EHT observations and imaging of 3C 279 at 20 μas

Jae-Young Kim (MPIfR)


with the EHT collaboration and EHT AGN & MWL WGs
Layout

• Background
• EHT observations
• Key results – images, rapid variability
• Analysis – imaging, dynamic model-fitting
• Discussions, interpretations
• Conclusions & outlook
Introduction
AGN jet physics on various scales

Key questions to address
- Magnetic launching: Blandford & Znajek (black hole) vs. Blandford & Payne (disk)
- Magnetic field, velocity stratification, and collimation profile in the acceleration and collimation zone
- Transition between the Poynting (ordered B, accelerating) to kinetically-flux (partially disordered B, conical) regimes.

Polarimetric VLBI imaging at resolution $\lesssim 50$ μas ($\lesssim 10^4 R_s$) is required
High resolution imaging of various AGN jets

Major science motivations:

1. study jet formation for different source classes (FRI/FRII, FSRQ/BLLac), luminosities, BH masses
2. test specific models, BP vs. BZ, magnetic vs. kinetic, etc.
3. compare hot accretion, thick disk (SgrA*, RIAF), vs. cold accretion, thin disk (FSRQs)
4. location of γ-ray emission, SSC vs ECs; seed photons?
5. AGN often highly polarized → B-field in jet launching region
6. RM studies → densities and matter composition (internal & ambient)
7. Address differences in B-field topology and jet speed between source classes (SgrA*, LLAGN, RGs, BLLacs, FSRQs)

Padovani+2017 (AARev)
3C 279: an archetypal blazar

- One of fastest AGN jets observed by VLBI ($\gamma \sim 10-40$)
  - First AGN jet showing apparent superluminal motions on monthly timescale (Whitney+71, Cohen+71)
  - Many speeds seen in the jet ($\sim 10c - 40c$) with acceleration, deceleration, and curvatures

z=0.536
20 $\mu$as $\sim 1700 \, R_S$ (for $\sim 10^9 \, M_{\odot}$)
3C 279: an archetypal blazar

- Bright and highly variable gamma-ray emission
  - One of first EGRET sources (Fichtel+ 1994), arguably the most studied gamma-ray AGN
  - Rapid gamma-ray variabilities (record holder: 5 min!)
    - Often requires jet $\gamma > 100$ (how to achieve?)
    - Invoke various models (turbulences, jet-in-jet, hadronic plasma etc)
  - Important to identify and determine by VLBI technique:
    - jet acceleration & collimation zone
    - most variable regions
    - jet composition

Fermi @ $>100$ MeV

Ackermann+16
3C 279: an archetypal blazar

- Rapid (optical) polarization variability (e.g., Abdo+10)
  - EVPA swings over days, often coincident with fast gamma-ray flares
  - Polarization variability often deterministic (e.g., not random-walk events; Kiehlmann+16)

- High VLBI linear & circular polarization detections
  - Constrains jet plasma composition; significant amount of $e^+e^-$ pair (e.g., Wardle+99; Homan+09)
Past 1mm VLBI observations of 3C279

- Presence of **ultracompact jet features** repeatedly found: pilot 1mm VLBI obs. (up to 7Gλ; Lu+13; Wagner+15)

- **Detailed structure** of those compact features however remained **elusive** (only crude model-fitting)

- **Imaging** the ultracompact structure is **crucial**
Observations & key findings
Event Horizon Telescope imaging of the archetypal blazar 3C 279 at an extreme 20 microarcsecond resolution

Jae-Young Kim1, Thomas P. Krichbaum1, Avery E. Broderick2,3,4, Maciek Wielgus5,6, Lindy Blackburn5,6, José L. Gómez7, Michael D. Johnson1,2, Katharine L. Condon1,6, Andrew Chael9,10, Kazunori Akiyama11,12,13,15, Svetlana Jorstad14,15, Alan P. Marscher8,14, Sara Issaoun16, Michael Janssen16, Chi-kuan Liao14,17,18, Tuomas Savolainen19,20,1, Dominik W. Pesce5,6, Feryal Özel17, Antxon Alberdi14, Walter Alecf, Kekiuchi Asada3, Anne-Kathrin Baczko1, David Ball17, Mislav Baloković5,6, John Barrett12, Dan Bintley22, Wilfred Boland23, Geoffrey C. Bower24, Michael Bremer5, Christiana D. Brinkmeyer18, Roger Brissenden19, Silike Britzen19, Dominique Broguière23, Thomas bruyn20, Do Yong Byun36,37, John E. Carlstrom28,29,30,31, Shami Chatterjee22, Koushik Chatterjee22, Ming-Tang Chen25, Yongjun Chen34,35, Ilje Cho26,27, Pierre Christon17, John E. Conway3, James M. Cordes26, Geoffrey B. Crew12, Yuzhu Cui37,38, Jory Davelaar15, Maríafe de Laurentis39,40,41, Roger Deane42,43, Jessica Dempsey22, Gregory Desvignes42,43, Jason Dexter3, Shepherd S. Doeleman16, Ralph P. Eaton14, Heino Falcke18, Vincent L. Fish17, Ed Fomalont11, Raquel Fraga-Encinas16, Per Frirberg17, Christian M. Fromm40, Peter Galison17,45, Charles F. Gammie48,49, Roberto García25, Olivier Gentaz23, Boris Georges6,51, Ciriacco Goddi16,51, Roman Gold51, Ming-feng Guo26,51, Mark Gurwell17, Kazuhiko Hada27,38, Michael H. Hecht17, Ronald Hesper52, Luis C. Ho53,54, Paul Ho17, Mareki Honma57,58, Chih-Wei L. Huang34,51, Lei Huang53,54, David H. Hughes17, Shiro Ikeda13,50,56,57,38, Makoto Inoue17, David James17,38, Buell T. Jannuzi14, Britton Jeter14, Wu Jiang19,22, Alejandra Jimenez-Rosales15, Taeyun Jung26,38, Mansour Karami27,38, Ramesh Karuppusamy15, Tomohisa Kawashima19, Garrett K. Keating19, Mark Kettings59, Junhan Kim18, Jongsoo Kim18, Motoki Kino13,30, Jun Yi Koay17, Patrick M. Koch1, Shoko Koyama19, Michael Kramer1, Carsten Kramer25, Cheng-Yu Ku16, Tod R. Lauer12, Sang-Sung Lee25, Yan-Rong Li13, Zhiyuan Li20,45, Michael Lindqvist9, Rococ Lico17, Kuo Liu18, Elisabetta Liuzzo57,67, Wen-Ping Lu13,20,71,72, Sara Markoff12,71,72, Daniel P. Marrone12, Iván Martí-Vidal12,44, Satoko Matsushita17, Lynn D. Matthews12, Lia Medeiros11,72, Karl M. Menten16, Yostuke Mizuno10, Izumi Mizuno10,22, James M. Moran18,19, Katarina Morvay13,22, Monika Moselbrodza16, Cornelia Müller16, Hiroshi Nagai13,38, Neil M. Nagar29, Masanori Nakamura17, Ramesh Narayan16, Gopal Narayan17, Inyuh Natarajan1, Roberto Neri15, Chunhong Ni3,4, Aristeidis Notou5, Hiroki Okino13,37,78, Héctor Olivares3, Gisela N. Ortiz-León1, Tomoki Oyama31, Daniel C. M. Palumbo16, Nimesh Patel17, Jongho Park2,6, Ue-Li Pen17,29,80,81, Vincent Pietu17, Richard Plambeck15, Aleksandr Popstefanija17, Oliver Porth13,39,40, Ben Prather9, Jorge A. Preciado-López11, Dimitrios Psaltis17, Jun-Quan Qu17, Venkatesh Ramakrishnan29, Ramprasad Rao24, Mark G. Rawlings3, Alexander W. Raymond5,6, Luciano Rezzolla17, Bart Rippard15,43,44, Freek Roelofs15,43,44, Alan Rogers12, Eduard Ros17, Mel Rosé17, Arash Roshaninesh17, Helge Rottmann1, Alan L. Roy1, Chet Ruszkycl1, Benjamin R. Ryan6,8, Kazi L. J. Rych17, Salvador Sánchez17, David Sánchez-Arguelles12,55,58,59, Mahito Sasaki17, Peter Schloerb17, Karl-Friedrich Schuster17, Li Jing Shao17, Zhiqiang Shen13,35,38, Des Small29,41,42, Bong Won Sohn37,29,41, Jason SooHoo16,24, Fumie Tasaki17, Paul Tiede17,41,42, Remo P. J. Tilianu16,50,51, Michael Titus17, Kenji Toma92,93, Pablo Tome17, Tyler Trent17, Thalia Traianou17, Sias Tripepa17, Shuichi Tsuda25,26, van Bemmel18, Daniel R. van Rossum16, Jan Wagner46, John Wardle16, Derek Ward-Thompson17, Jonathan Weintraub6,6, Norbert Wex17, Robert Wharton14,15, George N. Wong38, Qingsen Wu18, André Young16, Ken Young2, Ziri Younsi59,40, Feng Yuan43,51,100, Ye-Fei Yuan101, J. Anton Zensus1, Guanyao Zhao16, Shan-Shan Zhao16,45, and Ziyuan Zhu17 (The Event Horizon Telescope Collaboration)

(Affiliations can be found after the references)

Submitted: January 13, 2020
EHT 2017 observations of 3C 279

- Full-track observations over four nights in 2017 Apr (as main target and calibrator)
- SPT provides maximum N-S baselines: ~8.9 Glambda
- Also accompanying MWL VLBI observations by GMVA 86 GHz, VLBA 43/15 GHz
- Other dense MWL observations at all wavelengths (radio – TeV)

Comparison: M87 uv-coverage

Kim+20, submitted
Zooming into the core of 3C279

- First image of 3C279 at 20 μas resolution (see also EHTC+19c,d)
- Robust fringe detections up to 8.9 Glambda in all days, mild variability seen in the amplitudes
- The 1mm core structure elongated perpendicular to outer jet – not visible in the low-frequency images
Four days average images over three imaging pipelines (4x3; SMILI, ehtim, Difmap)
- The perpendicular core structure persistent over four days
- Significant flux variability in the core, and small changes in other details
• CP clearly varies over days; indicating structure change on inter/intra-day timescales

• More pronounced in bigger triangles; variability mainly comes from small scales

• Amplitudes don’t change much

• What is actually varying in images?

Substantial time variability!
Can closure phases vary just by \(~1\ \mu as\) shift?

- Yes, they can
- Also by flux changes, but somewhat weaker effects
- High enough SNR make the data sensitive
- Challenges to traditional VLBI data analysis
EHT-specific model-fitting analysis tools

Examples from EHTC+19f

- Various MCMC and relevant packages available: Themis (Broderick+20), Dynasty (Pesce+), GENA (Fromm+19)
- Fitting to various EHT measurements possible (closures, baseline visibilities etc)
- “Dynamic” modeling analysis also possible (in progress)
3C279 jet kinematics on daily & μas scales

April 5-11, 2017
Δt = 0.00 hr

Themis fully time-variable Gaussian model-fitting

(This is a gif animation)
Full posterior distributions from Themis time-variable model-fitting

Fully dynamical model-fitting -- fluxes, positions, sizes, and their time derivatives
μas scale jet kinematics in detail

- Extremely high S/N → ~1-2 μas level of positional uncertainty (classically, positional accuracy ~ Beam/SNR).
- C1 components move southward, only when C0-0 is used as reference.
- All components move by ~1-2 μas/day (~10-20c) w.r.t. C0-0.
- App. speeds comparable to VLBA 15/43 GHz monitoring results on mas (pc) scales (e.g., Jorstad+17).
- C0-1 and C0-2 clearly show non-radial motions w.r.t. C0-0.
Discussions
Origin of the peculiar subnuclear structure

Broad jet base, perhaps associated with the accretion disk and/or edge-brightened jet, similar to 3C 84 (see Giovannini+18 for more discussions)?
Broad jet base/accretion disk?

- Viewing angles differ by large amounts: Radio galaxies (e.g., M87, 3C84, ...: ~> 20 deg) vs. Blazars (e.g., 3C279: ~< 2 deg)

- Accretion disk (or base of a circular jet) would rather appear circular than narrow elliptical for small viewing angle

Nearly face-on view of circular accretion disk (or jet base)  edge-on view (thus more elliptical)
Other explanations?

- Many! for example…
- Oblique shocks
- Illuminating patterns (plasma instabilities) on the jet surface
- Large scale magnetic reconnection (a long, linear string of “plasmoids”)
Spatially bent jet in 3C279

- A number of evidence suggesting presence of curvature in the 3C279 jet (e.g., Homan+03, Jorstad+04, Abdo+10, Aleksic+14, Homan+15, ...)

- May explain the complex geometry & kinematics without introducing unnecessary complexity

Fig. from Young 2010
Testing a bent jet model for the “core”

- Many suitable families of parameters to fit the apparent speed using a constant Lorentz factor but varying viewing angles along the jet (by a few degrees.).

- 90 deg apparent P.A. change would require \(\sim 90 \times \sin(1-2 \text{ deg}) \sim 1.5-3.0 \text{ deg jet viewing angle change; internally consistent values.}\)

Assuming constant Gamma=20 for C0-1 and C0-2 (theta \(\sim 3 \text{ and 1.5 deg}.\))
Comparison with pre-ALMA EHT obs. of 3C 279

- In Apr 2011, similar innermost jet feature orientation was found by pre-ALMA EHT, during very high radio flux state.
- Later 2011, VLBA 43 GHz saw bright jet component in similar direction, later aligned to larger-scale jet.
- 2017 EHT observations may be similar.

NB: data point size ~ comp. flux.
What causes jet bending/rotation?

- **Binary SMBHs and/or BH+disk precession** (Abraham & Carrara 98; Qian+19; $P \approx 22$ yrs for 3C 279) $\rightarrow$ EHT jet structure similarity between 2011 and 2017 would constrain period $\sim< 6$ yrs, ruling out this scenario

- **Jet being collimated by interaction with ISM** (e.g., Homan+15) $\rightarrow$ misaligned AGN jet components tend to align with pre-established direction

- **Excitation of emission going along helical magnetic field in the jet** $\rightarrow$ Inner jet dynamics (e.g., Mertens+16) & polarization (Asada+02; Marscher+08; Hovatta+12; Kiehlmann+16)

- Understanding which one of these works better would require additional constraints (outlook)
How does the EHT 3C279 jet connect to the downstream?

- EHT jet speeds (~10-20c) are comparable to historical mas-scale speed measurements (before 2017)
- Constrains jet acceleration zone to be potentially < 3000Rs projected (~< 8x10^4 Rs deprojected)
- However in 2017 the 3C279 jet was exceptionally fast at ~>0.5 mas; ~37c speed (Larionov+20 in press)
Brightness temperature in the nuclear region

- Observed $T_b \sim 10^{10-11}$ K → Intrinsic $T_b' \sim < 10^{9-10}$ K considering Doppler factors of at least $\sim 10-20$
- $T_b \sim > 10^{12}$ K and $T_b' \sim 10^{11}$ K at lower frequencies (Kovalev+05; Jorstad+17)
- EHT values far below Compton limit ($\sim 5 \times 10^{11}$ K) and the equipartition value ($\sim 5 \times 10^{10}$ K)

**Table 2.** Summary of geometric and dynamical properties of the jet components discussed in §4.2.1 and §4.2.2.

<table>
<thead>
<tr>
<th>ID</th>
<th>$\beta_{app}$ (c)</th>
<th>$\theta$ (°)</th>
<th>$\Gamma$</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curved jet case$^a$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C0-1</td>
<td>16$^{+3}_{-2}$</td>
<td>$\leq 1.5$</td>
<td>$\geq 20$</td>
<td>$\geq 32$</td>
</tr>
<tr>
<td>C0-2</td>
<td>20$^{+1}_{-1}$</td>
<td>$\leq 2.9$</td>
<td>$\geq 20$</td>
<td>$\geq 20$</td>
</tr>
<tr>
<td>C1-0/1/2</td>
<td>(13 – 15) ± 2</td>
<td>$\geq 6 – 8$</td>
<td>$\geq 20$</td>
<td>$\leq 5 – 7$</td>
</tr>
<tr>
<td>Straight jet case$^b$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1-0/1/2</td>
<td>(13 – 15) ± 2</td>
<td>2</td>
<td>16 – 17</td>
<td>24 – 25</td>
</tr>
</tbody>
</table>
Interpretations of the low T’b

• Much depends on the core opacity at 230 GHz

• Optically thick (turnover ~ 1mm)
  • may represent some upstream emission of the jet. Signature of under-accelerated (thus slow) jet underlying the 1mm core.
  • Also T’b ~10^\((9-10)\)K << T’b,eq ~ 5\times 10^{10} K: more magnetic energy dominated flow (cf. kinetic power dominated)

• On the other hand, Tb may simply decrease with freq. if 3C279 becomes optically thin @ 1mm

• EHT spectral index measurement between 230 and 345 GHz would be helpful (also EHT polarimetry).
Conclusions

• EHT imaging analysis of the 3C 279 jet at 230 GHz
  • Peculiar “perpendicular” nuclear structure
    • Several physical interpretations
  • Rapid day-to-day closure phase variations; ~1-2 uas/day motions
    • Also complex kinematics; spatially bent jet provides good explanations
  • Unexpectedly low intrinsic brightness temperature (~< 10^{10} K)
    • May be a signature of very low jet opacity at 230 GHz

• Still some details quite remain elusive
  • How to improve / what to do more?
Outlook
EHT and MWL connections

- Significant radio flux variability within the EHT subnuclear structure within \( \sim 1 \) week; factors \( \sim 2 \) or more changes

- Also rapid gamma-ray variability; details under analysis
Constraining the curved jet structure

- Rapid linear polarization variability (both $mL$ and EVPA)
- Indicates small variable size and ordered evolution of structure (associated with motions?)
- Can independently reconstruct the curved jet parameters

Optical polarization of 3C279

Figure from Aleksik+2014;
Detailed model from Nalewajko 2010

Note: lines are from predictions, NOT fitting

Plot removed
Comparison uv-coverages 2017 - 2020 (for 3C279)

EHT 2017

8 stations

EHT 2020

11 stations (+GLT+KP+NOEMA)
Inner region

Larger scale

Note: the simulations assume ideal conditions (no gain errors)
Final outlook – hope to have soon

• Science side:
  • MWL / polarization
  • More sources (many already observed in 2017; all under analysis)

• Instrument side:
  • Expanding EHT in 2020
  • e-KVN and EAVN-high 230 GHz
  • Will provide a lot of insights about future EHT time-variable studies

• People, more people!