Millimeter-VLBI with ALMA and the Origin of Jet Power

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Abstract:

Very Long Baseline Interferometry (VLBI) performed at short millimeter and sub-millimeter wavelength (mm-VLBI) is a powerful observing method to study and directly image – with micro-arcsecond resolution – the very central regions in galaxies, quasars and other active galactic nuclei (AGN). With a spatial resolution ranging from a few to a few ten Schwarzschild radii, future millimeter- and sub-millimeter VLBI imaging can reach the immediate vicinity of several nearby super-massive Black Holes, such as the one in the Galactic Center (Sgr A*, 1R_S = 10 μas) and in M87 =Virgo A (1R_S = 3.7 μas). The continuing development of the VLBI technology, the upgrade of the VLBI capabilities of existing mm-telescopes (IRAM, eSMA, SMTO, CARMA), and the participation of new telescopes (APEX, ALMA) in mm-VLBI, will provide a better global uv-coverage and higher sensitivity. With this so called Event Horizon Telescope (EHT), it will be possible to image and study the effects of General Relativity in the strong gravitational field near massive Black Holes.

Why mm-VLBI ?

The angular resolution of an interferometer increases towards shorter wavelength (A ~ λ/D, D: distance between telescopes). VLBI at short mm- and sub-mm wavelength (mm- and submm- λ) therefore allows to image compact emission regions in galactic and extragalactic radio sources, which are not observable at longer (cm-) wavelength (due to opacity and self-absorption). For nearby objects, like the Galactic Center (Sgr A*, d= 8 kpc, 1 R_S = 10μas) or e.g. M87 (d = 16 Mpc, 1 R_S = 3.7μas), the spatial resolution of mm-VLBI at and above 230 GHz reaches the scale of the event horizon (Fig. 3). If performed with sufficient high sensitivity (large telescopes like ALMA needed), the direct imaging of Black Holes and their post-Newtonian emission regions surrounding them, becomes possible. For the more distant AGN-jets, the high angular resolution offered by global mm-VLBI, allows an in-detail investigation of the astro-physical processes acting at the jet base and in the region, where the jet connects to the BH/accretion disk system (Fig. 1). Monitoring the jet kinematics on scales of a few 10-100 gravitational radii will help to better understand the (GR-MHD) processes, which lead to jet formation, jet acceleration and jet collimation in AGN. Observation of the polarized sub-mm radiation will allow to measure the magnetic field (strength and topology) and help to answer the question about their role in jet formation (are jets formed by a GR-MHD dynamo ?).

VLBI above 80 GHz – Previous Work and present status:

Sensitive global VLBI observations at 3mm wavelength (86 GHz) are regularly performed under the auspices of the Global Millimeter VLBI Array (GMVA, see web-link below), which combines the VLBA, the two IRAM telescopes (PV 30m, PdBI 6 x 15m), the MPIfR 100m telescope, and the telescopes at Onsala (20m) and Metsähovi (14m). The GMVA offers imaging with an angular resolution of 40-50 μas of compact sources brighter than typically $S_{86\,GHz}$ = 200-300 mJy. Figures 4 & 5 highlight some recent results, upon which is the detection of a <15 R_S core in M87, highly non-ballistical (helical) motion in 3C345, the transition from a center to an edge-brightened sub-pc jet in 3C273, a precessing jet nozzle in NRAO150, a new 3mm VLBI survey (127 sources) and the detection of an absorber in front of the counter-jet of Cygnus A. It is clear that with the addition of ALMA, the imaging sensitivity of VLBI at 86 GHz would be dramatically improved (by a factor of ~10), allowing to study thousands of compact radio sources with an array sensitivity of ~0.3 mJy / hour and an angular resolution of ~40 μas.

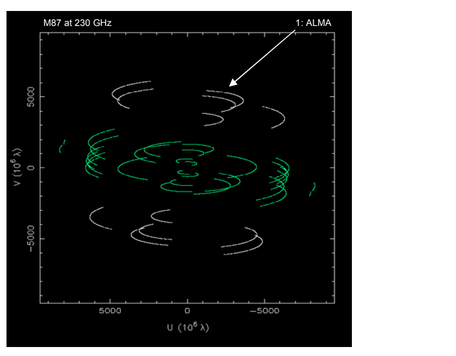
VLBI above 100 GHz offers even higher resolution, but is more challenging. The lack of a sufficiently large number of suitable mm-telescopes limited its imaging capabilities in the past. Over the last decade, the technical feasibility of VLBI at 2mm (150 GHz) and 1.3mm (230 GHz), was successfully demonstrated in several pilot experiments. This resulted in fringe detections on single baselines between Europe and the USA, and between North America and Hawaii for about a dozen of mm-bright radio sources. The transition from analog to digital VLBI data acquisition systems now allows to increase the observing bandwidth to several GHz. This leads to much improved detection sensitivities (~200 - 400 mJy) and promises more sensitive global VLBI imaging with ~15 μas resolution (at 230 GHz). Efforts are now being made to equip more telescopes for mm-/sub-mm VLBI and form a global VLBI network (Fig. 2), which is capable to directly image nearby Black Holes, their event horizon and the coupling between Black Holes and jets.

The obvious next steps are to increase the number of antennas, which can participate in mm-VLBI, phase-up the local interferometers for use as a single VLBI antenna (eSMA, CARMA, IRAM-PdBI), and add new stations (APEX, ASTE, LMT, ALMA, ...). In parallel to the ongoing efforts at 230GHz, it is also planned to push the observing frequency towards higher frequencies (345 GHz, 450GHz).

Future mm-VLBI: Antenna Specifications

Station	Location	Country	Altitude	eff. Diam.	Surface	Status	VLBI-ready
			[m]	[m]	mikron		
IRAM-interferometer	Plateau de Bure	France	2550	37	55	functional	yes
CARMA	Cedar Flat	CA,USA	2200	31	60	functional	yes
IRAM-30m	Pico Veleta	Spain	2900	30	67	functional	yes
SMA/JCMT/CSO (eSMA)	Mauna Kea	Hawaii, USA	4100	25	12	functional	yes
HHSMT	Mt. Graham	AZ, USA	3100	10	15	functional	yes
APEX	Chajnantor	Chile	5100	12	18	functional	in preparation
ASTE	Chajnantor	Chile	4860	10	20	functional	planned
ALMA	Chajnantor	Chile	5000	85	25	under construction	planned
possible other antennas:							
LMT	Sierra Negra	Mexico	4600	50	70	under construction	planned
SEST	La Silla	Chile	2300	15	70	decommissioned	no
KP-12m	Kitt Peak	AZ, USA	2000	12	75	functional	no
SPT	South Pole	Antarctica	2830	10	20	planned	-
CCAT	Chajnantor	Chile	5600	25	10	proposed	-

Properties of existing and future telescopes, which could participate in mm-VLBI at and above 230 GHz. To be able to image the Black Hole shadow / event horizon, participation of large and sensitive telescopes, like the phased ALMA array will be necessary. This allows to reach mJy-sensitivity and μas-scale resolution.



The uv-coverage for a mm-VLBI experiment on M87 at 230 GHz with the following stations: IRAM-30m, IRAM-interferometer, HHSMT, eSMA (SMA + JCMT + CSO), CARMA, LMT and one station in Chile (APEX/ASTE first, ALMA after 2012).

Motivation:

What are the physical proccesses acting at the centers of Quasars and in other Active Galactic Nuclei ? One needs to directly image the regions near the central Black Hole and study how the powerful radio-jets are launched and accelerated.

mm- and sub-mm VLBI with ALMA offers micro-arcsecond scale resolution and will help to answer the following questions:

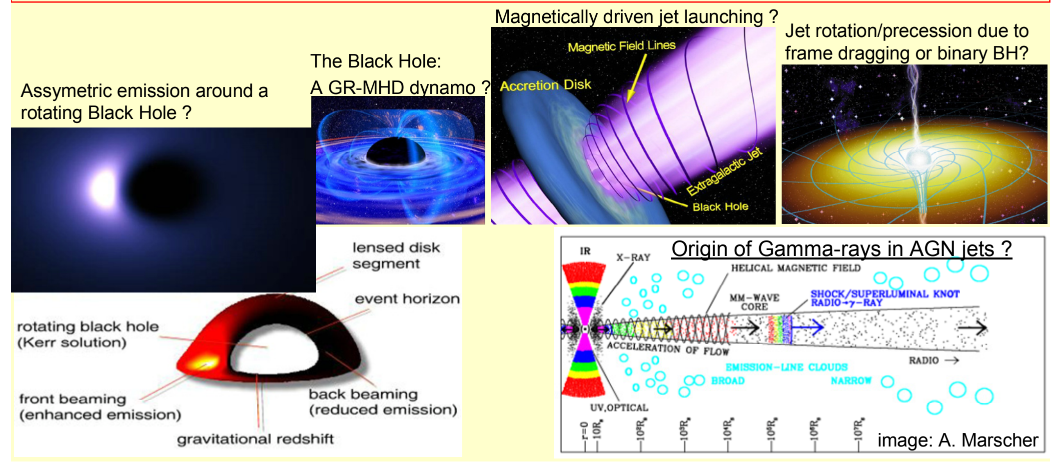
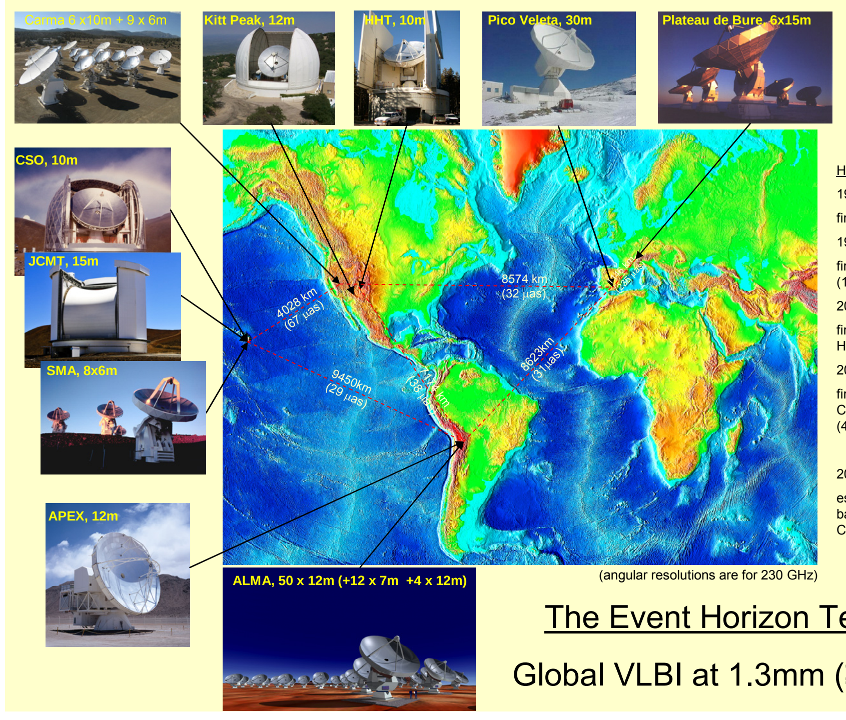


Figure 1

Present and future millimeter VLBI



The Event Horizon Telescope:

Global VLBI at 1.3mm (≥ 230 GHz)

Figure 2

Angular and Spatial Resolution of mm-VLBI

λ	ν	θ	z=1	z=0.01	d= 8 kpc
3 mm	86 GHz	45 μas	0.36 pc	9.1 mpc	1.75 μpc
2 mm	150 GHz	26 μas	0.21 pc	5.3 mpc	1.01 μpc
1.3 mm	230 GHz	17 μas	0.14 pc	3.4 mpc	0.66 μpc
0.87mm	345 GHz	11 μas	0.09 pc	2.2 mpc	0.43 μpc
linear size:			~10^3 R_s^9	20-100 R_s^9	1-5 R_s^6

for nearby sources, these scales correspond to 1 – 100 Schwarzschild radii, depending on distance and black hole mass !

→ mm-VLBI can directly image (!) the vicinity of SMBHs (Event Horizon, BH-Shadow, GR-theory) !

→ best candidates: Sgr A* (10 μas = 1 R_s^6) and M 87 (Cen A is far south, M81 & NGC4258 are weak)

→ The high sensitivity of ALMA is needed to map the emission around Black Holes in AGN.

Figure 3

How is the Jet in M87 created ?

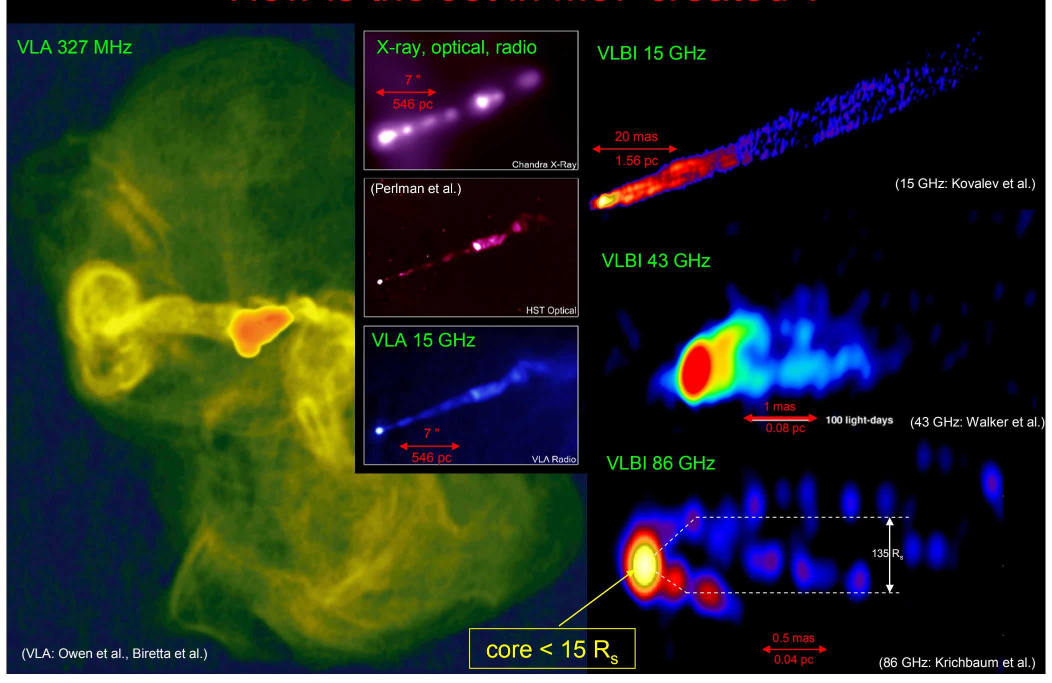


Figure 4

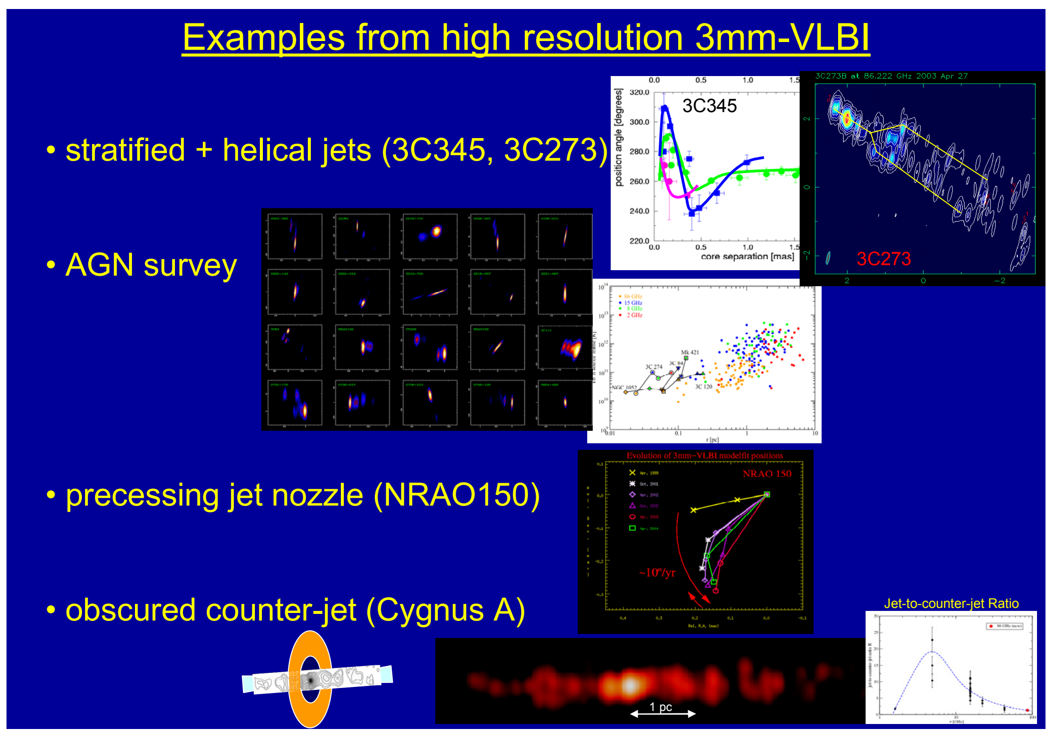


Figure 5

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GMVA Web Link: http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm (Global 3mm VLBI, including recent literature) :

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