähovi (14m), Yebes (40m), planned: GBT, LMT, ALMA
- USA: 8 x VLBA (25m)

Proposal deadlines: February 1st, August 1st

http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm
Kelvin-Helmholtz Instabilities
Elliptical body mode and double peaked transverse jet-profiles

HDR mm-VLBI imaging resolves jet transversely and traces cause of instability to origin
Non-ballistic (helical) motion in the jet of quasar 3C345

results from F. Schinzel, PhD Thesis 2011
The jet of 3C273 at 86 GHz

Moving patterns in a stratified jet rotating around its z-axis

Precession $P \sim 16$ yrs

Component ejection after major flare

Pattern speed: 4.2 c

Longitudinal displacement of the jet axis

$55 \mu$as resolution or 1000 Rs
The swinging jet of NRAO150: sub-mas scales

3 mm-VLBI shows jet rotation with an angular speed of \( \sim 10^\circ/yr \) and an extrapolated rotation period of 20 – 30 yrs

Agudo et al. 2007 (AA)
Size of jet base appears too small for magnetic sling-shot acceleration. Direct relation to BH more likely $\rightarrow$ a GR-MHD Dynamo?

Size of the jet base (uniform weighting):

$197 \times 54 \, \mu \text{as} = 21 \times 6 \, \text{light days} = 54 \times 15 \, \text{R}_s$

transverse width of jet at 0.5 mas: $\sim 140 \, \text{R}_s$
A 3mm VLBI survey of 127 AGN:

$$T_{b,s} = \frac{2 \ln 2}{\pi k_B} \frac{S_{\text{tot}} \lambda^2}{d^2} (1 + z)$$

Brightness temperature decreasing with frequency?

Brightness temperature increasing along jet; evidence for intrinsic acceleration?

mm-VLBI surveys of AGN can discriminate between fundamental models of jet formation

Figure adopted from A. Marscher (1995)
Global 7mm VLBI maps of Cyg A (EVN, VLA, VLBA, GBT)

First 43 GHz image from DivX Software Correlator

Jet acceleration from 0.1c – 0.7c

Magnetic acceleration

Vlahakis & Königl, 2003

U. Bach et al. 2008
overwhelming evidence for:

- jet acceleration from sub-pc to pc distances
- core-sheath structure at jet base (hollow jet)
- rotation of jet base / whole jet around z-axis
- small gap between base of jet and counter-jet
- high brightness temperature within < few 10 Rs

but:

more good quality images with high spatial resolution (< 0.1 pc) needed
(multi-frequency, multi-epoch, preferably with polarization)
Magnetically driven relativistic Jets

Accelerating forces: Magnetic driving is most efficient

inner and outer field lines guide plasma flow above the disk

model explains observed:
- conical jet opening
- helical motion
- jet speeds up to $\gamma \sim 50$
- acceleration $f(z)$

Lorentz-factor and Poynting-to-mass flux ratio for inner and outer field lines

Check this using mm-VLBI!

Vlahakis & Königl 2003, 2004; Vlahakis 2006
BP versus BZ mechanism

Blandford – Payne mechanism:
centrifugal acceleration in magnetized accretion disk wind

Blandford – Znajek mechanism:
measure
Jet speed $f(r,z)$
Jet width $f(z)$
$T_B f(z)$
→
Shape of Nozzle
Magnetic Field
BH Spin
etc.

need to reach
scale of a few $R_G$
Geodetic Precession in curved space-time

central mass is not rotating:
geodetic precession, de Sitter precession

central mass is rotating:
frame dragging, Lense-Thirring effect

\[ \Omega = \omega + \frac{\alpha^2}{R^2} \frac{\lambda}{1 - \omega \lambda} \]
Are GR-MHD effects near the BH the main jet driver?

matter and fields are forced to co-rotate with the horizon

torque due to misalignment of \( \mathbf{L} \) from accr. disk and Kerr BH

\( \rightarrow P = 0.3 - 20 \) yrs appear possible

(e.g. Caproni et al., 2004)

<table>
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<th>known „precessing“ sources:</th>
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<td>3C84</td>
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<td>3C345</td>
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3C345: A Binary Black Hole?

The assumption of a supermassive binary Black Hole in 3C345 explains:

1. observed helical trajectories of the jet components
2. flux density changes of the jet components
3. optical variability
4. morphology and evolution of the jet

Combination of flux density evolution and kinematic data allow determination of mass and orbit of BBHs.
Spectral variability of 3C454.3 after gamma-ray flare (May 2005):

**Effelsberg:**
1.4 – 32 GHz

**Pico Veleta:**
90 – 230 GHz

**SMA:**
230, 350 GHz

\( \nu_m \sim 100-300 \) GHz

*variability amplitudes peak in mm/sub-mm band*

combined data:

Krichbaum, Fuhrmann, Ungerechts, Wiesemeyer, Gurwell et al.

**monthly**

2004 - 2007

*11 days or 1.2\( \mu \)as or 95 \( R_s \)*

T. Krichbaum, et al. 2007
Variability Timescale for Keplerian Motion around a BH

Angular velocity of co-rotating matter in BH orbit

\[ \Omega = \frac{M^{1/2}}{r^{3/2} + aM^{1/2}} \]

\[ r = \frac{R}{R_g} \]

\( a = \text{spin parameter} \)

Black hole mass and Period

non rotating BH: \( a = 0, \ r > R_{LSO} = 6 \ R_g \)

rotating Kerr BH: \( a > 0, \ r > R_{LSO} = 1 \ R_g \) (\( a=0.9982, \ r= 1.2 \ R_g \))

example: SgrA*, \( M = 4 \times 10^6 \ M_\odot, \ P=30 \ \text{min} \) for \( a=0 \), \( P=5 \ \text{min} \) for \( a=0.9982 \)

M87, \( M = 3 \times 10^9 \ M_\odot, \ P=16 \ \text{days} \) for \( a=0 \), \( P=60 \ \text{hrs} \) for \( a=0.9982 \)

Need to search for rapid and quasi-periodic flux density variations and do quasi-simultaneous mm-VLBI monitoring to determine the mass and spin of the SMBH.
Superluminal ejection during Gamma-ray outburst

1510-089 43 GHz VLBA

mm-VLBI relates gamma-ray production with variability in VLBI core. Need high angular resolution and dense time sampling!

Correspondence between Gamma-Ray Flares and Time of Ejections of Superluminal Knots

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<th>$\tau$</th>
<th>Knot</th>
<th>$T_0$ RJD</th>
<th>$T_\gamma$ RJD</th>
<th>$\Delta T_\gamma$ days</th>
<th>$\beta_{app}$ c $10^{-6}$ ph cm$^{-2}$ s$^{-1}$</th>
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<td>77±51</td>
<td>10.2±2.2</td>
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new jet components appear within < ~60 days

Jorstad et al. 2009, Marscher et al. 2010
Optical Polarization angle swings during mm-optical-gamma-ray flare

Sketch: polarization angle swing due to motion of shock in a magnetized helical jet

3C279: similar behaviour  
(Abdo et al. 2010, Nat 463, 919)
• resolution $\sim 110 \times 40 \, \mu\text{as}$
• core unresolved at 86 GHz
  – size smaller than 0.03 pc (gaussian fit)
  – $M_{\text{BH}}=10^9 \, M_{\odot}$, $1 \, R_S=10^{-4} \, \text{pc}$
  – size $\sim 320 \times 210 \, R_S$
  – $T_B > 4 \times 10^9 \, \text{K}$
• $S_t=150 \, \text{mJy}$, $S_c=45 \, \text{mJy}$

Giroletti et al. 2004, 2008
Main questions addressed by mm-/sub-mm VLBI

- What are the physical conditions in regions of strong gravitational field near SMBHs?
- How are the powerful jets created and launched? Test of GR-MHD dynamo model.

In detail:
- for nearby sources image silhouette around BH, determine its mass, spin, polarization
- measure shape & morphology of jet at its origin
- determine properties of jet nozzle, size, orientation, opening angle & time variability
- measure linear and transverse jet profile (ridgeline, hollow jet, stratification)
- measure jet speed, acceleration, compare to max. possible Lorentz-factor of dynamo
- find reason for helical jet structure (geodetic precession, MRI or KH instabilities)
- measure brightness temperature profile, leptonic or hadronic jet composition
- study outburst /ejection relation (broad-band variability, gamma-ray/TeV production)
- polarization of the jet nozzle, topology of B-field, overcome Faraday rotation at mm-λ

For all this one needs a high as possible observing frequency and a small as possible observing beam in combination with good (mJy) sensitivity.

→ Global mm/submm-VLBI monitoring using the most sensitive mm-antennas
Imaging Black Holes and the Central Engine with mm-/sub-mm VLBI
(now called Event Horizon Telescope)
## Future 1mm-VLBI – Sensitivities

\(7\sigma \text{ in [mJy]}\)

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</table>

assume: 4 GHz (16 Gbit/s) bandwidth, 20 s integration time, 2 bit sampling

**expected \((7\sigma)\) detection limits:**

Pico-SMTO/APEX : \(\sim 110\) mJy

plus PdBure /CARMA : \(\geq 40\) mJy

plus ALMA : \(\geq 12\) mJy

numbers will improve if phase corrections are used to prolonge coherence
Phase coherence at 230 GHz in October 2010

PV - PdB (phased)

good VLBI-phasing efficiency of the 6 elements of the PdB interferometer

old correlator supports only 1 GBit/s (16 MHz, MK5A), correlation with DiFX

new correlator will allow phasing and processing of 32 MHz bands.

SNR = 350 – 450 reached after 6 mins of incoherent integration!
Performance of a global 1mm VLBI array

1. SMTO-CARMA-JCMT
2. SMTO-CARMA-Hawaii
3. + Apex
4. + Pico Veleta
5. + PdBure
6. + ALMA
7. +LMT+SPT+GL
8. +2x4GHz (32 Gb/s)

With the participation of ALMA the baseline sensitivity will be lowered to 1-5 mJy (depending a bit on BW). With 10 VLBI stations 1.5 mJy / hr can be reached.
Global VLBI at 1mm and shorter

- image SMBH in Sgr A*
- image SMBH / central engine of M87
- BH – jet connection on $\leq 100 \ R_s$ in nearby AGN (another 5-10 targets)
- jets on scales of 100-1000 $R_s$ (dozens of AGN)

- need time resolution (several epochs per year)
- need spectral information (complementary VLBI at 3mm, 7mm, ....)
- need monitoring of total flux densities and SED

- need ahead planning, roadmap, MoU
- need proposal and schedule coordination
Near future planning for mm-/sub-mm VLBI

- in 2012/13 use PdBI at 1 Gbit/s and DiFX. Buy Mk5C & DBBC
  The combination of Pico-PdB-APEX plus rest of the world gives good sensitivity and uv-coverage. Baseline sensitivity of Pico-PdB-APEX ~ 0.1-0.2 Jy.
- global VLBI with both IRAM instruments, APEX, ASTE, HHT, SMA, CARMA, etc., (regular VLBI imaging of AGN, jets, etc. → global VLBI array)
- go to 345 GHz as soon as possible. For this, the next 2 logical steps are:
  1. short baseline Pico-PdBI VLBI using 1 Gbit/s and old Mk5A
  2. long baseline Pico/PdB(1)-APEX VLBI using 4 Gbit/s (Mk5C), $7\sigma = 0.4$ Jy
- phasing of PdB (IRAM internal development ~ 4-5 yrs ?, participate in phased array processor development for ALMA)
- more sensitive global sub-mm VLBI with ALMA (> 2016/17, at this time APEX may run out of funding)
End