The Nature of Radio Cores

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Going really deep into blazar jets
AGN plasma-physics

Physical parameters

- Structure / kinematics
- Magnetic fields
- Density, opacity
- Shock evolution
- Outflow geometry

Observables

- Time-resolved maps
- Linear polarization
- Spectral index
- Faraday rotation
The Korean VLBI Network (KVN)

- Three 21-m antennas
- Full bandwidth 256 MHz
- Simultaneous observations at 22, 43, 86, 129 GHz
- Full polarization observations at two frequencies simultaneously
Target selection criteria

1. Total and polarized emission should be bright enough to be detected by KVN. Polarized emission should be detectable at least at 86 GHz.

2. $\gamma$-ray emitters: all targets are monitored by Fermi-LAT (to probe the connection $\gamma$-ray $\leftrightarrow$ radio flux and polarization)

3. Cover both quasars (FSRQs) and BL Lacs (for source type statistics)

Final target selection needed some trial and error
Observations so far

p16st01i (22 & 86 GHz), p16st01j (43 & 129 GHz) / Dec 9, 10 (2016)
p17st01a (22 & 86 GHz), p17st01b (43 & 129 GHz) / Jan 16, 17
p17st01c (22 & 86 GHz), p17st01d (43 & 129 GHz) / Feb 26, 27
p17st01e (22 & 86 GHz), p17st01f (43 & 129 GHz) / Mar 22, 23
p17st01g (22 & 86 GHz), p17st01h (43 & 129 GHz) / Apr 21, 22
p17st01i (22 & 86 GHz), p17st01j (43 & 129 GHz) / Jun 1, 2
p17st02a (22 & 86 GHz), p17st02c (43 & 129 GHz) / Sep 24, 25
p17st02d (22 & 86 GHz), p17st02e (43 & 129 GHz) / Oct 25, 26
p17st02f (22 & 86 GHz), p17st02g (43 & 129 GHz) / Nov 17, 18

*In 2017: 24 hrs x 2 days x 8 months = total 384 hrs*

(3 more observing days coming in December)
## Final list of targets

<table>
<thead>
<tr>
<th>Quasars: 8</th>
<th>BL Lacs: 5</th>
</tr>
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<tbody>
<tr>
<td>3C 279 (z~0.158)</td>
<td>BL Lac (z~0.069)</td>
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<tr>
<td>3C 345 (z~0.538)</td>
<td>0716+714 (z~0.3)</td>
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<tr>
<td>3C 273 (z~0.595)</td>
<td>OJ287 (z~0.306)</td>
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<tr>
<td>3C 454.3 (z~0.859)</td>
<td>1749+096 (z~0.322)</td>
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<tr>
<td>NRAO530 (z~0.902)</td>
<td>0235+164 (z~0.94)</td>
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<tr>
<td>CTA102 (z~1.037)</td>
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<tr>
<td>NRAO150 (z~1.51)</td>
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<tr>
<td>1633+38 (z~1.814)</td>
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<td></td>
<td><strong>Radio galaxies: 1</strong></td>
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<td>3C 84 (z~0.018)</td>
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**Total: 14 sources**
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<tr>
<th>Source</th>
<th>DEC (9)</th>
<th>JAN (9)</th>
<th>FEB (11)</th>
<th>MAR (11)</th>
<th>APR (16)</th>
<th>JUN (10)</th>
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The Stokes parameters

**Trigonometric notation**

\[
\begin{align*}
I &= \langle E_R^2 \rangle + \langle E_L^2 \rangle \\
Q &= 2 \langle E_R E_L \cos \delta' \rangle \\
U &= 2 \langle E_R E_L \sin \delta' \rangle \\
V &= \langle E_R^2 \rangle - \langle E_L^2 \rangle
\end{align*}
\]

**Complex exponential notation**

\[
\begin{align*}
I &= \langle E_R E_R^* \rangle + \langle E_L E_L^* \rangle \\
Q &= \langle E_R E_L^* \rangle + \langle E_L E_R^* \rangle \\
U &= -i \left[ \langle E_R E_L^* \rangle - \langle E_L E_R^* \rangle \right] \\
V &= \langle E_R E_R^* \rangle - \langle E_L E_L^* \rangle
\end{align*}
\]
D-Term correction: 22 GHz, 3C 84

Red & Green: D-terms from the two antennas
Blue: sum of D-terms

RL/RR ratio
Binned data
Calibrated vis.

22 GHz
Binned
Calibrated
D-Term correction: 43 GHz, 3C 84

RL/RR ratio

Binned data

Calibrated vis.
D-Term correction: 129 GHz, CTA 102

**RL/RR ratio**

**Binned data**

**Calibrated vis.**

---

**RL/RR ratio**

**Binned data**

**Calibrated vis.**
D-Term accuracy – 22 GHz
D-Term accuracy – 129 GHz
Faraday rotation

(Observed angle) = (Intrinsic angle) + (Rotation measure) \times (Wavelength)^2

(Rotation measure) \propto \int_{l.o.s.} (l.o.s. magnetic field strength) \times (Electron density) \times d(path)
Rotation measure in VLBI cores (jet bases)

Rotation measures in the jet base of AGN increase as function of observing frequency:

\[ R\bar{M} \propto \int N_e B_d dl \]

\[ l \propto d \]

\[ B_d \propto d^{-1} \]

\[ N_e \propto d^{-a} \]

\[ B_z \propto d^{-2} \]

\[ B_\phi \propto d^{-1} \]

Power-law assumption;
\( a = 2 \): Conical or Spherical Jets

Prediction of helical B-field geometry

\[ |RM| \propto d^{-a} \]

“Core-shift”

\[ d_{\text{core}, \nu} \propto \nu^{-1} \]

\[ |RM_{\text{core}, \nu}| \propto \nu^a \]

\( a = 0.9 \sim 3.8 \): O'Sullivan & Gabuzda 2009

\( a \sim 1.8 \): Jorstad et al. 2005

\( a \sim 1.9 \): Trippe et al. 2012

\( a \sim 3.6 \): Algaba et al. 2013

→ indicates that B-field and particle density increase as one goes “deep” into the jets.
KVN polarization maps: 3C 279

EVPA at the core

3C279

$\chi$ [deg]

$\lambda^2$ [cm$^2$]

$|RM| \propto v^a$

Core, $a = 3.20 \pm 0.55$ Rad/m$^2$
KVN polarization maps: OJ 287

- EVPA at the core

OJ287

EVPA at the core

\[ \chi \text{ [deg]} \]

\[ \chi^2 \text{ [cm}^2] \]

\[ |RM| \text{ [rad/m}^2] \]

\[ |RM| \propto v^a \]

Core, \( a = 0.98 \pm 0.64 \text{ Rad/m}^2 \)
KVN polarization maps: 0235+164

EVPA at the core

0235+164

EVPA at the core

0235+164

|RM| \propto v^3

Core, a = 4.10 \pm 0.67 \text{ Rad/m}^2
Median rotation measure as function of frequency

\[
RM \propto \nu^a
\]
Distribution of RM powerlaw index

\[ a_{\text{mean}} = 2.46 \pm 1.16 \]
RM signs can change within a few months

2016 December

\[ \chi \text{ [deg]} \]
\[ \lambda^2 \text{ [cm}^2\text{]} \]

OJ287

2017 January

\[ \chi \text{ [deg]} \]
\[ \lambda^2 \text{ [cm}^2\text{]} \]

OJ287

2017 March

\[ \chi \text{ [deg]} \]
\[ \lambda^2 \text{ [cm}^2\text{]} \]
RM seems to saturate at high frequencies

Optical data: Steward Observatory monitoring program
The radio core as re-collimation shock
The case of BL Lac

Simulation

Core shift data

$\text{Core position (arb. units)}$

$\text{Observing frequency (GHz)}$

$r_m \propto \nu^{0.9}$

Theoretical core shift

Observed

Dodson+ (2017); also: Kim+ (2017)
Y. Mizuno

Going really deep into blazar jets

Visible at (sub)mm?

Mostly conical/spherical; some variable?
➢ We started a systematic KVN polarimetric monthly monitoring campaign of 14 radio-loud AGN

➢ Observed levels of polarizations are up to about 30% (in 3C 273)

➢ Faraday rotation measures are of order $10^3$ to $10^5$ rad/m$^2$ and increase with frequency, can be highly variable in a given source

➢ RM–frequency scaling laws have power law indices $a$ of order 2, consistent with conical/spherical outflows, but seem to be variable

➢ Saturation of RM might point toward the radio cores becoming optically thin at (sub)mm, cores could be re-collimation shocks