Observing Relativistic Jets in Active Galactic Nuclei with ngVLA

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Abstract

Active galactic nuclei (AGN) are the most energetic objects in the Universe that are ultimately powered by the accretion onto the central supermassive black holes (SMBH). In particular, powerful relativistic jets are the manifestation of AGN activities, while the formation and emission mechanisms of relativistic jets remain a central question in high-energy astrophysics since the first discovery of such phenomena. Here we overview some potential science cases on AGN jets addressed by ngVLA. Its superb observing capability (μJy sensitivity at sub-milliarcsecond angular resolution with the long-baseline-array mode) operated at centimeter wavelengths is best suited to study the physics of relativistic jets.

Key words: galaxies:active — radio continuum:galaxies — technique: interferometric

1. Introduction

It is widely believed that active galactic nuclei (AGN) are powered by the accretion of material onto the supermassive black holes (SMBH). Approximately 10% of known AGN are radio-loud and exhibit powerful relativistic jets. AGN jets are one of the most spectacular phenomena in the Universe and observable on a wide range of spacial scales from sub-pc to Mpc. Elucidating the formation, propagation and internal physical properties (radiative and kinetic energy densities, magnetic field strength and configuration) of AGN jets is a half-century-long quest in high-energy astrophysics. Besides, as they can transport a significant fraction of gravitational energy back into their host galaxies and intergalactic space, detailed high resolution studies are essential in the above contexts and in understanding their role in the cosmological evolution of galaxies.

Recently, the Event Horizon Telescope (EHT) operated at millimeter wavelengths has obtained the first SMBH shadow image in the nucleus of M87, a nearby radio galaxy with a poweful radio jet (EHT Collaboration et al. 2019). This has opened a new window for high frequency observational studies of AGN. However, the millimeter-VLBI image of M87 does not show any extended emission around the photon ring, despite the dominance of prominent jet at larger scales. This could be due to the limited imaging sensitivity of the EHT array and/or due to the low-level ($\sim$mJy) jet emission at such high frequencies.

In this context, radio observations at centimeter wavelengths are advantageous to observe jet formation scales after its launching from SMBH, thanks to the steep spectral nature of nonthermal synchrotron emission of the jet. Indeed, various important jet physics and questions such as the collimation and acceleration are associated with a wide range of distances above subpc/pc scales, which cannot be probed by mm-wavelength observations. The ngVLA and its long-baseline-array (LBA) capability that achieves unprecedented sensitivity and mas/submas-scale resolution at $\sim$1–100 GHz can uniquely probe a vast range of physical scales associated with the AGN jets, from their formation/propagation region to termination.

Here we introduce some potential science cases on AGN jets that can be best addressed with ngVLA, in particular with use of the LBA mode.

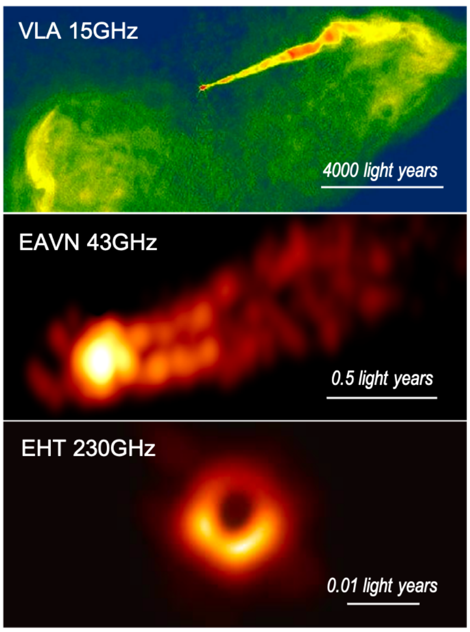

Fig. 1. Radio images of M87 jet at various spatial scales. (Top) VLA 15 GHz image (NRAO). (Middle) EAVN 43GHz image (EAVN Collaboration). (Bottom) EHT 230 GHz image (EHT Collaboration et al. 2019).

2. Imaging the acceleration and collimation zone

One of the remarkable features of AGN jets is that they are very well collimated (<5 deg) even at large scales (up to ∼kpc-Mpc). The key question is how and where the flow starts to be collimated after launching. A widely favored scenario of powerful AGN jet formation suggests that a jet is produced via strong magnetic fields amplified by a spinning BH (Blandford & Znajek 1977) or/and the inner accretion disk (Blandford & Payne 1982). The flow is initially slow and the subsequent acceleration is realized by gradually conversion of the magnetic energy into kinetic one, while the ambient pressure from the external medium collimates the flow. As a consequence, the theory suggests that an acceleration and collimation zone (ACZ) is formed over distances of $\sim$10–10^5 Schwarzschild radii (R_s) from BH (e.g., Komissarov et al. 2009). To test this observationally, in recent years high-resolution VLBI analyses of jet morphology have been performed for a growing number of objects. The best example is M87, where the jet collimation profile was robustly determined by various authors (e.g., Asada & Nakamura 2012; Hada et al. 2013) over in total 7 orders of magnitude in gravitational radii of SMBH (see Fig.4 for a compilation plot by Nakamura et al. 2018). It was found that the jet shows a parabolic collimation profile over $\sim$100–10^6 R_s, which is consistent with the magnetic models. Remarkably, the jet transitions into a conical shape at the Bondi radius, suggesting that the surrounding gases bound by the gravitational potential of SMBH play a key role in confining the jet. However, the number of sources for which the jet collimation profile was determined is still very limited (of the order of ten) and mostly biased towards Fanaroff-Riley-I (FR-I) type jets whose jet power is relatively low. To test how such features are common to AGN jets, it is important to investigate the jet geometry and structural transitions for a variety of objects (including FR-II objects) by imaging the ACZ of jet flows over a wide range of distances. For FR-II sources (i.e., highly debeamed from us) this would require imaging rms noise levels of $\leq$10 μJy even for nearby targets (e.g., 3C 452; Giovannini et al. 2001). Ultra-high-sensitivity ngVLA along with its mas-submas angular resolution at 1–115 GHz, will be a unique way to achieve this requirement.

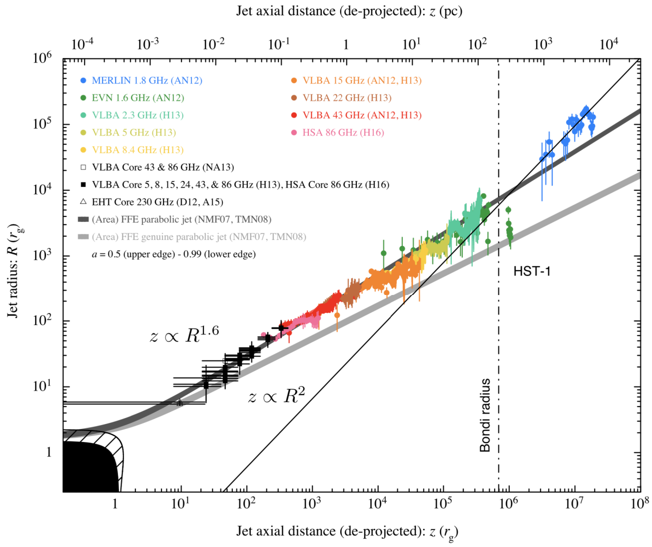

Fig. 2. Jet collimation profile of M87 jet (Nakamura et al. 2018)

3. Imaging multi-layered jet

An increasing number of AGN jets show edge-brightened structures when resolved transversely. Broadband spectral modeling studies on powerful AGN jets suggest that a relativistic jet is not a simple uniform flow but composed of two distinct layers, i.e., an outer "sheath" flow and a central "spine" flow (Ghisellini et al. 2005). Similar arguments are also yielded from GRMHD simulations (e.g., McKinney & Blandford 2009), suggesting that the central spine can be produced by extracting the rotational energy of the spinning BH while the outer sheath may be connected to the innermost part of the accretion disk. Hence, probing the transverse structure of AGN jets is essential to constrain their formation mechanisms. Since jet transverse structures can be typically resolved on mas-submas scales and the central stream is much dimmer than the bright limbs, high-sensitivity radio imaging at cm wavelengths would be best suited to address this. Indeed, recent high-resolution high-sensitivity radio images of the M87 jet at cm wavelengths have begun to discover substructures in the central dim part of the jet, which could be associated with the interior spine component (Asada et al. 2016; Hada 2017). To test how common spine-sheath structures are in AGN jets (particularly in the relatively dimmer FR-II jets as described above), further enhancement of image sensitivity (down to a few μJy levels) at these frequencies is crucial, which is possible with ngVLA.

4. Magnetic fields in the ACZ: helical scenario and estimation

According to the current leading scenario of AGN jet production, differential rotation in the BH ergosphere or inner part of accretion disk creates tightly-twisted magnetic fields (e.g., Meier et al. 2001). Searching for signatures of such helical magnetic fields is a longstanding quest in observational studies of relativistic jets.

This may be best addressed by high-resolution polarimetric radio observations. If a jet possesses helical magnetic fields, one should see systematic Faraday rotation-measure (RM) gradients across the jet due to the gradual change of the field component along our line-of-sight (Broderick & McKinney 2010). The first observational hint of such transverse RM gradients was reported in the pc-scale jet of 3C273 (Asada et al. 2002), and to date similar features have been claimed in ∼30 pc-scale jets (Hovatta et al. 2012; Gabuzda et al. 2017), suggesting that the presence of helical fields may be common in AGN jets. However, the previous arguments are mostly based on patchy polarization signals covering only a small fraction of the entire jet area, since the SNR of polarization/RM maps are typically ∼10 times lower than those of total intensity images. To definitively test the global magnetic-field configuration in a jet, we need polarization/RM maps covering the whole jet area. A factor of 10 sensitivity improvement by ngVLA will be able to create jet polarization maps at comparable levels as currently done for total intensity, which may robustly detect RM gradients across the jet in >100 sources. In particular, accurate RM measurements require multiple bands which covers a wide frequency range. Therefore, having multi-frequency ngVLA images simultaneously over 1–100 GHz can greatly facilitate this study.

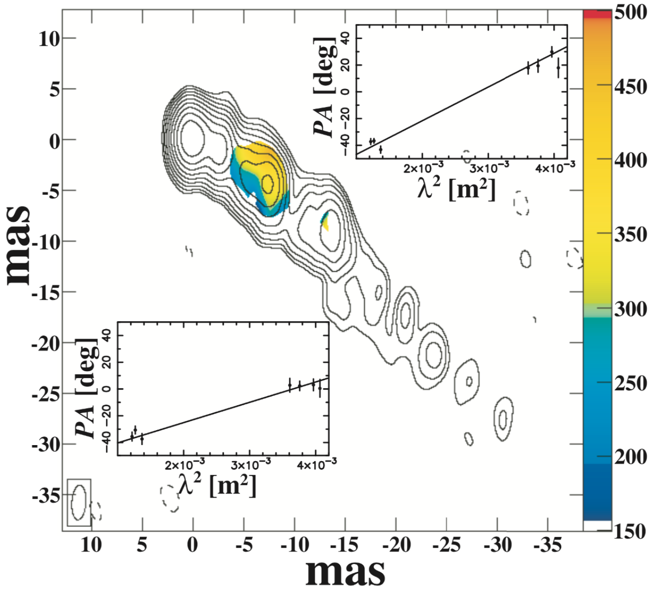

Fig. 3. First indication of Faraday rotation measure gradient across the jet in 3C 273 obtained with VLBA at 5 and 8 GHz (Asada et al. 2002)

5. (Sub-)pc-scale imaging of AGN thermal components

Another unique opportunity with ngVLA is that we will for the first time be able to probe the thermal emission of AGN at unprecedented resolution. While AGN are an efficient site of particle acceleration as evident from broadband radio-to-γ-ray nonthermal emission, AGN contain various thermal components such as accretion disks, winds/outflows, tori, broad/narrow line regions. Understanding the nature of these components are very important to test the validity of the AGN unification scenario, and direct imaging these regions would be the best approach for that. However, these components are typically confined within the central $\sim$pc (or much less) of the nucleus, and this requires mas-scale angular resolution for an AGN at a distance of 100 Mpc. While only VLBI can achieve this level of resolution, the current VLBI sensitivity (typically $T_B > 10^{6-7}$ K) prevents us from detecting the thermal components via emission, and instead only a few cases were exceptionally probed via absorption (Kameno et al. 2001; Jones et al. 2001; Haga et al. 2015). With its superb sensitivity of ngVLA with the LBA mode, one can reach a sensitivity level of $T_B{\sim}10^{3-4}$ K at (sub)mas angular resolution. This will for the first time allow us to resolve and image the thermal accretion disks and also winds/outflows from the disks that confine the nonthermal jet. Therefore ngVLA will allow us to directly image a whole system of AGN that is relevant to accretion and ejection, fueling and feeding, that is key to fully understand the nature of AGN and its evolution.

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