Science with an ngVLA: High-resolution Imaging of Radio Jets Launched by AGN

Matthew L. Lister, Kenneth I. Kellermann, and Preeti Kharb

1Dept. of Physics and Astronomy, Purdue University, West Lafayette, IN, USA; mlister@purdue.edu
2NRAO, Charlottesville, VA, USA; kkellerm@nrao.edu
3NCRA-TIFR, Pune, India; kharb@ncra.tifr.res.in

1. Bridging AGN Jet Studies from Parsec through Kiloparsec Scales

Jetted plasma outflows from active galactic nuclei (AGN) represent the most energetic phenomena in the known universe, and play a key role in regulating galaxy formation through feedback processes (Harrison et al. 2018). The JVLA and VLBA have played an indispensable role in understanding the physics of these powerful jets and their environments, via high angular resolution full polarization imaging and astrometric studies. By bridging the current interferometric gap between the JVLA and VLBA with intermediate baselines, the ngVLA offers exciting new opportunities to explore the intermediate regions downstream of the high Lorentz factor pc-scale AGN jets imaged by VLBI, where entrainment, deceleration, collimation and particle acceleration all take place. The ability to image exceedingly faint radio emission on scales of 10s to 100s of milliarcseconds will lead to new breakthroughs in resolving some of the most pressing questions regarding the formation, structure, and evolution of AGN jets. These are in turn crucial for a more complete understanding of the formation of supermassive black holes and galaxies in the early universe and their subsequent evolution.

2. Magnetic field structure

Since AGN jets are fundamentally magnetically-driven phenomena, polarimetric observations provide numerous physical insights otherwise unattainable via total intensity imaging. As we describe in the specific science topic sections below, the full (linear and circular) polarization capabilities of the ngVLA represent a major advance over existing instruments, as applied to AGN jet studies. Specifically, Faraday depth, rotation, and depolarization measurements offer a direct means of probing the properties of jet plasma and its surrounding medium, as well as the overall magnetic field. VLBA polarimetric imaging has revealed complex pc-scale magnetic phenomena, such as MHD waves (Cohen et al. 2014), stationary features (Jorstad et al. 2017), and structures consistent with planar and conical shocks (Marscher et al. 2008). On kiloparsec scales, polarization studies of radio lobes (Fig. 1) have been a crucial element supporting the unification of radio galaxies and quasars (Garrington et al. 1988), and provide one of the only means of studying large scale magnetic fields in galaxy clusters (Bonafede et al. 2010). Although difficult to measure with existing radio telescope arrays, the de-
tections of circular polarization (Homan & Lister 2006) and Faraday rotation gradients (Gabuzda et al. 2017) in a few pc-scale AGN jets have revised our views of internal jet physics over the last decade, and have prompted many detailed numerical studies to better understand the jet launching and collimation process (e.g., Broderick & McKinney 2010; Tchekhovskoy & Bromberg 2016). With the new 50-250 km baselines and substantially improved sensitivity afforded by the ngVLA, it will be possible to study the magnetic field structure of lobes and terminal jet hotspots in AGN in unprecedented detail. This will lead to a better understanding of particle acceleration mechanisms and how relativistic jet flows are decelerated.

Figure 1. VLA image of the radio galaxy Fornax A. In this hue-intensity image the brightness corresponds to the intensity of the lobes while the highly polarized structure is saturated white and regions of increasing depolarization are shaded red. Image courtesy of NRAO/AUI.

3. Launching and Collimation Mechanisms

Current theory and numerical simulations for the launching of jets favor scenarios that typically involve a supermassive black hole and accretion disk in the nucleus of the host galaxy. Magnetic fields play an important role, due to the large kinetic power of the outflows, and the lack of sufficient thermal and radiation pressure in the accretion disk region. A toroidal field component can provide a means of producing the highly collimated jets imaged by VLBI. Magnetic fields also provide the means of extracting energy and angular momentum from the accretion disk and a rotating black hole.

High resolution radio imaging of nearby AGN jets has revealed important details regarding collimation near the base of the jet. In the case of the nearby AGN M87, the jet initially has a wide opening angle, which is sharply collimated at \( \sim 100 \) Schwarzschild radii \( (R_s) \) to a roughly parabolic profile (Hada et al. 2013). Only at \( \sim 10^2 R_s \) does the jet take on a conical shape expected for simple adiabatic expansion (Asada & Nakamura 2012). Some magnetic launching models (e.g., Komissarov et al.
High-resolution ngVLA Imaging of Radio Jets Launched by AGN

2007) predict strong collimation once the jet flow passes through the fast-magnetosonic point, when the bulk conversion of magnetic to kinetic energy takes place. Multi-epoch VLBI imaging of the inner M87 jet has also shown an evolution of the flow velocity that can be explained in the framework of MHD jet acceleration and this type of energy conversion (Mertens et al. 2016; Walker et al. 2018b). Since M87 is unusually close (16 Mpc), the ngVLA will be the only instrument capable of probing faint structure in the jet further downstream, including the intriguing HST-1 knot region, which has been seen to exhibit much higher internal proper motions (up to ~ 4 c) than the (sub-luminal) inner jet (Giroletti et al. 2012). This type of analysis can also be extended to many other nearby radio galaxies such as NGC 6251 (Tseng et al. 2016) and PKS 0227-369 (Potter & Cotter 2013). At present, the only instrument capable of probing these scales is e-MERLIN, which, having only 7 antennas, cannot provide the dual-sensitivity needed to probe the diffuse and compact structures that are present in these nearby jets. The ngVLA will provide 10 times the continuum imaging sensitivity of e-MERLIN at 5 GHz in one tenth the integration time.

4. Jet Structure

With its unprecedented sensitivity and baselines out to 1000 km, the ngVLA holds the exciting prospect of transversely resolving for the first time the jets of many nearby radio galaxies such as NGC 315, 3C 66B, 3C 264, and NGC 4261 out to large projected distances. Since radio galaxy jets are oriented closer to the plane of the sky, they suffer less from projection and relativistic beaming effects. In a handful of cases with current instruments, the (de-boosted) receding jet can be imaged and compared with the approaching jet, giving an accurate measurement of the viewing angle, which is often impossible to determine by other means. This technique also provides detailed information on the velocity field and magnetic field configuration in the jets, and has been used extensively by Laing & Bridle (2014) to make important discoveries regarding the accelerations of jet plasma and its interaction with the external medium at the jet boundary. Although currently limited to slower and less beamed (FR-I class) jets, with the ngVLA it will be possible to study the receding jets and velocity fields in the most powerful (FR-II class) AGN (Figure 2). In particular, more examples of enhanced radio emission at the jet boundaries will be found, which have been studied so far in only the nearest AGN jets such as M87 (Fig. 3), Mrk 501 (Giroletti et al. 2008), and 3C 84 (Nagai et al. 2014). At present it is unclear whether this phenomenon is a result of interaction with the external medium, or differential beaming associated with a transverse jet velocity profile, a corkscrew-like rotation of the flow (Walker et al. 2018b) or helical magnetic fields (Clausen-Brown et al. 2011).

5. Bending

Many jets have 'S'-shaped or more complex curvatures which have been variously attributed to nozzle precession, hydrodynamic instabilities, jet-cloud collisions, or ram pressure from the external medium. By tracing the jet at high resolution from pc to kpc scales, ngVLA studies will help to distinguish between these scenarios for individual objects, and determine for the first time the range and form of bending in the AGN jet population (Fig. 4). The ngVLA will also probe a much larger variety of 'U'-shaped
Figure 2. The 1.4 GHz extended luminosity with respect to redshift for the original MOJAVE sample (Kharb et al. 2010b). Black and red circles denote quasars and BL Lac objects, respectively, while green squares denote radio galaxies. Core-only sources are represented as upper limits with downward arrows. The solid lines indicate the FRI–FRII divide (extrapolated from 178 MHz to 1.4 GHz assuming a spectral index, $\alpha=0.8$), following Ledlow & Owen (1996) and Landt et al. (2006). The purple line denotes the sensitivity limit for the historical VLA which was used to carry out the MOJAVE study, while the magenta line denotes the sensitivity limit for the ngVLA (see http://ngvla.nrao.edu/page/refdesign). ngVLA will be able to detect more than twice as many “hybrid FRI/II” sources, compared to previous studies, revolutionising the study of radio-loud AGN.

galaxies, which have been used successfully to identify galaxy clusters and directly study their intergalactic medium (Paterno-Mahler et al. 2017). Opportunities will also exist for studying large scale hydrodynamic instability modes in AGN jets, which manifest themselves as apparent helical structures on $\sim 100$ pc scales (Hardee et al. 2005). It will be possible to trace out to large projected distances the extreme apparent bends in highly aligned AGN jets (blazars), which on occasion directly cross our line of sight, providing useful data for testing radiative transfer and jet emission models (Homan et al. 2002; Alberdi et al. 1997).
Figure 3. VLBA image of the radio jet in M87. With a high resolution of 430 by 210 microarcseconds (1.3 by 0.64 light-months), it reveals that the jet appears brighter at its edge compared to the center, and collimation of the jet is occurring within 100 Schwarzschild radii. Image courtesy of NRAO/AUI.

6. Precession

A recent discovery from long-term VLBA studies is that bright superluminal features in pc-scale AGN jets will frequently emerge in a particular direction that changes slowly on decadal timescales (Lister et al. 2013). The net result is that at any given time, only the 'energized' portion of the jet containing recently ejected features is visible with current interferometers. Over time, subsequent ejections 'fill in' the jet, revealing its true conical shape in stacked images (Pushkarev et al. 2017). Evidence of helical-type jet morphology has been seen on kpc-scales with the JVLA that is suggestive of precession, and a particularly intriguing class of 'X-shaped' radio galaxies may represent cases where a dramatic 90° or more shift has occurred in the jet direction over time. The ngVLA will be vital for connecting the dynamic morphology seen on pc-scales with emission immediately downstream, and for identifying cases where the jet direction is actively shifting.

7. Proper Motions and Astrometry

The VLBA is a remarkable tool for precision jet astrometry, being able to measure the speeds and accelerations of thousands of individual jet features on decade or more timescales. Large surveys are able to directly witness jet kinematics through time-lapse imaging, and have revealed that powerful AGN jets are still undergoing collimation and acceleration on scales of tens to hundreds of parsecs downstream of the central engine (Homan et al. 2015; Jorstad et al. 2017), and occasionally in abrupt fashion (Homan et al. 2003). Recent work with HST and JVLA data on two AGN has shown that this type of astrometry can also be performed on kiloparsec scale jet features (Meyer et al. 2017a). The unprecedented sensitivity and > 50 km baselines of the ngVLA, in combination with improved resolution afforded by JWST, will extend these measurements to a much larger set of more distant and more powerful AGN. Such studies are crucial for
8. Knots and Hotspots

Considerable uncertainties still exist in our understanding of the emission processes in bright jet knots in kpc-scale jets (Fig. 5). Recent multi-wavelength studies with the JVLA, ALMA, HST, and Chandra have shown that simple inverse-Compton scattering models with single-electron populations cannot adequately account for the spectral energy distributions of jet knots (e.g., Meyer et al. 2017b; Jester et al. 2006). In some cases, such as M87, jet knots have been postulated to be the sites of variable gamma-ray emission, but detailed supporting data are lacking. Multi-epoch, multi-frequency polarimetric imaging with the longest ngVLA baselines will make it possible to perform spectral ageing, Faraday depth and magnetic field analyses of jet knots with unprecedented resolution and sensitivity. The terminal hotspots of AGN jets, where the flow undergoes abrupt deceleration while interacting the intergalactic medium, represent important targets for ngVLA studies of feedback mechanisms, and for resolving why some AGN display hybrid jet morphologies (Fig. 2). In hybrid AGN, one jet appears to be of high power, with a terminal hotspot, while the other has properties more consistent with a lower power flow that is decelerated gradually along its length by entrainment with the external medium (Gopal-Krishna & Wiita 2000). Hotspots and radio lobes are also useful for probing the past activity history of the jets, especially at longer radio wavelengths which sample the older electron population.

9. Radio-Loud and Radio-Quiet Quasars

Fifty years after the discovery of quasars, the distinction between radio-loud quasars (RLQ) and radio quiet quasars (RQQ) is still being debated. Some authors have reported a clear bi-modal separation in radio/optical luminosity ratio $R$ while others have claimed that the distribution is continuous with no evidence for two populations (see...
Kellermann et al. 2016 for a review). Using the JVLA, Kimball et al. (2011) and Kellermann et al. (2016) have detected radio emission from essentially all 176 quasars in a volume-limited sample from the SDSS contained within a narrow range of red shift. Only about 10-15% of the SDSS quasars fall in the radio-loud classification, irrespective of whether the RLQs are defined by $R$ or by luminosity. Condon et al. (2013) have shown that the radio emission from the RQQ is due to star formation in the host galaxy and is not directly related to the SMBH which gives rise to the AGN. All quasars are thought to harbor a SMBH needed to support the huge optical-IR luminosity which defines the category of quasars. Why then is only a small fraction, 10-15% of quasars RL? Many explanations have been offered, including intermittent activity, absorption of the radio emission by intervening medium, host galaxy properties, magnetic fields, and black hole spin or accretion rate. A particularly elegant interpretation was suggested by Scheuer & Readhead (1979) that RLQ are just the subset of quasars whose relativistic beams are oriented nearly along the line of sight. But at the time, it appeared that too large a fraction of optically selected quasars appeared radio loud and that the observed detection rate as a function of decreasing flux density was not consistent with simple beaming models. Using more modern radio observations of optically selected quasars and now knowing that relativistic jets often have finite width and significant bends, as well as recognizing that optically selected quasars are not necessarily randomly oriented in the sky, the observed fraction (10-15%) of RLQ and the observed number flux density relations now appear consistent with relativistic beaming models. However, the extended radio emission seen in more than half of RLQs represents a clear challenge to the relativistic beaming interpretation of the RL/RQ dichotomy. Kinematic observations of kpc (arcsec) scale are difficult as the expected motions are typically only a few tenths of a milliarcsec per year. Currently there is evidence of modest superluminal
motion in 7 mm observations of M87 (Walker et al. 2018a), and in the kpc-scale jets of a few AGN ( § 7). High-resolution-high sensitivity proper motion observations with the ngVLA will give further insight to the importance of relativistic beaming in kpc scale radio jets and its implications for the RL/RQ dichotomy.

10. Low-luminosity/Radio-quiet AGN

More than 80% of AGN, comprising Seyfert and Low Ionization Nuclear Emission Line Region (LINER) galaxies, do not possess collimated plasma outflows on kpc-scales. Weak AGN outflow emission is often indistinguishable from outflows due to galactic stellar activity or nuclear starbursts (e.g., Gallimore et al. 2006). Disentangling AGN and stellar contributions to the radio emission are essential to understanding the nature of the AGN in low luminosity AGN (LLAGN), and in discerning why the vast majority of AGN do not produce large-scale jets. Multi-scale observations from parsec to kpc-scales can trace the connection between an AGN jet and kpc-scale lobes observed in many LLAGN (Fig. 4). Polarization-sensitive imaging can further distinguish between the stellar and AGN outflows, due to presumably more organized magnetic field structures and higher degrees of polarization in AGN outflows compared to stellar outflows. The ngVLA will detect fainter radio emission in LLAGN and in doing so will trace AGN outflows as they are launched from the black hole-accretion-disk systems and propagate through the ISM of their host galaxies.

References

Alberdi, A., Krichbaum, T. P., Graham, D. A., Greve, A., Grewing, M., Marcaide, J. M., Witzel, A., Booth, R. S., Baath, L. B., Colomer, F., Doeleman, S., Marscher, A. P., Rogers, A. E. E., Schalinski, C. J., & Standke, K. 1997, A&A, 327, 513
Asada, K., & Nakamura, M. 2012, ApJ, 745, L28. 1110.1793
Bonafede, A., Feretti, L., Murgia, M., Govoni, F., Giovannini, G., Dallacasa, D., Dolag, K., & Taylor, G. B. 2010, A&A, 513, A30. 1002.0594
Broderick, A. E., & McKinney, J. C. 2010, ApJ, 725, 750. 1006.5015
Clausen-Brown, E., Lyutikov, M., & Kharb, P. 2011, MNRAS, 415, 2081. 1101.5149
Cohen, M. H., Meier, D. L., Arshakian, T. G., Homan, D. C., Hovatta, T., Kovalev, Y. Y., Lister, M. L., Pushkarev, A. B., Richards, J. L., & Savolainen, T. 2014, ApJ, 787, 151. 1404.0976
Condon, J. J., Kellermann, K. I., Kimball, A. E., Ivezić, Ž., & Perley, R. A. 2013, ApJ, 768, 37. 1303.3448
Gabuzda, D. C., Roche, N., Kirwan, A., Knuettel, S., Nagle, M., & Houston, C. 2017, MNRAS, 472, 1792. 1709.09062
Gallimore, J. F., Axon, D. J., O’Dea, C. P., Baum, S. A., & Pedlar, A. 2006, AJ, 132, 546. astro-ph/0604219
Garrington, S. T., Leahy, J. P., Conway, R. G., & Laing, R. A. 1988, Nat, 331, 147
Giroletti, M., Giovannini, G., Cotton, W. D., Taylor, G. B., Pérez-Torres, M. A., Chiaberge, M., & Edwards, P. G. 2008, A&A, 488, 905. 0807.1786
Giroletti, M., Hada, K., Giovannini, G., Casadio, C., Beilicke, M., Cesarini, A., Cheung, C. C., Doi, A., Krawczynski, H., Kino, M., Lee, N. P., & Nagai, H. 2012, A&A, 538, L10. 1202.0013
Gopal-Krishna, & Wiita, P. J. 2000, A&A, 363, 507. astro-ph/0009441
Gourgouliatos, K. N., & Komissarov, S. S. 2018, Nature Astronomy, 2, 167
High-resolution ngVLA Imaging of Radio Jets Launched by AGN

Hada, K., Kino, M., Doi, A., Nagai, H., Honma, M., Hagihara, Y., Giroletti, M., Giovannini, G., & Kawaguchi, 2013, ApJ, 775, 70. 1308.1411

Hardee, P. E., Walker, R. C., & Gómez, J. L. 2005, ApJ, 620, 646. astro-ph/0410720

Harrison, C. M., Costa, T., Tadhunter, C. N., Flütsch, A., Kakked, D., Perna, M., & Vietri, G. 2018, Nature Astronomy, 2, 198. 1802.10306

Homan, D. C., & Lister, M. L. 2006, AJ, 131, 1262. astro-ph/0511838

Homan, D. C., Lister, M. L., Kellermann, K. I., Cohen, M. H., Ros, E., Zensus, J. A., Kadler, M., & Vermeulen, R. C. 2003, ApJ, 589, L9

Homan, D. C., Lister, M. L., Kovalev, Y. Y., Pushkarev, A. B., Savolainen, T., Kellermann, K. I., Richards, J. L., & Ros, E. 2015, ApJ, 798, 134. 1410.8502

Homan, D. C., Wardle, J. F. C., Cheung, C. C., Roberts, D. H., & Attridge, J. M. 2002, ApJ, 580, 742. astro-ph/0208065

Jester, S., Harris, D. E., Marshall, H. L., & Meisenheimer, K. 2006, ApJ, 648, 900. astro-ph/0605529

Jorstad, S. G., Marscher, A. P., Morozova, D. A., Troitsky, I. S., Agudo, I., Casadio, C., Foord, A., Gómez, J. L., MacDonald, N. R., Molina, S. N., Lähteenmäki, A., Tammi, J., & Tornikoski, M. 2017, ApJ, 846, 98. 1711.03983

Kellermann, K. I., Condon, J. J., Kimball, A. E., Perley, R. A., & Ivezić, Ž. 2016, ApJ, 831, 168. 1608.04586

Kharb, P., Hota, A., Croston, J. H., Hardecastle, M. J., O’Dea, C. P., Kraft, R. P., Axon, D. J., & Robinson, A. 2010a, ApJ, 723, 580. 1009.0702

Kharb, P., Lister, M. L., & Cooper, N. J. 2010b, ApJ, 710, 764. 1001.0731

Kimball, A. E., Kellermann, K. I., Condon, J. J., Ivezić, Ž., & Perley, R. A. 2011, ApJ, 739, L29. 1107.3551

Komissarov, S. S., Barkov, M. V., Vlahakis, N., & Königl, A. 2007, MNRAS, 380, 51. astro-ph/0703146

Laing, R. A., & Bridle, A. H. 2014, MNRAS, 437, 3405. 1311.1015

Landt, H., Perlman, E. S., & Padovani, P. 2006, ApJ, 637, 183. astro-ph/0509718

Ledlow, M. J., & Owen, F. N. 1996, AJ, 112, 9. astro-ph/9607014

Lister, M. L., Aller, M. F., Aller, H. D., Homan, D. C., Kellermann, K. I., Kovalev, Y. Y., Pushkarev, A. B., Richards, J. L., Ros, E., & Savolainen, T. 2013, AJ, 146, 120. 1308.2713

Marscher, A. P., Jorstad, S. G., D’Arcangelo, F. D., Smith, P. S., Williams, G. G., Larionov, V. M., Oh, H., Olmstead, A. R., Aller, M. F., Aller, H. D., McHardy, I. M., Lähteenmäki, A., Tornikoski, M., Valtaoja, E., Hagen-Thorn, V. A., Kopatskaya, E. N., Gear, W. K., Tosti, G., Kurtanidze, O., Nikolashvili, M., Sigua, L., Miller, H. R., & Ryle, W. T. 2008, Nat, 452, 966

Mertens, F., Lobanov, A. P., Walker, R. C., & Hardee, P. E. 2016, A&A, 595, A54. 1608.05063

Meyer, E., Sparks, W., Georganoopoulos, M., van der Marel, R., Anderson, J., Sohn, S., Biretta, J., Norman, C., Chiaberge, M., & Perlman, E. 2017a, Galaxies, 5, 8. 1701.05846

Meyer, E. T., Breiding, P., Georganoopoulos, M., Oteo, I., Zwaan, M. A., Laing, R., Godfrey, L., & Ivison, R. J. 2017b, ApJ, 835, L35. 1702.00015

Nagai, H., Haga, T., Giovannini, G., Doi, A., Orienti, M., D’Ammando, F., Kino, M., Nakamura, M., Asada, K., Hada, K., & Giroletti, M. 2014, ApJ, 785, 53. 1402.5930

Paterno-Mahler, R., Blanton, E. L., Brodwin, M., Ashby, M. L. N., Golden-Marx, E., Decker, B., Wing, J. D., & Anand, G. 2017, ApJ, 844, 78. 1611.00746

Potter, W. J., & Cotter, G. 2013, MNRAS, 429, 1189. 1212.2632

Pushkarev, A. B., Kovalev, Y. Y., Lister, M. L., & Savolainen, T. 2017, MNRAS, 468, 4992. 1705.02888

Scheuer, P. A. G., & Readhead, A. C. S. 1979, Nat, 277, 182

Tchekhovskoy, A., & Bromberg, O. 2016, MNRAS, 461, L46. 1512.04526

Tseng, C.-Y., Asada, K., Nakamura, M., Pu, H.-Y., Alagba, J.-C., & Lo, W.-P. 2016, ApJ, 833, 288. 1610.06351

Walker, R. C., Hardee, P. E., Davies, F. B., Ly, C., & Junor, W. 2018a, ArXiv e-prints. 1802.06166
