Formation of the radio jet in M87 at 100 Schwarzschild radii from the central black hole

William Junor*, John A. Biretta† & Mario Livio†

* *Department of Physics and Astronomy, University of New Mexico, 800 Yale Boulevard, NE, Albuquerque, New Mexico 87131, USA*
† *Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218, USA*

Massive galaxies often are the source of well collimated jets of material that flow outwards for tens to hundreds of kiloparsecs from the regions surrounding the presumed black holes at their centres. The processes by which the jets are formed and collimated have been important problems for many years[1], and observations have hitherto had insufficient spatial resolution to investigate the length scales associated with these processes[2,3]. Here we report observations at 43 GHz of the inner regions of the nearby active galaxy M87. The data show a remarkably broad jet having an 'opening angle' of $\sim 60°$ near the centre, with strong collimation of the jet occurring at $\sim$30–100 Schwarzschild radii (r_S) from the black hole: collimation continues out to $\sim 1{,}000\, r_S$. These results are consistent with the hypothesis that jets are formed by an accretion disk around the central black hole, which is threaded by a magnetic field[4].

The E0 galaxy M87 at the centre of the Virgo cluster contains one of the nearest[5] (14.7 Mpc from Earth) extragalactic jets[6–9]. Hubble Space Telescope spectroscopy of its nucleus has given strong evidence for a rapidly rotating ionized gas disk at its centre[10–12], from which the presence of a central black hole is inferred, the mass of which is about 3×10^9 solar masses (for which $r_S = 2GM/c^2 \approx 0.0003$ pc, where G is the gravitational constant, M is the black-hole mass, and c the speed of light; the Schwarzschild radius is the radius of the event horizon, the 'boundary' of a black hole. The proximity of M87, together with this large inferred black hole mass (and hence large r_S), make M87 an ideal target for studies of the initial jet-formation process. We note that jets are also associated with young stellar objects and stellar-mass black holes within our own Galaxy[13,14], but the small mass and small implied physical scale makes their formation regions extremely difficult to probe.

Centimetre-wavelength very-long-baseline interferometry (VLBI) has been used to study the M87 jet on parsec scales[15–17]. At these resolutions the jet is quite narrow, and has an opening angle comparable to that measured on kiloparsec scales. To investigate the jet formation and to probe even finer scales, we have recently made VLBI observations with a global array of radio telescopes at a wavelength of 7 mm using the best available receivers and recording equipment. The principal target, M87 (3C274, J1230 + 1223), and a number of calibrator sources were observed with a global array of radio telescopes on 3 March 1999. The resulting image for M87 is shown in Figs 1 and 2. This image has unprecedented resolution[3,17], particularly in the direction across the jet's axis, thus allowing study of the jet's collimation.

The core of M87 is clearly detected, as well as jet emission extending out to some 2 milliarcseconds (mas) from the core. The jet appears to be strongly limb-brightened; most of the jet emission of the inner 1 mas extends along ridgelines at position angles of $\sim 315°$ and $\sim 256°$ relative to the core (Fig. 1). These smooth ridgelines of emission extending directly away from the core (especially the northwest limb) underscore interpretation of the jet structure as a cone with a well defined opening angle. We have found very good consistency between this new image and those from the earlier 1.3-cm-wavelength[17] observations with lower resolution, and from an earlier 7-mm global VLBI programme with poorer sensitivity (W.J., J.A.B. and M.L., manuscript in preparation).

The most remarkable feature of the image we report here is the rapid broadening of the jet opening angle as the core is approached on scales below 1 mas (0.1 pc). The jet opening angle, as defined by

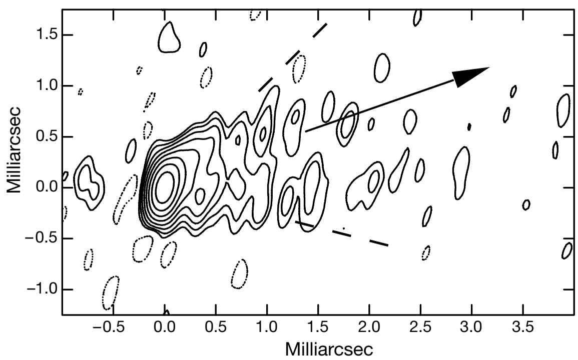

Figure 1 Image of the nucleus of M87 at 43.237 GHz on 3 March 1999. The synthesized beam is 0.33 mas × 0.12 mas (1 mas is 0.071 pc at the distance of M87) with the major axis in position angle −12.3°. The peak brightness in the image is 228 mJy per beam and the r.m.s. noise in the image well away from the bright structure is 0.38 mJy per beam. Contours are plotted at −1, 1, 2, 4, 8, 16, 32, 64 and 128 mJy per beam. The solid arrow indicates the direction of the 20″ jet, while the dashed lines indicate the position angles of the limb-brightened structure within 1 mas of the core. The antenna array consisted of the 10 telescopes of the Very Long Baseline Array (VLBA), 13 telescopes of the Very Large Array (VLA) phased together, and telescopes located at Effelsberg (Germany), Medicina (Italy), Metasahovi (Finland), Onsala (Sweden) and Yebes (Spain). Left circular polarization data were recorded at each telescope using 8 channels of 8 MHz bandwidth and 2 bit sampling. The data were correlated at the VLBA correlator, and later transferred to the AIPS package for calibration of the complex visibilities and imaging in a standard manner[25]. The complex visibility data have been weighted by the inverse fourth power of the signal-to-noise ratio of the complex visibility to improve the contribution of the higher spatial frequencies to the image.

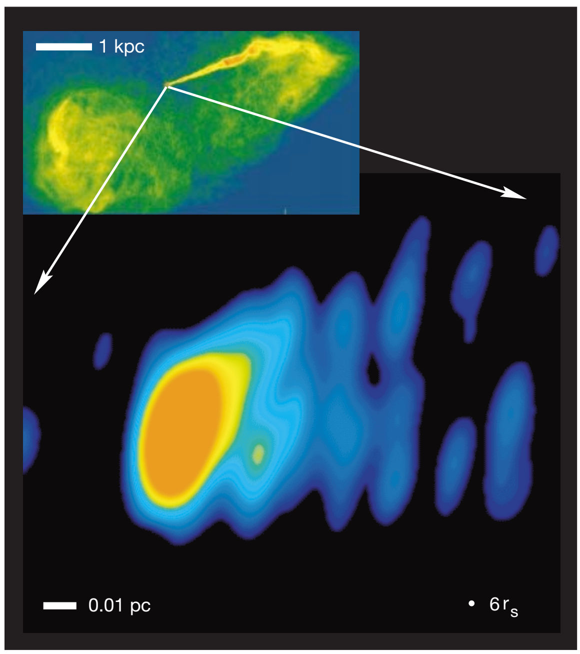

Figure 2 Pseudo-colour rendition of the nucleus of M87 at 43 GHz on 3 March 1999. See Fig. 1 for details. The filled white circle at lower right indicates $6r_S$, which is the diameter of the last stable orbit around a non-rotating black hole. The inset (top left) is a 15-GHz VLA image illustrating the large-scale jet.

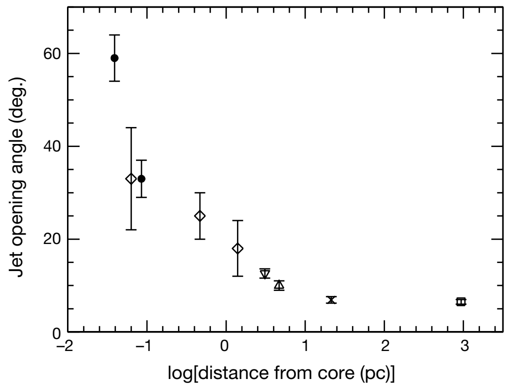

Figure 3 Jet full opening angle as function of distance from the core for M87. Results for a gaussian full-width at quarter-maximum (FWQM) fit[15] are given where jet width is not well-resolved. Uncertainties reflect the effect of image noise on the width measurement. Data are taken from references as follows: filled circles, this paper ($r = 0.1$ pc point using tapered image); open diamonds, ref. 17 FWQM; open inverted triangle, ref. 15 FWQM (new fit assuming zero jet width at core); open triangle, VSOP satellite data plus VLBA data at 5 GHz (W.J., J.A.B., F. Owen and M. Begelman, unpublished results); cross, VLBA 609 MHz FWQM (W.J. and J.A.B., unpublished results); open square, ref. 18.

the limb-brightened structures, is $\sim 60°$ on scales <0.5 mas (0.04 pc). We believe this to be the broadest angle seen in any extragalactic jet. The angular width of the jet on different size scales has been plotted as a function of radial distance from the core in Fig. 3. It is clear that the jet is progressively wider closer to the core, and that the jet does not adopt its final configuration until a few parsecs from the core. Apparently, there is strong collimation of the jet occurring on scales $\geqslant 0.04$ pc from the central 'engine', which corresponds to $\geqslant 100\, r_S$. The region in which the jet is first formed cannot be much larger than our resolution diameter, or $\sim 30\, r_S$. This is within an order of magnitude of the innermost stable orbit radius for a (non-rotating) black hole at $3\, r_S$.

We note that the evidence for a rapid increase in the opening angle near the core is independent of possible projection effects. While the inclination angle, θ, between the jet axis and the observer will tend to broaden the apparent opening angle by $\sim(\sin\,\theta)^{-1}$ (where θ lies between 10° and 40° in M87[18,9]), it does so similarly all along the jet. Also, the ratios between the jet diameter (or width) where it is being collimated and other relevant length scales (r_S and the size of the accretion disk) are also independent of θ. It is unlikely that the inclination angle θ varies in M87 (that is, that the jet is bent) as the projection of the jet on the sky appears remarkably collinear from 0.02 to 2,000 pc.

The central 'engine' which powers active galactic nuclei (AGN) is thought to be a super-massive black hole with an orbiting accretion disk fed by material raining in from the host galaxy. Magneto-hydrodynamic (MHD) models involving accretion disks are currently favoured for the acceleration and collimation of jets[4,19]. In these models, MHD 'fluid' from the accretion disk is accelerated along poloidal magnetic field lines threading the disk to speeds which are of order of the keplerian speeds. The outflow in these models could also remove angular momentum from the accretion disk[20,21]. Collimation of the MHD wind is achieved either through 'hoop stresses' where the field becomes predominantly toroidal, or via poloidal collimation, if the magnetic flux is strongest at the disk's outer radius. Beyond the Alvén surface, as the gas is no longer attached to the field lines, the field gets wound up by the rotation, thus naturally generating a toroidal field.

These observations are, to our knowledge, the first to show that jets in AGN do not reach their final collimated configuration until a distance many tens of Schwarzschild radii from the 'engine'. On the smallest physical scales yet probed in this AGN (~ 0.04 pc), the observed outflow already is weakly collimated (opening angle ≈ 1 rad) in the direction of the large-scale jet. This gives the ratio of the collimation distance, r_{coll}, to the fiducial scale $r_{coll}/r_S \approx 100$. This is consistent with a picture in which the jet is formed (that is, accelerated and collimated) by an accretion disk[22,23,4]. In particular, our observations seem to favour MHD models in which the jet originates from a disk outflow, rather than emanating already collimated from the vicinity of the black hole.

Evidence for limb-brightening in jets is relatively rare, and has previously been detected only on larger scales[15,24]. We now consider whether the strong limb-brightening on sub-parsec scales observed here is related to the collimation process itself. Limb-brightening suggests a high synchrotron emissivity, and hence higher magnetic field, in the surface of the jet. This would be consistent with a large-scale magnetic field (that is, from a disk) playing an important role in the collimation process. In order to distinguish further among different specific collimation models, we are currently investigating the magnetic field geometry on these small scales with VLBI polarimetry. □

Received 26 July; accepted 13 September 1999.

1. Begelman, M. C., Blandford, R. D. & Rees, M. J. Theory of extragalactic radio sources. *Rev. Mod. Phys.* **56,** 255–351 (1984).
2. Zensus, A. J. Parsec-scale jets in extragalactic radio sources. *Annu. Rev. Astron. Astrophys.* **35,** 607–636 (1997).
3. Tingay, S. J. *et al*. The subparsec-scale structure and evolution of Centaurus A: the nearest active radio galaxy. *Astron. J.* **115,** 960–974 (1998).
4. Livio, M. Astrophysical jets: a phenomenological examination of acceleration and collimation. *Phys. Rep.* **311,** 225–245 (1999).
5. Jacoby, G. H., Ciardullo, R. & Ford, H. C. Planetary nebulae as standard candles. V—The distance to the Virgo Cluster. *Astrophys. J.* **356,** 332–349 (1990).
6. Curtis, H. D. The planetary nebulae. *Publ. Lick Obs.* **13,** 55–74 (1918).
7. Biretta, J. A. in *Astrophysical Jets* (eds Burgarella, D., Livio, M. & O'Dea, C.) 263–304 (Cambridge Univ. Press, 1993).
8. Biretta, J. A. in *The Radio Galaxy M87* (eds Röser, H. J. & Meisenheimer, K.) (Springer, Heidelberg, in the press).
9. Biretta, J. A., Sparks, W. B. & Macchetto, F. Hubble Space Telescope observations of superluminal motion in the M87 jet. *Astrophys. J.* **520,** 621–626 (1999).
10. Ford, H. C. *et al*. Narrowband HST images of M87: Evidence for a disk of ionized gas around a massive black hole. *Astrophys. J.* **435,** L27–L30 (1994).
11. Harms, R. J. *et al*. HST FOS spectroscopy of M87: Evidence for a disk of ionized gas around a massive black hole. *Astrophys. J.* **435,** L35–L38 (1994).
12. Macchetto, F. D. *et al*. The supermassive black hole of M87 and the kinematics of its associated gaseous disk. *Astrophys. J.* **489,** 579–600 (1997).
13. Fender, R. P., Bell-Burnell, S. J. & Waltman, E. B. The radio-jet X-ray binaries. *Vistas Astron.* **41,** 3–13 (1997).
14. Ray, T. P. & Mundt, R. in *Astrophysical Jets* (eds Burgarella, D., Livio, M. & O'Dea, C.) 145–175 (Cambridge Univ. Press, 1993).
15. Reid, M. J., Biretta, J. A., Junor, W., Muxlow, T. W. B. & Spencer, R. E. Subluminal motion and limb brightening in the nuclear jet of M87. *Astrophys. J.* **336,** 112–120 (1989).
16. Biretta, J. A. & Junor, W. The parsec-scale jet in M87. *Proc. Natl Acad. Sci. USA* **92,** 11364–11367 (1995).
17. Junor, W. & Biretta, J. A. The radio jet in 3C274 at 0.01 pc resolution. *Astron. J.* **109,** 500–506 (1995).
18. Biretta, J. A., Zhou, F. & Owen, F. N. Detection of proper motions in the M87 jet. *Astrophys. J.* **477,** 582–596 (1995).
19. Ouyed, R., Pudritz, R. E. & Stone, J. M. Episodic jets from black holes and protostars. *Nature* **385,** 409–414 (1997).
20. Blandford, R. D. Accretion disc electrodynamics—a model for double radio sources. *Mon. Not. R. Astron. Soc.* **176,** 465–481 (1976).
21. Lovelace, R. V. E. Dynamo model of double radio sources. *Nature* **262,** 649–652 (1976).
22. Blandford, R. D. in *Astrophysical Jets* (eds Burgarella, D., Livio, M. & O'Dea, C.) 15–33 (Cambridge Univ. Press, 1993).
23. Spruit, H. C. in *Cosmical Magnetism* (ed. Lynden-Bell, D.) 33–44 (Kluwer, Dordrecht, 1994).
24. Owen, F. N., Hardee, P. E. & Cornwell, T. J. High-resolution, high dynamic range VLA images of the M87 jet at 2 centimeters. *Astrophys. J.* **340,** 698–707 (1989).
25. Zensus, J. A., Diamond, P. J. & Napier, P. J. (eds) *Very Long Baseline Interferometry and the VLBA* (ASP Conf. Ser 82, Astronomical Soc. of the Pacific, San Francisco, 1995).

Acknowledgements

We thank the staff at the participating observatories for their help, and the software developers at NRAO. The Very Large Array and the Very Long Baseline Array are facilities operated by Associated Universities Inc. under agreement with the National Science Foundation. W.J. thanks the National Science Foundation for support. M.L. was supported by NASA.

Correspondence and requests for materials should be addressed to W.J. (e-mail: bjunor@astro.phys.unm.edu).