Studying the Innermost Jet of M 87 with mm-VLBI Observations

© J.-Y. Kim[1], T. P. Krichbaum[1], Ru-Sen Lu[1], M. Bremer[2], J. A. Zensus[1], R. C. Walker [3], the M87 collaboration

[1]Max Planck Institut für Radioastronomie, Bonn, Germany
[2]Institut de Radio Astronomie Millimétrique, Saint Martin d'Héres 38406, France
[3]National Radio Astronomy Observatory, Socorro, USA

M87 is one of the nearest AGN with a pronounced jet and hosting a central supermassive black hole (SMBH). The close distance to the source and the large mass of the central SMBH make M87 an ideal target to investigate various aspects on the formation and evolution of relativistic jets on the smallest spatial scale. Here, we present preliminary results from our ongoing study on M87 based on global VLBI observations at 86 GHz. GMVA observations in May 2015 resulted in a new image showing a complex jet morphology on sub-mas scales. Stacking available VLBI images obtained at different epochs reveals a persistent shape of the jet base. This allows us to trace the jet collimation from $100R_{\rm sch}$ down to $\sim 50R_{\rm sch}$.

Keywords: Galaxies: active — Galaxies: individual (M87) — Galaxies: jets — Techniques: interferometric.

1 Introduction

M 87 (1228+126, 3C 274, Virgo A) is a giant elliptical galaxy located near the center of the Virgo cluster. The object is famous for its relativistic jet, which extends to kpc scales. In the radio bands and with very long baseline interferometry (VLBI) the jet can be traced to its origin, down to sub-pc scales.

M87 is one of the closest extragalactic jet systems being located at the distance of 16.4 Mpc [1]. The central SMBH mass $M_{\rm BH}$ estimated by stellar dynamics is very large, $6.6 \times 10^9 M_\odot$ [2], although gas-dynamical models suggest roughly a factor of two smaller mass [3]. The combination of the large black hole mass and the distance results in an exceedingly high *spatial* resolution: 1 milli-arcsecond (mas) $= 128R_{\rm sch}$ where $R_{\rm sch}$ is the Schwarzschild radius. This implies that M87, along with the compact radio source Sgr A* at the center of our Galaxy, provides the best opportunity to study physical conditions event-horizon-scales in active galaxies.

In particular, global VLBI observations at 86 GHz (GMVA; [4]) can achieve a superb angular resolution of $\sim 50\mu$as, which at the distance of M87 corresponds to a spatial scale of only $\sim 6R_{\rm sch}$. Such a high spatial resolution allows us to spatially resolve the jet launching region and study the jet properties and the jet formation very close to its origin. The GMVA observations also support other ongoing VLBI studies of M87 such as the Event Horizon Telescope project (EHT; [5]) by providing a link between complex radio emission geometry in the vicinity of the black hole probed by EHT (at $< 6R_{\rm sch}$) and the plasma flow extending over larger scale at $> 6R_{\rm sch}$. In this article we present a new 86 GHz VLBI image from GMVA observations in May 2015, which is combined with earlier maps. From this we derive and discuss the jet collimation profile.

2 Observations and Data Reduction

For this study we analyze four GMVA data sets from observations of M87 performed in 2004, 2005, 2009 and 2015. From the VLBA data archive, we also add a VLBA+GBT data set at 86 GHz from 2014 [6]. As for the details of the observations and data reduction, we refer to [7] where additional information on the observing details, such as observing dates and participating stations and frequency setup is provided. Special issues related to calibration and imaging will be described elsewhere.

3 Collimation of the jet base

First we present the high resolution images of the M87 jet base. Fig. 1 shows the image of our latest observation (May 2015) with two different resolutions. The array includes mm-VLBI stations including the IRAM 30 m, the phased PdB interferometer (with 5 antennas), and the 100 m Green Bank Telescope, and achieved an off-source rms noise level of 0.16 mJy/beam with a full-track (u,v) coverage. Thanks to the low noise level we now see a variety of features in the image. The jet is basically limb-brightened until the edges come close to each other near the core. Weak emission from the counter jet is also visible, although the counter-jet appears much fainter (a few mJy) than the main jet. In addition, we see evidence for some central emission located about half way between the northern and southern limb. This emission becomes clear beyond ~ 0.4 mas from the core (e. g. see Fig. 2, left panel). The fine-scale structures such as the location of the brightest blobs also change a lot with time. The sparse time sampling of the available 86 GHz maps, however, prevents us from a proper tracking of the moving features. The source images from the other epochs can be found from [7]. We also note that the low source declination ($\sim 12°$) and lack of VLBI stations at southern latitudes make the observing beam roughly 4 times more elongated in the N–S direction. It is difficult to transversely resolve the jet structure at the region right near the core because the flow is extended in the E–W direction. The situation can be dramatically improved when powerful mm-VLBI stations located in the southern hemisphere such as phased ALMA [8] will be included in the array.

An important aspect of the high-fidelity imaging of a transversely resolved jet is the possibility to determine the shape of the jet near its origin. We therefore

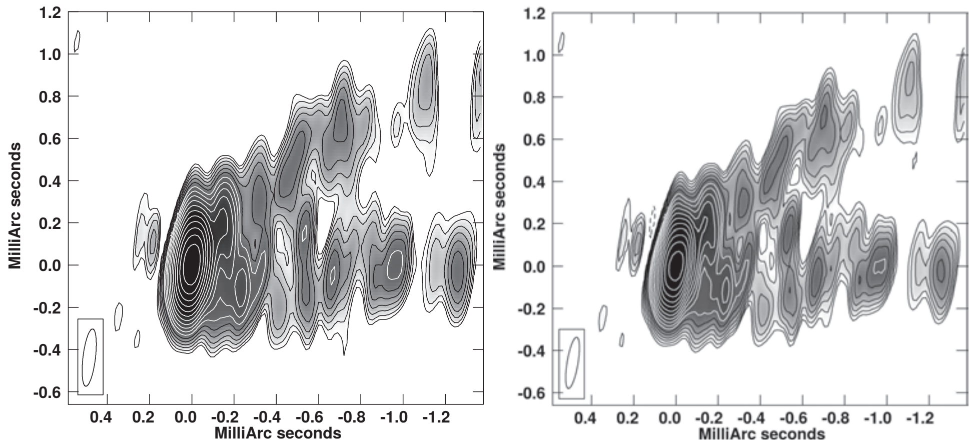

Fig. 1. The images of M87 jet base obtained by GMVA observations performed in 2015 May 16. The contour levels are $(-1$, 1, 1.4, 2, 2.8, ...$)\times 1$ mJy/beam. The observing beam is indicated at the left bottom corner of each panel. The beam sizes in the left/right panels are from natural/uniform weighting, respectively

stacked the 3 mm VLBI images. For the stacking we use the observations from 2004, 2005, 2009, 2014, and 2015. Details of the stacking process are described in [6]. After stacking we sliced the jet cross-section at the distance z from the core and fitted two Gaussians to measure the separation of the northern and southern limb. After the measurement was done, the jet width $W(z)$ was fitted by a power law z^k where the k is a dimensionless power-law index. From the measured jet diameter we also calculated the apparent jet opening angle as a function of the projected distance. To represent the true distance scale we de-projected the angular distance on the sky by using the jet viewing angle $\theta = 18^\circ$ estimated by [9]. The derived collimation profile is shown in Fig. 2. The jet shape is well described by a single power-law. The fitting result remains relatively stable against changes of the convolving beam and repeated tests for the same distance range. We note that the power law index $k = 0.523 \pm 0.010$ derived from our analysis is slightly smaller than the one derived by [10] and [6]. A more detailed analysis for the individual epochs is in progress and will be presented in the next papers.

4 Summary and Future Works

In this article we presented a new image of the innermost jet of M87 from our Global 3 mm VLBI observations and preliminary results from our analysis. The new 2015 epoch image shows many features including a complex limb-brightened structure, evidence for faint central emission, and the weak counter jet. By stacking the images from all epochs, we were able to obtain a rather persistent jet collimation profile of the innermost region. We find an efficient jet collimation with significant variations of the jet opening angle on 0.1–1 mas scales, which is in agreement with the previous finding by [6], but several details are in contrast to other literature

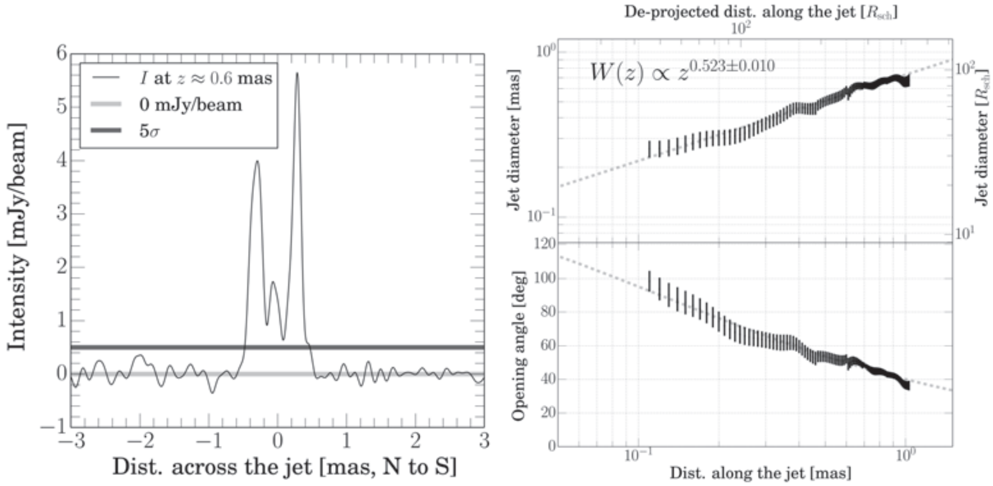

Fig. 2. *Left* : A slice intensity profile of the jet cross-section at ~ 0.6 mas from the core, obtained by using the stacked image in [6]. The measured intensity is shown as the thin black line and the zero level and off-source rms noises are indicated by the thick grey lines. *Right* : The collimation profile of the M87 jet base obtained by the Gaussian fitting to the stacked 3 mm VLBI map. The points with error bars are from the measurements and the dashed grey lines are the fitting lines to the data

such as [10] and [6]. Deeper analysis focused on various aspects of the physical conditions of the innermost jet of M87 will be presented in other publications.

References

1. *Bird S., Harris W. E., Blakeslee J. P., et al.* The inner halo of M 87: a first direct view of the red-giant population // Astron. Astrophys. — 2010. — Vol. 524. — P. 71–79.
2. *Gebhardt K., Adams J., Richstone D., et al.* The Black Hole Mass in M87 from Gemini/NIFS Adaptive Optics Observations // Astrophys. J. — 2011. — Vol. 729. — P. 119–131.
3. *Walsh J. L., Barth A. J., Ho L. C., et al.* The M87 Black Hole Mass from Gas-dynamical Models of Space Telescope Imaging Spectrograph Observations // Astrophys. J. — 2013. — Vol. 770. — P. 86–96.
4. *Krichbaum T. P., Roy A., Lu R.-S., et al.* Millimeter VLBI observations: Black Hole Physics and the Origin of Jets // PoS(EVN 2014). — 2014. — No. 013.
5. *Doeleman S. S., Fish V. L., Schenck D. E., et al.* Jet-Launching Structure Resolved Near the Supermassive Black Hole in M87 // Science — 2012. — Vol. 338. — P. 355–358.
6. *Hada K., Kino M., Doi A., et al.* High-sensitivity 86 GHz (3.5 mm) VLBI Observations of M87: Deep Imaging of the Jet Base at a Resolution of 10 Schwarzschild Radii. // Astrophys. J. — 2016. — Vol. 817. — P. 131–147.

7. *Kim J. -Y., Lu R.-S., Krichbaum T. P., et al.* Resolving the base of the relativistic jet in M87 at $6R_{\mathrm{sch}}$ resolution with global mm-VLBI // Galaxies — 2016. — Vol. 4. — P. 39–46.
8. *Fish V., Alef W., Anderson J., et al.* High-Angular-Resolution and High-Sensitivity Science Enabled by Beamformed ALMA // astro-ph. — 2013. — arXiv:1309.3519.
9. *Mertens F., Lobanov A. P., Walker .R. C., et al.* Kinematics of the jet in M87 on scales of 100–1000 Schwarzschild radii // Astro. & Astrophys. — 2016. — Vol. 595. — P. 54–73.
10. *Asada K., Nakamura M.* The Structure of the M87 Jet: A Transition from Parabolic to Conical Streamlines // Astrophys. J. Lett. — 2012. — Vol. 745. — P. 28–32.