galaxies

MDPI

Article

The Structure and Propagation of the Misaligned Jet M87

Kazuhiro Hada

Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, 2-21-1, Osawa, Mitaka, Tokyo 181-8588, Japan; kazuhiro.hada@nao.ac.jp

Academic Editors: Jose L. Gómez, Alan P. Marscher and Svetlana G. Jorstad
Received: 18 July 2016; Accepted: 14 December 2016; Published: 26 December 2016

Abstract: Due to its proximity, M87 is a prime target for next-generation high-resolution VLBI at short millimeter wavelengths, by which the jet launching region and the black hole shadow are expected to be resolved and imaged sometime soon. Along with this situation, high-quality VLBI imaging and monitoring at lower frequencies play an important role in complementing the high-frequency data. Here, we present our recent and ongoing observational studies of the M87 jet on pc-to-subpc scales based on ultra-deep VLBI imaging programs at 86 GHz and 15 GHz. The high-dynamic-range images have allowed us to obtain some remarkably improved views on this jet. We also introduce the KVN and VERA Array (KaVA), a new regularly-operating VLBI network in East Asia, which is quite suitable for studying the structure and propagation of relativistic jets. Some early results from our pilot study for M87—including the detection of superluminal motions near the jet base—implying an efficient magnetic-to-kinetic conversion at these scales, are reported.

Keywords: galaxies: active; galaxies: individual (M87); galaxies: jets; radio continuum: galaxies

---

1. Introduction

It has been nearly 100 years since the first extragalactic jet was discovered in the nearby elliptical galaxy M87. Since then, tremendous efforts have been made both observationally and theoretically to understand the physics of relativistic jets in active galactic nuclei (AGN). In particular, high-resolution VLBI observations are unique in that they can directly probe the innermost active regions, playing a major role in constraining the structure and propagation of the relativistic jets (e.g., [1]).

The jet of M87 is privileged because one can resolve the jet formation scales near the central engine thanks to its proximity (∼16 Mpc) and the large mass of the central black hole (∼$6 \times 10^9\ M_\odot$ Note that gas-dynamical estimates of the black hole mass in M87 are a factor of 2 smaller (e.g., [2])) [3]. The recent advent of the Event Horizon Telescope (EHT) has allowed observational studies of this jet on a scale of several Schwarzschild radii (R_s) [4,5]. The EHT is quite promising to image the shadow of the central black hole and the jet launching within the inner part of the accretion disk. This may allow us to determine whether the jet is ultimately launched from the black hole (Blandford–Znajek process; [6]) or from the accretion disk (Blandford–Payne process; [7]). Moreover, the effect of gravitational lensing can enhance the brightness of the counter-jet near the black hole, which might further enable us to constrain the mass loading radius of the jet [8,9]. Along with this situation, the traditional lower-frequency VLBI also gains in importance. While the EHT can image the jet base of M87 on horizon scales, the steep spectral nature of the nonthermal emission as well as the rapid cooling time scales prevents us from imaging the downstream flow at such high frequencies. Since the magnetically-dominated jet paradigm, currently the most favored scenario in jet formation, is a gradual process requiring several orders of magnitude in distance to fully convert the magnetic energy into the kinetic one, it is necessary to follow up the subsequent flow evolution at lower frequencies. Indeed, recent VLBI studies of M87 at centimeter wavelengths have revealed a parabola-shape collimation profile over a wide range of distance from ∼100 to ∼100,000 R_s, providing a telling clue to the magnetic processes [10–12]. In addition, cm-VLBI offers high-cadence monitoring programs. The M87 jet has intensively been monitored by many VLBI programs over the past years, pinpointing the sites of active gamma-ray flares (e.g., [13–17]) as well as measuring the jet motions (e.g., [18–21]). Such excellent capabilities of imaging and monitoring of the low-frequency VLBI can be further improved by the recent rapid improvement of data recording rate. Here, we overview our recent and ongoing VLBI observations of the pc-to-subpc regions of the M87 jet, which are yielding fresh insights into the structure of this jet. In Section 2, we recapitulate our recent study with the high-sensitivity array at 86 GHz. In Section 3, we present a fresh result obtained from our new high-dynamic range imaging at 15 GHz. In Section 4, we introduce our new monitoring project of this jet with the KVN and VERA Array.

2. Jet Base Imaging at 86 GHz with HSA

As represented by recent successful progress of the Global-Millimeter-VLBI-Array (GMVA), VLBI at 86 GHz is an important transition between EHT and cm-VLBI. For M87, EHT probes the jet within 10 R_s from the black hole, while VLBI at 43 GHz and lower frequencies routinely images the jet beyond 100 R_s. Consequently, the scales between ∼10 and ∼100 R_s from the black hole are the target for 86 GHz VLBI, but previous VLBA or GMVA observations were not enough to produce detailed jet images on these scales because of the limited sensitivity and image quality [22,23].

To improve our knowledge of the M87 jet on these scales, in February 2014 we performed new high-sensitivity 86 GHz VLBA observations at 2 Gbps in conjunction with the Green Bank Telescope (GBT) [24]. Thanks to the significant improvement of the overall array sensitivity, we obtained a high-quality jet image down to a scale of 10 R_s. The resulting image dynamic range is greater than 1500 to 1, the highest ever obtained for this source at 86 GHz. The new 86 GHz image clearly confirmed some important features known at lower frequencies, i.e., a wide opening angle jet base, a limb-brightened intensity profile, a parabolic collimation profile and a counter jet. The limb-brightened structure is continuously seen at least down to 0.2 mas (<28 R_s, projected) from the core, where the apparent opening angle becomes as wide as ∼100°, much broader than the famous value of 60° known at 43 GHz [25,26].

While the jet is largely parabolic, the detailed jet shape within 100 R_s is actually more complicated. A possible structural change of the jet near the black hole was first suggested in our previous multi-frequency analysis of the VLBI core [11]. In the new 86 GHz image, we found a constricted structure at ∼35 R_s (projected) from the core, where the jet cross-section is locally shrinking. This suggests that an external pressure contribution from the inner part of accretion flow (presumably an ADAF-type hot accretion flow or associated corona) may be dynamically important in confining the jet on this scale (see [24] for more detailed discussion).

Additionally, we obtained the first VLBI 86 GHz polarimetric result for this jet. While it is still challenging to reveal the whole polarimetric structure, we detected some polarized features near the jet base. The detection of the polarization signals at 86 GHz implies that the magnitude of the Faraday rotation measure (RM) toward the jet base is no larger than ∼(5–10) × 10^4 rad cm^{-2}, consistent with the result reported in the recent SMA 230 GHz polarimetric study [27]. Moreover, one of the polarized features has a fractional polarization up to ∼20%, the highest value ever seen on pc-to-subpc scales of this jet. This indicates the presence of a well-ordered magnetic field in the formation and collimation zone of the M87 jet.

3. Parsec-Scale Structure of the M87 Jet with the VLBA at 15 GHz

As confirmed in our 86 GHz images, the strongly limb-brightened intensity profile is one of the most notable characteristics of the M87 jet (Figure 1). In order to explain such a limb-brightening profile (assuming that the emissivity across the jet is uniform in the rest frame), a commonly invoked scenario is the spine–sheath structure, in which the jet has a velocity gradient across the jet such that the flow becomes faster toward the jet's central axis [28]. In the context of the spine–sheath paradigm, however, the limb-brightening of M87 may be puzzling. While the viewing angle of this jet is still controversial, the 6 c superluminal motions observed at HST-1 prefer a relatively small viewing angle of $\theta < 19^\circ$. For such θ, the faster flow tends to be more Doppler-boosted to us. This may result in $\delta_{\rm spine} > \delta_{\rm sheath}$ (where $\delta_{\rm spine}$ and $\delta_{\rm sheath}$ are the Doppler factor of spine/sheath), indicating that the jet would become ridge-brightened. Therefore, the following question naturally arises: why do we not see any pronounced spine component in this jet?

In order to tackle this question, in December 2015, we made a new full-track, 2 Gbps VLBA observation of M87 at 15 GHz in concert with the phased-VLA. The aim of this observation is to reveal an unprecedented view of the (sub)pc-scale structure of this jet by obtaining an ultra-deep image. To this end, the frequency of 15 GHz is an optimal choice since we can achieve a great sensitivity at a sub-mas angular resolution.

In Figure 2a, we show a clean map of M87 obtained from this observation. Thanks to the excellent quality of the dataset, we successfully produced a very high-quality image. For a naturally-weighted image, we obtained an off-center rms noise level of $\sim$33 µJy beam^{-1}. This is roughly two times better than that of the previous high quality 15 GHz map [18].

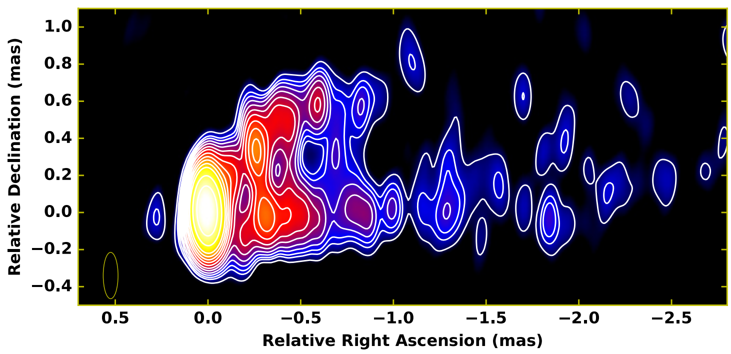

Figure 1. VLBA+GBT 86 GHz image of M87 jet [24].

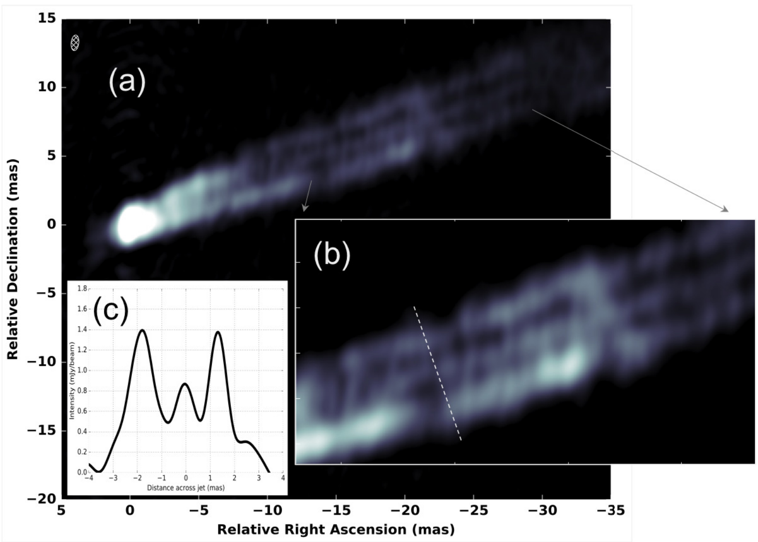

Figure 2. (**a**) VLBA+Y27 15 GHz image of the M87 jet observed in December 2015. This image is produced with a natural weighting scheme. The beam size is 1.14 × 0.55 mas (shown in the upper left corner); (**b**) Zoom-up view of the parsec-scale region of the jet; (**c**) Slice of the total intensity at a distance of 15 mas from the core (shown by the dashed line in the panel (**b**)).

The most remarkable finding from this image is that we detected a persistent triple-ridge structure very clearly. In addition to the well-known northern/southern bright limbs, there is another ridge in the central stream of the jet. Figure 2b is a close-up view the jet between 10 and 30 mas and Figure 2c is a slice across the jet at a radial distance of 15 mas from the core. While the triple profile can also be seen closer to the core, the relative brightness of the central ridge to the outer limbs seems to become more prominent at >10 mas (>0.8 pc projected) from the core. The width of the central ridge is remarkably narrow: typically, it is a factor of 8 narrower than the total jet width, and also a factor of ∼2 narrower than the individual widths of the northern/southern limbs. Moreover, the width of the central ridge is not constant along the jet but gradually increasing similarly to the total jet width. A tentative measurement of the collimation profile of the central ridge results in $r \propto z^{0.5}$, implying a slightly stronger collimation efficiency than that of the total width ($r \propto z^{0.56}$; [10,11]), although a more detailed treatment is required to make a definitive statement.

Some scenarios could possibly explain the origin of the central ridge. If the jet is multi-layered, one possibility is that the central ridge is a part of the outer sheath associated with the same layer of the northern/southern limbs. The near side of the sheath with a slightly smaller effective viewing angle might produce some boosted emission between the northern and southern limbs. However, this scenario would not easily reproduce the observed ultra-narrow width and the possible stronger collimation of the central ridge. Alternatively, the more likely scenario would be that the central ridge is intrinsically different from the outer sheath, and associated with a true spine component in the interior of the jet. If there is a sharp gradient in speed between the inner spine and the outer sheath, the boundary between them may become a natural site of efficient particle acceleration. This results in the production of enhanced emission at the surface of the spine, which may potentially reproduce a triple structure as seen in our image. To better understand the nature of the central component, it will be very important to examine its spectral and kinematic properties, and their differences from those of the sheath.

Finally, we briefly comment on the counter jet. Our new 15 GHz image indeed detected the emission from the counter jet, extending a few mas toward the east from the core. Interestingly, the extension of the detected counter jet was mostly the same as that seen in the previous 15 GHz map [18], despite a factor of 2 better image quality of our map. This indicates that the brightness of the counter jet is sharply decreasing with distance, suggesting the presence of bulk flow acceleration on this scale.

4. Sub-pc Jet Monitor of M87 with KaVA

While significant progress has recently been made in constraining the collimation properties of the M87 jet, the debate about the kinematic properties of this jet is still very lively despite a number of studies over the past years. Regarding the kpc scales, the proper motions are relatively well defined thanks to detailed optical studies [29,30]. The jet at these scales is mostly superluminal from ∼6 c at ∼100 pc (HST-1) to ∼1 c at >1000 pc (Knot C), showing a global deceleration trend from HST-1 outward.

In contrast, the kinematics at pc–to–sub scales is quite elusive, and a variety of speeds were reported from various VLBI monitoring programs (e.g., [14,18,19,24,26]). The diversity of the results could reflect the presence of multiple velocity components in the jet, such that one is associated with a pattern speed and another traces a bulk flow. On the other hand, such a scattering of the observed speeds can also be caused if the sampling interval is sparse. To date, the most detailed program was performed by Walker et al. in 2007–2008 with VLBA at 43 GHz [19,31], where they monitored M87 every 3 weeks (January–August 2007) or ∼5 days (January–April 2008). They found fast (superluminal) motions that might be missed in the other monitoring programs. Unfortunately, their massive program is triggered only occasionally along with TeV events. Since M87 is the only jet where the magnetic acceleration scales are directly accessible, it would be of great value to make a similar but more continuous, and independent monitoring program.

4.1. Brief Summary of KaVA

The KVN and VERA Array (KaVA) is the first international VLBI network in East Asia, consisting of three 21 m dishes in Korea (KVN) and four 20 m dishes in Japan (VERA) (Figure 3). Since 2010, we have been making efforts to combine the two arrays under a collaboration between KASI and NAOJ. The aim of this project is to form a single better performance array by complementing each other. Indeed, the increases of the number of baselines (from 3/6 for KVN/VERA to 21 for KaVA) and the baseline coverage (from 300–400 km/1000–2300 km for KVN/VERA to 300–2300 km for KaVA) significantly improve the overall array sensitivity and the imaging performance [32]. All the data observed by KaVA are correlated at the Korea–Japan Joint VLBI Correlator installed at KASI.

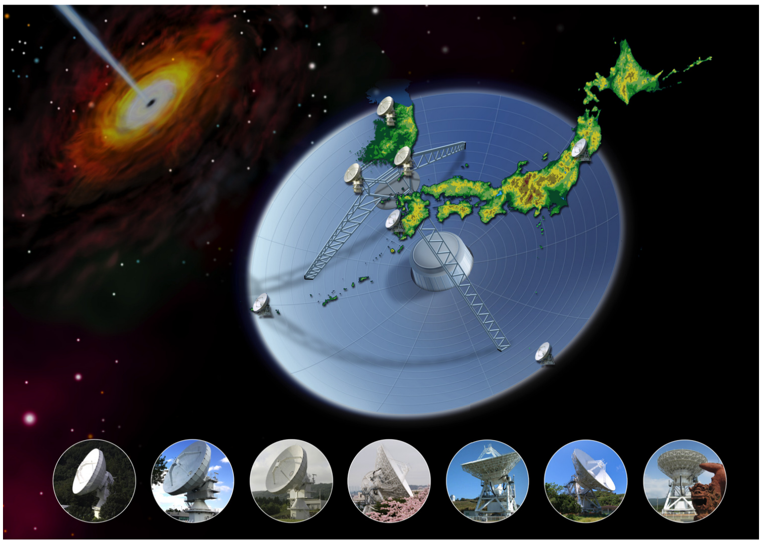

Figure 3. The KVN and VERA Array. From the left corner, the pictures of telescopes are Yonsei, Ulsan, Tamna, Mizusawa, Iriki, Ogasawara, and Ishigaki, respectively.

Completing a few-year commissioning phase, regular scientific operations of KaVA started from the beginning of 2014. The common frequency bands of 22 GHz and 43 GHz are available, and the typical angular resolutions are 1.2 mas and 0.6 mas, respectively. A recording rate of 1 Gbps is currently offered. A nice capability of this array is that KaVA operates for a quasi-full year, except for the annual maintenance period between mid June and July. Also, the well-organized scheduling scheme allows a frequent multi-epoch program. Therefore, KaVA is quite suitable for studying detailed kinematics and structural evolutions of relativistic jets.

4.2. Pilot Study of M87 Monitor with KaVA

We made a KaVA pilot monitoring program of the M87 jet from December 2013 to June 2014. During this period, M87 was monitored at 22 GHz at a typical interval of 2 weeks, obtaining the data for a total of 13 epochs. The imaging performance of KaVA was overall good and the jet emission of M87 was recovered down to 10 mas at sufficient SNR , and the lower level emission was detected another ∼10 mas outward. The off-center image rms noise level was generally below 0.5 mJy beam^{-1}.

In Figure 4, we show an example of multi-epoch images of M87 obtained by this program. It is evident that the jet structure on (sub-)pc scales is variable on time scales of weeks to months, indicating the existence of fast motions. A notable structural change can be seen at a projected distance of ∼1 pc (or 1800 R_s) from the core, where the jet shows a relatively well-defined "head" due to the sharp brightness decrease outward. We found that this feature was moving superluminally (∼1.1 c). The more quantitative treatment of the jet motions is currently being worked on, and our preliminary analysis is further suggesting an acceleration signature with distance.

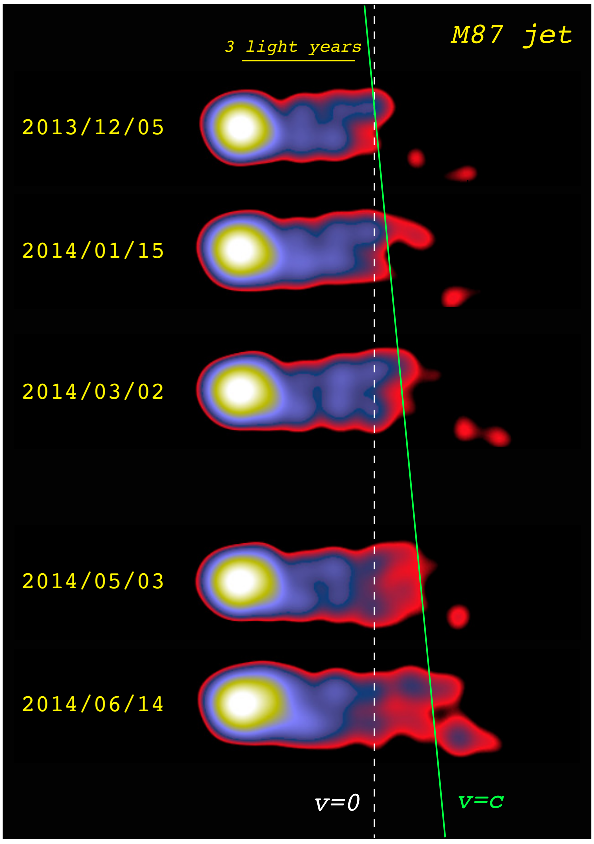

Figure 4. Multi-epoch KaVA 22 GHz images of the M87 jet. All the images are convolved with a 1 mas circular beam. The green straight line corresponds to a constant velocity at the speed of light.

The detection of the superluminal motions and the possible acceleration with KaVA are quite important. While there was only one VLBA program reporting superluminal motions near the jet base [14,19], our results provide an independent confirmation of the presence of such fast motions at the same scale. This indicates that the M87 jet is already well accelerated (the intrinsic speed faster than 0.8 c) at this scale, and may consistently explain why the counter jet of M87 is so weak.

The global acceleration profile beyond the jet base to HST-1 is still a matter of debate. A transition from subluminal to superluminal motions at a large distance (>100 mas) has been reported by a yearly EVN monitor program [21]. They suggest that efficient magnetic acceleration occurs from >100 mas of the jet. The presence of superluminal motions near the jet base is in contrast to that picture, implying that an efficient magnetic-to-kinetic conversion takes place rather near the jet base. A quite similar acceleration profile has also been reported by Mertens et al. based on VLBA 43 GHz data [31].

5. Summary

We have overviewed our recent and ongoing high-quality VLBI observations at 86 GHz and lower frequencies. The 86 GHz image with VLBA+GBT revealed a detailed jet-base structure at a resolution of 10 R_s. The capability of the 86 GHz VLBI network is currently rapidly expanding, and the forthcoming addition of ALMA to GMVA will dramatically improve the array performance at this frequency, and will provide us an unprecedented image of the jet launching, the surrounding accretion flow and the associated magnetic field structures.

The new 15 GHz observation revisits the (sub)pc-scale structure of the M87 jet. The ultra-deep image has started to unveil a persistent central ridge structure in addition to the well-known limb-brightening profile. The central ridge may represent the spine flow in the interior of the jet. Measurements of the kinematics and the spectral properties are essential to better understand the nature of this component.

We finally presented our new biweekly monitoring program of M87 with KaVA at 22 GHz. The program is actively ongoing, but the early observations already yield some interesting results, such as the detection of superluminal motions near the jet base. This nicely demonstrates that KaVA is indeed a powerful VLBI array for studying motions and structural changes of relativistic jets. From this year, we have upgraded the M87 program. We are monitoring M87 both at 22 and 43 GHz quasi-simultaneously. This will allow us to track jet motions over the wider range of distance. Also, the dual-frequency multi-epoch data will enable us to derive a set of accurate spectral index maps and their detailed evolution with time. All of these programs are quite complementary and also will have a synergy by collaborating with EHT.

Acknowledgments: The author acknowledges all of the collaborators relevant to each project. The VERA is a facility operated by National Astronomical Observatory of Japan in collaboration with Japanese universities. The KVN is a facility operated by the Korea Astronomy and Space Science Institute. The Very Long Baseline Array, the Very Large Array and the Green Bank Telescope are operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc. The European VLBI Network is a joint facility of independent European, African, Asian, and North American radio astronomy institutes. This work was partially supported by KAKENHI (26800109). Part of this work was done with the contribution of the Italian Ministry of Foreign Affairs and University and Research for the collaboration project between Italy and Japan.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lister, M.L.; Cohen, M.H.; Homan, D.C.; Kadler, M.; Kellermann, K.I.; Kovalev, Y.Y.; Ros, E.; Savolainen, T.; Zensus, J.A. Mojave: Monitoring of jets in active galactic nuclei with vlba experiments. VI. Kinematics analysis of a complete sample of blazar jets. *Astrophys. J.* **2009**, *138*, 1874–1892.
2. Walsh, J.L.; Barth, A.J.; Ho, L.C.; Sarzi, M. The M87 black hole mass from gas-dynamical models of space telescope imaging spectrograph observations. *Astrophys. J.* **2013**, *770*, 86–96.
3. Hada, K.; Doi, A.; Kino, M.; Nagai, H.; Hagiwara, Y.; Kawaguchi, N. An origin of the radio jet in M87 at the location of the central black hole. *Nature* **2011**, *477*, 185–187.
4. Doeleman, S.S.; Fish, V.L.; Schenck, D.E.; Beaudoin, C.; Blundell, R.; Bower, G.C.; Broderick, A.E.; Chamberlin, R.; Freund, R.; Friberg, P.; et al. Jet-Launching structure resolved near the supermassive black hole in M87. *Science* **2012**, *338*, 355–358.
5. Akiyama, K.; Lu, R.-S.; Fish, V.L.; Doeleman, S.S.; Broderick, A.E.; Dexter, J.; Hada, K.; Kino, M.; Nagai, H.; Honma, M.; et al. 230 GHz VLBI observations of M87: Event-horizon-scale structure during an enhanced very-high-energy γ-ray state in 2012. *Astrophys. J.* **2015**, *807*, 150–160.
6. Blandford, R.D.; Znajek, R.L. Electromagnetic extraction of energy from Kerr black holes. *Mon. Not. R. Astron. Soc.* **1977**, *179*, 433–456.
7. Blandford, R.D.; Payne, D.G. Hydromagnetic flows from accretion discs and the production of radio jets. *Mon. Not. R. Astron. Soc.* **1982**, *199*, 883–903.
8. Dexter, J.; McKinney, J.C.; Agol, E. The size of the jet launching region in M87. *Mon. Not. R. Astron. Soc.* **2012**, *421*, 1517–1528.
9. Mościbrodzka, M.; Falcke, H.; Shiokawa, H. General relativistic magnetohydrodynamical simulations of the jet in M87. *Astron. Astrophys.* **2016**, *586*, A38.
10. Asada, K.; Nakamura, M. The structure of the M87 jet: A transition from parabolic to conical streamlines. *Astrophys. J.* **2012**, *745*, L28–L32.
11. Hada, K.; Kino, M.; Doi, A.; Nagai, H.; Honma, M.; Hagiwara, Y.; Giroletti, M.; Giovannini, G.; Kawaguchi, N. The innermost collimation structure of the M87 jet down to $\sim$10 Schwarzschild radii. *Astrophys. J.* **2013**, *775*, 70–76.
12. Nakamura, M.; Asada, K. The Parabolic Jet Structure in M87 as a Magnetohydrodynamic Nozzle. *Astrophys. J.* **2013**, *775*, 118–128.
13. Cheung, C.C.; Harris, D.E.; Stawarz, Ł. Superluminal radio features in the M87 jet and the site of flaring TeV γ-ray emission. *Astrophys. J.* **2007**, *663*, L65–L68.

14. Acciari, V.A.; Aliu, E.; Arlen, T.; Bautista, M.; Beilicke, M.; Benbow, W.; Bradbury, S.M.; Buckley, J.H.; Bugaev, V.; Butt, Y.; et al. Radio imaging of the very-high-energy γ-ray emission region in the central engine of a radio galaxy. *Science* **2009**, *325*, 444–448.
15. Abramowski, A.; Acero, F.; Aharonian, F.; Akhperjanian, A.G.; Anton, G.; Balzer, A.; Barnacka, A.; Barres de Almeida, U.; Becherini, Y.; Becker, J.; et al. The 2010 very high energy γ-ray flare and 10 years of multi-wavelength observations of M87. *Astrophys. J.* **2012**, *746*, 151–168.
16. Hada, K.; Kino, M.; Nagai, H.; Doi, A.; Hagiwara, Y.; Honma, M.; Giroletti, M.; Giovannini, G.; Kawaguchi, N. VLBI observations of the jet in M87 during the very high energy γ-ray flare in 2010 April. *Astrophys. J.* **2012**, *760*, 52–56.
17. Hada, K.; Giroletti, M.; Kino, M.; Giovannini, G.; D'Ammando, F.; Cheung, C.C.; Beilicke, M.; Nagai, H.; Doi, A.; Akiyama, K.; et al. A strong radio brightening at the jet base of M87 during the elevated very high energy gamma-ray state in 2012. *Astrophys. J.* **2014**, *788*, 165–177.
18. Kovalev, Y.Y.; Lister, M.L.; Homan, D.C.; Kellermann, K.I. The inner jet of the radio galaxy M87. *Astrophys. J.* **2007**, *668*, L27–L30.
19. Walker, R.C.; Ly, C.; Junor, W.; Hardee, P.J. A VLBA movie of the jet launch region in M87. *J. Phys. Conf. Ser.* **2008**, *131*, 012053.
20. Giroletti, M.; Hada, K.; Giovannini, G.; Casadio, C.; Beilicke, M.; Cesarini, A.; Cheung, C.C.; Doi, A.; Krawczynski, H.; Kino, M. The kinematic of HST-1 in the jet of M87. *Astron. Astrophys.* **2012**, *538*, L10–L13.
21. Asada, K.; Nakamura, M.; Doi, A.; Nagai, H.; Inoue, M. Discovery of sub- to superluminal motions in the M87 Jet: An implication of acceleration from sub-relativistic to relativistic speeds. *Astrophys. J.* **2014**, *781*, L2–L6.
22. Rioja, M.; Dodson, R. High-precision astrometric millimeter very long baseline interferometry using a new method for atmospheric calibration. *Astron. J.* **2011**, *141*, 114–128.
23. Krichbaum, T.P.; Graham, D.A.; Bremer, M.; Alef, W.; Witzel, A.; Zensus, J.A.; Eckart, A. Sub-Milliarcsecond Imaging of Sgr A* and M 87. *J. Phys. Conf. Ser.* **2006**, *54*, 328.
24. Hada, K.; Kino, M.; Doi, A.; Nagai, H.; Honma, M.; Akiyama, K.; Tazaki, F.; Lico, R.; Giroletti, M.; Giovannini, G.; 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**, *817*, 131–147.
25. Junor, W.; Biretta, J.A.; Livio, M. Formation of the radio jet in M87 at 100 Schwarzschild radii from the central black hole. *Nature* **1999**, *401*, 891–892.
26. Ly, C.; Walker, R.C.; Junor, W. High-frequency VLBI imaging of the jet base of M87. *Astrophys. J.* **2007**, *660*, 200–205.
27. Kuo, C.Y.; Asada, K.; Rao, R.; Nakamura, M.; Algaba, J.C.; Liu, H.B.; Inoue, M.; Koch, P.M.; Ho, P.T.P.; Matsushita, S.; et al. Measuring mass accretion rate onto the supermassive black hole in M87 using faraday rotation measure with the submillimeter array. *Astrophys. J.* **2014**, *783*, L33–L37.
28. Ghisellini, G.; Tavecchio, F.; Chiaberge, M. Structured jets in TeV BL Lac objects and radiogalaxies. Implications for the observed properties. *Astron. Astrophys.* **2005**, *432*, 401–410.
29. Meyer, E.T.; Sparks, W.B.; Biretta, J.A.; Anderson, J.; Sohn, S.T.; van der Marel, R.P.; Norman, C.; Nakamura, M. Optical proper motion measurements of the M87 jet: New Results from the hubble space telescope. *Astrophys. J.* **2013**, *774*, L21–L26.
30. Biretta, J.A.; Sparks, W.B.; Macchetto, F. Hubble Space telescope observations of superluminal motion in the M87 jet. *Astrophys. J.* **1999**, *520*, 621–626.
31. Mertens, F.; Lobanov, A.P.; Walker, R.C.; Hardee, P.E. Kinematics of the jet in M 87 on scales of 100–1000 Schwarzschild radii. *Astron. Astrophys.* **2016**, *595*, 54–73.
32. Niinuma, K.; Lee, S.-S.; Kino, M.; Sohn, B.-W.; Akiyama, K.; Zhao, G.-Y.; Sawada-Satoh, S.; Trippe, S.; Hada, K.; Jung, T.; et al. VLBI observations of bright AGN jets with the KVN and VERA Array (KaVA): Evaluation of imaging capability. *Publ. Astron. Soc. Jpn.* **2014**, *66*, 103–118.