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High-resolution very-long-baseline interferometry: the sharpest view of the Universe

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Abstract

Very-long-baseline interferometry (VLBI) is experiencing a new era with highest resolutions reached at millimetre and submillimetre wavelengths and with antennas in space. A summary of the present status of these enterprises is given, with a special focus on Global-Millimetre VLBI Array (GMVA) and Event Horizon Telescope (EHT) observations of selected blazars, and on the major RadioAstron Key Science Programs. VLBI science opens new frontiers, also owing to major progress in hardware, data recording, and analysis methods. Present efforts focus on scientific targets such as Sgr A*, M 87, 3C 84, 3C 273, and NGC 1052. We will discuss in more detail the power of this approach in the case of the latter source.

1 Introduction

To enhance the resolving power of an interferometer, the baseline length limitation set by the Earth diameter can be overcome by putting an antenna in space. Another way is going to shorter wavelengths, at the price of facing several technical challenges: the influence of water vapour and turbulence in the atmosphere reduces the coherence time, the specifications for the observing telescopes have to be more stringent in surface accuracy and performance.

The main targets in VLBI science are active galactic nuclei (AGN) at high resolution, emitting non-thermally at the highest known brightness temperatures. We provide a selection of those

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Table 1: Resolving power of present highest-resolution interferometers for selected active galactic nuclei. The last column shows the equivalent size of a resolution of 50 microarcseconds, expressed in units of Schwarzschild radii.

Source	D_L [Mpc]	$\log M_\bullet$ [$M_\odot$]	R_s [lt-min]	50 μas [R_s]
Sgr A*	0.008	6.5	0.5	6
Cen A	3	7.7	8.2	553
NGC 1052	18	8.2	5.2	350
M 87	22	9.5	518.9	18
3C 84	71	8.9	130.3	218
IC 310	77	8.5	51.9	592
Mrk 421	130	9.0	164.1	310
3C 120	138	8.7	82.2	655
Mrk 501	142	8.3	32.7	1687
AP Lib	212	8.4	41.2	1939
Cyg A	250	9.4	412.2	215
BL Lac	292	8.2	26.0	4102
3C 273	738	8.9	130.3	1741
0716+714	1499	10.5	5189.3	71
OJ 287	1637	10.3	3274.2	114
3C 279	2996	8.9	130.3	4042
3C 454.3	5330	9.3	327.4	1961
CTA 102	6743	8.9	130.3	5189
NRAO 150	10844	9.7	822.4	867
0836+710	16945	9.0	164.1	4266

and the equivalent size in gravitational radii of a resolution of 50 μas in Table 1. Most of these sources are addressed by the studies presented below. A general overview of the status of this research was given at the recent conference *Dissecting the Universe: Workshop on Results from High-Resolution VLBI*, at the Max-Planck-Institut für Radioastronomie (MPIfR) in Bonn, Germany; see webpage.

2 Resolving active galactic nuclei cores

Once the technical challenges set by millimetre VLBI have been addressed, observations can look deeper into relativistic outflows going beyond the self-absorbing regime of syncrotron radiation. Images from compact objects as seen through plasma (either intrinsic at the region of the astrophysical object or in the path towards Earth) will be affected by scattering, causing their apparent size to grow proportionally to the square of the observing wavelength. For linearly polarised emission, Faraday rotation will change the polarisation angle also by a factor proportional to wavelength squared, and only observations at short wavelength will reveal the 'true' orientation of the electric field vector.

2.1 Tuning λ: Millimetre VLBI

Over the last four decades, VLBI at centimeter wavelengths has revealed important details on the nature of AGN jets (e.g., [4]). Recent progress in technology and methods has pushed observations towards shorter wavelengths. This yields a sharper view of the nuclear environment of supermassive black holes.

The Global Millimetre VLBI Array (GMVA) The GMVA[c] is an array managed by the MPIfR comprising a world-wide array of telescopes capable of operating at λ3 mm, among them, the Yebes and the Pico Veleta antennas in Spain. The array operates regularly with two sessions per year, and is providing ground-breaking results in AGN jet research. Several recent highlights show: the relationship between gamma-ray emission and magnetic field in OJ 287 [14]; imaging and magnetic field determination in the galaxy NGC 1052 [2]; detection of a jet-offset feature in Mrk 501 [22]; relationship of the gamma-ray and the millimetre morphology of PKS 1502+106 [20]; detailed study of the accretion disk region and the jet base in Cyg A [5, 6]; magnetic field orientation in 4C 39.25 [1] and S5 0716+714 by [29]; and, last but not least, striking imaging results of M 87 comparing different methods [21]. The GMVA has been defined as the network provider for λ3 mm observations together with the phased ALMA.

The Event Horizon Telescope (EHT) The EHT (see webpage and) is a collaboration to provide deep, very high angular resolution data from the environment of the central black holes in Sgr A*, M 87, and in other AGN sources, based on VLBI observations at λ1.3 mm [11]. To achieve this, an addition to the ALMA capabilities was developed, the so-called ALMA Phasing Project, aiming to sum up all ALMA antennas as a single-dish telescope, that can then be added to a global VLBI interferometer [27]. Imaging techniques such as a revised Maximum Entropy Method [8] or BSSpM (Bi-Spectrum Sparse Modeling) [15], are now being applied to these data, going beyond the commonly used CLEAN algorithm. One key aspect will be the calibration of the polarised emission, to better understand the magnetic fields at the extreme conditions close to the central black hole [17, 28]. At present, different antennas are beign outfitted world wide and fringe tests are being performed; see e.g., the report on first 230 GHz fringes with the APEX telescope on 3C 279 by [33]. The first large EHT observational campaign including phased ALMA will be performed in early 2017.

2.2 Tuning D, space-VLBI with RadioAstron

The idea of incorporating space-born antennae to VLBI networks has been developed since the 1970s. The first dedicated mission was *HALCA*, an 8-meter telescope, operating between

[c]The GMVA consists of telescopes operated by the MPIfR, IRAM, Onsala, Metsähovi, Yebes, and the VLBA. See webpage.

February 1997 and October 2003 [13]. Since 2011, the RadioAstron mission[d] conducts observations with the telescope *Spektr-R* at wavelengths of 1.3 cm, 6 cm, 18 cm, and 92 cm. Baselines can reach up to 350 000 km (28 Earth diameters), offering a corresponding increase in angular resolution, bringing, for instance, 1.3 cm space-VLBI observations to match ground-array λ1.3 mm (EHT) resolutions. The mission has achieved successful VLBI detections of extragalactic radio sources in the continuum at all four bands. Supporting ground-array observations include over 30 radio telescopes around the globe, among them the EVN[e], the VLBA[f], and the Australian Long Baseline Array[g]. Apart from individual source programs, special focus has been put in several key science programs (KSP). Data are postprocessed at the correlators in Astro Space Center in Moscow and in the MPIfR[h]. RadioAstron KSP on AGN comprise:

Nearby AGN A KSP program on nearby, bright active galactic nuclei, is addressing the targets M 87, 3C 84, Cen A, and Cyg A [30].

Powerful AGN The KSP program is addressing the sources 4C 71.07, 3C 345, and 3C 273 as primary targets. Imaging results of the source 4C 71.07 reveal filaments in the source in a complete new picture of the source [31].

Polarised emission of radio sources The KSP program is addressing the sources BL Lac, OJ 287, 3C 279, 3C 273, 3C 120, and 3C 345 as major targets. The first steps in the analysis were performed at the early-science program (ESP) prior to the KSP, to test the polarimetric performance of the mission. Imaging results of the ESP on the high-redshift quasar 0642+449 at 1.6 GHz show its complex polarised emission [26]. First results of the KSP are shown for BL Lac, reaching 21 μas resolution with ground-space fringes up to 7.9 Earth diameters [12]. These observations show details in the polarised emission suggesting a helical magnetic field, and polarised emission in two jet features.

Multi-band Brightness Temperature Study This KSP is addressing a sample of sixty compact AGN with known core shifts [23]. A survey result on the fine structure in 3C 273 yields a brightness temperature exceeding 10^{13} K (from the detection of an angular structure as small as 26 μas [24, 18]).

3 NGC 1052: a prime example of high-resolution science

NGC 1052 is a relatively strong radio source, in the road crossing between radio-loud and radio-quiet sources. Its radio morphology, with a double jet almost in the plane of the sky,

[d] The RadioAstron program is run by the Space Center of the Lebedev Physical Institute of the Russian Academy of Sciences and the Lavochkin Scientific and Production Association under a contract with the Russian Federal Space Agency, in collaboration with partner organizations in Russia and other countries.

[e] The European VLBI Network is a joint facility of independent European, African Asian, and north American radio astronomy institutes.

[f] The Very Long Baseline Array, operated by the National Radio Astronomy Observatory, a facility of the US National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

[g] The Long Baseline Array is part of the Australia Telescope National Facility which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

[h] The MPIfR DiFX correlator (see RadioAstron improvements at [7]) is jointly operated by the Max Planck Institute for Radio Astronomy (MPIfR) and the German Federal Agency for Cartography and Geodesy (BKG).

can be resolved at great detail owing to the small distance to the source, at about 18 Mpc. The source shows a gap in emission at the central region at centimetre wavelengths, caused by an absorbing torus around the central engine [32, 19].

Recently, GMVA observations have revealed its central structure, unveiling the central region where the powering black hole and the bases of the twin jet are located [2]. Values of the magnetic field in the range $10^2 - 10^5$ G were derived at event-horizon scales. Further observations are needed to test the jet-collimation region at the smallest accessible scales, to be reached with approved observations by the EHT together with phased ALMA in early 2017. This will allow us to test current theoretical models and to distinguish between a symmetric or asymmetric structure in the center, and to potentially resolve the compact region at the base of both jets.

Complementing these observations, in the framework of the RadioAstron programme, a 24-hr run on November 5, 2016, including the Australian LBA, the EVN, and the VLBA together with the phased VLA has observed the source at λ13 mm. The twin jets will most probably be resolved at scales matching the EHT, although it is possible that we cannot access to the innermost region if the free-free absorption from the torus is too strong. However, based on the experience compiled by e.g., [3] we may get a picture of the black hole environment matching the upcoming λ1.3 mm EHT observations.

4 Outlook

We enter the phase of scientific exploitation of the EHT and GMVA including phased ALMA. Concerning space-VLBI, future plans include a Russian mission at shorter wavelengths than RadioAstron, *Millimetron* with VLBI options, altough not designed directly for that. Further plans, e.g., by the Chinese space agency including two antennas in space (see report) are still under consideration. Several methodological improvements and new science are emerging. Brightness temperature estimates can now be formally addressed from visibility data with high reliability (both in mm- and space-VLBI) after a recent study [25]. Concerning data extraction, hybrid imaging may not provide the needed information due to data scarcity, and other approaches such as model fitting or ancillary imaging methods are needed. Scattering can introduce spurious compact images, which cannot be addressed by simulations [16, 18].

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