Global Millimeter VLBI Array Survey of Ultra-compact Extragalactic Radio Sources at 86 GHz

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Why 86 GHz (~ 3 mm) VLBI Survey?

- Angular resolution $\sim \lambda/B$
- Synchrotron radiation, optically thin at mm wavelengths
- Unique tool to look at the inner jets of AGN (“VLBI cores”)
- $\sim 50 \mu$as resolution at 86 GHz (B $\sim 9000$ km)
- A linear scale as small as $10^3 - 10^4$ Schwartzschild radii

86 GHz VLBI zoom into a region where acceleration and collimation of relativistic jets takes place [Vlahakis & Königl 2004; Lee et al. 2016; Asada et al. 2014, Mertens et al. 2016]
The **Global MM-VLBI Array (GMVA)**

Telescopes - 8 VLBA + 6 European stations (Pv,PdB,Ef,On,Ys,Mh)

*Image Credit: [http://www.mpifr.de/div/vlbi/globalmm](http://www.mpifr.de/div/vlbi/globalmm)*
Sky Distribution of Survey Targets

162 unique radio sources
- 89 Quasars, 26 Blazars, 22 Galaxies & 25 unidentified sources.

Source Selection
Results. I : 3mm maps

- Made 3mm maps of 174 (162 unique) radio sources
- with very high resolution of 40-100 μas

- FIRST 3mm VLBI maps of 138 radio sources
- Increase the database of sources ever imaged with VLBI at 86 GHz by a factor of ~ 1.5
Results. I: 3mm maps

3C84

\[ T_b = (0.45 \pm 0.09) \times 10^{10} \text{K} \]

DEC = 41°

0.185x0.116 mas

3C273B

\[ T_b = (1.46 \pm 0.53) \times 10^{10} \text{K} \]

0.434x0.125 mas
Results. I: 3mm maps

1128+385

$T_b = (1.54 \pm 0.47) \times 10^{11}$K

DEC = 38°

0.196x0.041 mas

0657+172

$T_b = (1.92 \pm 0.60) \times 10^{11}$K

DEC = 17°

0.323x0.036 mas
3mm maps of 174 (162 unique) radio sources (Nair et al. 2018)
Modelling the Source Structure

- Represented source structure by circular Gaussian Modelfits
- Estimated total flux ($S_{\text{tot}}$), peak flux ($S_{\text{peak}}$), position w.r.t phase center ($r, \theta$), FWHM size ($d$)
- Estimated brightness temperature:

$$T_b = \frac{2 \ln(2)}{\pi k_B} \frac{S_{\text{tot}} \lambda^2 (1 + z)}{d^2}$$
Results. III: Population modelling for the brightness temperature $T_b$ - **VLBI cores**

Probability density of brightness temperature, 

$$ p(T_b) \propto \left[ 2 \gamma_j \frac{\left( \frac{T_0}{T_b} \right)^{\epsilon} - \left( \frac{T_0}{T_b} \right)^{2}\epsilon - 1 \right]}{\gamma_j^2 - 1} \right]^{1/2} $$

where $\delta = \left( \frac{T_b}{T_0} \right)^{\epsilon}$

$T_0$ - intrinsic bright. temp

$T_b$ - observed bright. temp

$\delta$ - doppler factor

(Lobanov et al. 2000)

$T_b$ range: 

$[1.1 \times 10^9 \text{ K} - 5.5 \times 10^{12} \text{ K}]$

$T_{0,\text{core}}$ [86 GHz]

$= (3.77 \pm 0.14) \times 10^{11} \text{ K}$

($\sim$ Inverse Compton limit, $5 \times 10^{11} \text{ K}$, Kellermann & Pauliny-Toth 1969)
**Results. III**: Population modelling for the brightness temperature $T_b$ – *Jet Components*

![Graph showing population modelling for the brightness temperature $T_b$](image)

- **$T_b$ range**: $[5.8 \times 10^7 \text{ K} - 4.0 \times 10^{11} \text{ K}]$

- **$T_{0,\text{jet}}$ [86 GHz]**
  \[ (1.42 \pm 0.19) \times 10^{11} \text{ K} \]

  (slightly greater than Equipartition limit, $5 \times 10^{10} \text{ K}$, *Readhead 1994*)
Results. IV: Do jets expand adiabatically?

\[ T_{b,J} = T_{b,C} \left( \frac{d_J}{d_C} \right)^{-\xi} \]
\[ \xi = \frac{[2(2s+1)+3a(s+1)]}{6}, \]
\[ s = 2.0, \quad \alpha = -0.5, \quad a = 1 \]
(Marscher 1990)

**Blue squares - observed** \( T_b \)

**Red circles - predicted** \( T_b \)


\[ \text{CORE} - T_b - [1.1 \times 10^9 \, K - 5.5 \times 10^{12} \, K] \]
\[ \text{JET} - T_b - [5.8 \times 10^7 \, K - 4.0 \times 10^{11} \, K] \]

- Inverse-Compton
- Synchrotron
- Adiabatic
Results. IV: Do jets expand adiabatically?  
- More examples
Results. V: $T_b$ as a function of frequency

- $T_b$ at 86 GHz are systematically lower

- Decrease of $T_b$ at 86 GHz – kinematics of jets, acceleration or deceleration scenarios (Marscher 1995)?

→ 2 and 8 GHz data (Pushkarev & Kovalev 2012)
→ 15 GHz data (Kovalev et al. 2005)
**Results. V**: $T_b$ as a function of distance of cores from central black hole

$$T_b = T_{in} + (T_m - T_{in}) \{1 - (r \text{csch } r)^a}\} \quad \text{Lee et. al 2016}$$

$T_{in} = 3.7 \times 10^{10}$ K

Best fit for $T_m = (7.96 \pm 0.47) \times 10^{11}$ K

$a = 0.65 \pm 0.19$

$T_b(r)$ dependence shape expected for MHD acceleration

\textit{(Vlahakis & Königl 2004)}
Conclusions

- A large 86 GHz VLBI survey of compact radio sources
- 100% detection rate, 3 mm maps of 162 sources
- Source structure is represented with Gaussian model fits, accounting for resolution limits.
- $T_0$ for VLBI cores = $(3.77\pm0.14) \times 10^{11}$ K for $\gamma = 10$, IC limit
- $T_0$ for inner jet components = $(1.44\pm0.19) \times 10^{11}$ K
- Agreement with the predicted $T_b$ in shocks with adiabatic losses
- Multi-frequency measurements of brightness temperature suggest that the MHD acceleration may play an important role in the compact jets.
Thank You
**Results. V**: Radio luminosity and jet parameters to convert frequency to linear coordinate along the jet

\[
r = \left( \xi C_r L_{\text{syn}} \left( \frac{v}{1+z} \right)^{\frac{-1}{k r}} \right)^{1/3} \text{ pc}
\]

*(Lee et al. 2016)*
Radio luminosity and jet parameters to convert frequency to linear coordinate along the jet

Assuming the equipartition between the jet particle energy and the magnetic field energy, the total radiated synchrotron power from the emission region extending from $r_{\text{min}}$ to $r_{\text{max}}$ in the jet is

$$L_{\text{syn}} = \frac{1}{8} k_e \Lambda \gamma_j^2 c B^2 r^2 \varphi^2$$

where

$$\Lambda = \ln \left( \frac{r_{\text{max}}}{r_{\text{min}}} \right)$$
Radio luminosity and jet parameters to convert frequency to linear coordinate along the jet

The observed VLBI core at any given frequency is located at a region where the optical depth due to SSA, $\tau_s = 1$ in the jet.

$$\tau_s = C_2(\alpha) N_1 \left( \frac{eB_1}{2\pi me} \right)^{\frac{\varepsilon}{\varepsilon + 1}} \frac{\phi_0}{r^{-\varepsilon + n - 1}} \frac{1}{\nu^{\varepsilon + 1}}$$  \hspace{1cm} (Rybicki & Lightman 1979)

where $\varepsilon = (3/2) - \alpha$ and $C_2(\alpha) = 8.4 \times 10^{10}$. Equating $\tau_s = 1$, the physical distance of the VLBI core from the central engine as

$$r = \left( \nu^{-1} (1 + z)^{-1} B_1^{k_b} \left[ 6.2 \times 10^{18} C_2(\alpha) \delta_j^e N_1 \phi_0 \right] \frac{1}{\varepsilon + 1} \right)^{\frac{1}{k_r}} \text{ pc}$$

where $B = B_1 (r/r_j)^m$ and $N = N_1 (r/r_j)^n$ and $k_r = ((3-2\alpha)m+2n-2)/(5-2\alpha)$ and $k_b = (3-2\alpha)/(5-2\alpha)$ $m=1$ and $n=2$ can be assumed.

The absolute position of VLBI core $r$ is related with total radiated synchrotron luminosity $L_{\text{syn}}$ as

$$r = \left( \frac{1}{k_r} \right)^{1/3} \xi C_r L_{\text{syn}} \left[ \nu (1 + z) \right]^{\frac{-1}{k_r}} \text{ pc}$$  \hspace{1cm} (Lee et al. 2016)

$L_{\text{syn}}$ can be calculated from $L_{\text{syn}} = 4\pi D_L^2 F_t$ where $F_t$ is the flux density of core and total core flux can be obtained by integrating $F_t$ over $d\nu$ (over the range of frequencies say 2, 8, 15, 86 GHz).
Results. $V: T_b$ as a function of distance of cores from central black hole – *simple power law fit*
Results. V: $T_b$ as a function of distance of cores from central black hole – *multiple power law fit*

- $0.01 \text{ pc} < r < 0.5 \text{ pc}$: $T_b \sim r^{0.3}$
- $0.35 \text{ pc} < r < 10 \text{ pc}$: $T_b \sim r^{0.8}$
- $5 \text{ pc} < r < 100 \text{ pc}$: $T_b \sim r^{0.1}$
Result V: $T_b$ as a function of distance of cores from central black hole – All models

- $T_o(r)$ dependence expected for an MHD jet (dotted line) (Vlahakis & Königl 2004) on observed $T_b$
Brightness Temperature ($T_b$)

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

Minimum resolvable size of the Gaussian component,

$$d_{\text{min}} = \left\{ \frac{2^{(1+\beta)/2}}{\pi} \right\} \left\{ \pi ab \ln2\ln\left( \frac{\text{SNR}+1}{\text{SNR}} \right) \right\}^{1/2}$$

(A.P. Lobanov 2005)

And if $d < d_{\text{min}}$, then the lower limit of $T_b$ is obtained with $d = d_{\text{min}}$. 

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**Result. III :** 2D - $\chi^2$ distribution plot ($\gamma - T_0$)

$$T_0[K] \approx (7.7 \times 10^8) \gamma^{2.7}$$

$T_0 = 10^7 K - 10^{13} K$

$\gamma = 1.1 - 35$

**Fit is degenerating in the $\gamma$-$T_0$ space (along the narrow strip in the 2D - $\chi^2$ distribution)**

$$\chi^2_{\text{min}} = \chi^2_{\text{min}} + 2.3$$

(1$\sigma$ contours)

$$p(T_0) \propto \left[ \frac{2\gamma \left( \frac{T_0}{T_b} \right)^e - \left( \frac{T_0}{T_b} \right)^{2e} - 1}{\gamma_j^2 - 1} \right]^{1/2}$$
Population modelling for the brightness temperature $T_B$

where $T_b = \delta T_0$

$\delta$ is the doppler factor

Lobanov et al.2000

For $\gamma = 10$, the best fit $T_0 =$

$(3.77\pm0.14)x10^{11}$ K, and the model distribution rapidly grows discrepant from the observed one at $T_0 > 1.0x10^{12}$ K.

$T_B = 2\log(2) \frac{\pi}{k_B} \frac{S_{tot} \lambda^2 (1+z)}{d^2}$

Probability density of brightness temperature (theoretical model)
Results. II: $T_b$ Gaussian model fitting & $T_b$ from interferometric visibility

The limiting $T_{b,\text{lim}}$ agrees with $T_{b,\text{mod}}$ estimated from imaging method

The interferometric visibility

$$V = V_q e^{-i\Phi_q}$$

Angular extent of the emitting region,

$$\theta = \frac{2\sqrt{\ln 2} \lambda}{\ln \left(\frac{V_q + \sigma_q}{V_q}\right)}$$

$$T_{b,\text{lim}} = \frac{\pi B^2}{2k} \left(V_q + \sigma_q\right) \left(\ln \frac{V_q + \sigma_q}{V_q}\right)^{-1}$$

Lobanov A.P 2015
Results. II: $T_b$ Gaussian model fitting & $T_b$ from interferometric visibility

The limiting $T_{b,\text{lim}}$ agrees with $T_{b,\text{mod}}$ estimated from imaging method.
Modelling of inner jet: jet acceleration will be studied, based on modelling the evolution of brightness temperature

Modelling steps:

1. General idea: Brightness temperature observed at different frequencies and converted into linear distances from the central engine reflect two major processes in a relativistic plasma: acceleration of the plasma and energy losses in the plasma – inverse compton, synchrotron, or adiabatic.

2. Doppler boosting: Acceleration described by the velocity $\beta_j(z)$ and the corresponding Lorentz factor $\Gamma_j(z)$ results in an observed brightness temperature

$$T_b(z) = T_o \varepsilon(z) [\delta_j(z)]^{n-\alpha} = T_o \varepsilon(z) [\Gamma_j(z) [1 - \beta_j(z) \cos \theta]^{n-\alpha} ]^{-1}$$

Where $\varepsilon(z)$ is the energy loss factor, $\alpha$ – spectral index and power law index $n$ depends on the geometry of the emitting region (with $n = 1$ for a homogenous sphere).

3. Energy losses: The energy losses $\varepsilon(z) = z^\xi$ can be derived from for eg. Lobanov & Zensus (1999), Marsher (1990), yielding:

$$\xi = ((11-s)-a(s+1))/8 \quad \text{inverse- Compton losses}$$
$$\xi = -(4(s-1)+3a(s+1))/6 \quad \text{synchrotron losses}$$
$$\xi = (s(5-2s)-3a(s+1))/6 \quad \text{adiabatic losses}$$
Testing different acceleration models

1. Acceleration by radiation pressure: Following a model by Bodo et al. (1985), the evolution of jet speed due to radiation pressure acceleration can be described by the following eqn.

\[ \Gamma^2_j \beta_j \left( 1 - \beta_j^2 \right) \frac{d \beta_j}{d \zeta} = \frac{\beta_s^2}{r(\zeta)} \frac{d r(\zeta)}{d \zeta} - \frac{r_g}{r_0 \zeta^2} + \Gamma_j F(\zeta, \beta_j) \frac{r_g}{r_0} \frac{L_{bh}}{L_{edd}}, \]

2. Acceleration by tangled magnetic field: Following a model by Heinz and Begelman (2000)

\[ \Gamma_j(\zeta) = \Gamma_0 \zeta^{p/4} \left[ 1 - A_{\Lambda}(\zeta^{1-p/2} - 1) \right]^{(5b-6)/(4b-4)}, \]

3. Vlahakis and Königl Model – MHD model

\[ T_b = \frac{\alpha + 5/3}{\alpha + 1} \frac{c^2}{2k_B} \kappa \nu^{-\alpha - 2} \int \kappa_0 \delta d^3 \left[ \frac{B^2}{\gamma^2} + \frac{2}{\gamma} (B \cdot \hat{n}) \left( B \cdot \frac{V}{c} \right) - \frac{\delta^2}{\gamma^2} (B \cdot \hat{n})^2 \right]^{(\alpha + 1)/2} d\ell_{co}. \]