Perseus in Sicily: From Black Hole to Cluster Outskirts
Proceedings IAU Symposium No. 342, 2018
K. Asada, E. de Gouveia Dal Pino, M. Giroletti,
H. Nagai & R. Nemmen, eds.

doi:10.1017/S1743921318007226

A wide and collimated radio jet in 3C 84

Gabriele Giovannini

Physics and Astronomy Dpt, Bologna University
via Gobetti 93/2
40129 Bologna, Italy and
Radio Astronomy Institute-INAF
via Gobetti 101
40129 Bologna, Italy
email: ggiovann@ira.inaf.it

Abstract. I report observations of 3C84 (NGC 1275), the central galaxy of the Perseus cluster, made with an interferometric array including the orbiting radio telescope of the RadioAstron mission. The data transversely resolve the edge-brightened jet in 3C84 only 0.03 mas from the core, which is ten times closer to the central engine than was possible in previous ground-based observations. To better understand physical properties of this peculiar source, I will discuss its present properties in comparison to the past and more recent evolution in the radio band of 3C 84.

Keywords. 3C 84, VLBI

1. Introduction and historical activity

The radio source 3C 84 is identified with NGC 1275, the central galaxy of the cooling flow Perseus Cluster (Abell 426) at z = 0.0176. This FR-I type radio source has been studied extensively since the early days of radio astronomy. At low resolution the radio emission is extended and diffuse with a halo-core structure. The radio flux has been monitored since 1960, and episodes of violent flux increase have been reported (see Fig. 1).

In the mid-1980s, the radio flux became exceptionally bright, more than 60 Jy at centimetre wavelengths, and then it subsequently decreased to about 10 Jy by the early 2000s. Around 2005, it was reported that the radio flux had started to increase again (see Fig. 2).

Thanks to VLBI images it is possible to see that inside the central 10 parsecs, there is a bright core region and two symmetric lobes, with evidence for free-free absorption in the northern one (Walker *et al.* 2000). These mini-lobes were probably formed by the jet activity originating in the 1959-1960 radio outburst and are expanding at sub-luminal velocity. At higher angular resolution, the bright core region is resolved into a compact core and an one-sided complex jet emission. VLBI observations obtained at the epoch of the highest flux density (around 1985) show the presence of a compact bright component identified with the core (C or C1) and an one-sided short and bright emission named C2 (see e.g. Venturi *et al.* 1993). In the following years the structure expanded and decreased in flux density, as shown by the 1995.1 image (Romney *et al.* 1995). In early 2000s the total flux density decreased to $\sim$ 10 Jy (see e.g. Nagai *et al.* 2012). Around 2005 it was reported that the radio flux had started to increase again (Abdo *et al.* 2009). VLBI observations revealed that this flux density increase originated in the central parsec region and it was accompanied by the ejection of a new component named C3 (see Suzuki *et al.* 2012 and Nagai *et al.* 2014 and references therein).

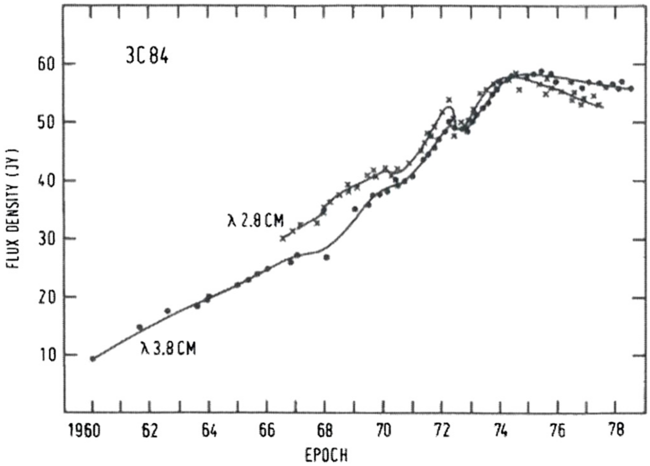

Figure 1. The total flux density of 3C 84 at 2.8 and 3.8 cm wavelength as a function of time. The Figure is taken from Preuss *et al.* (1979)

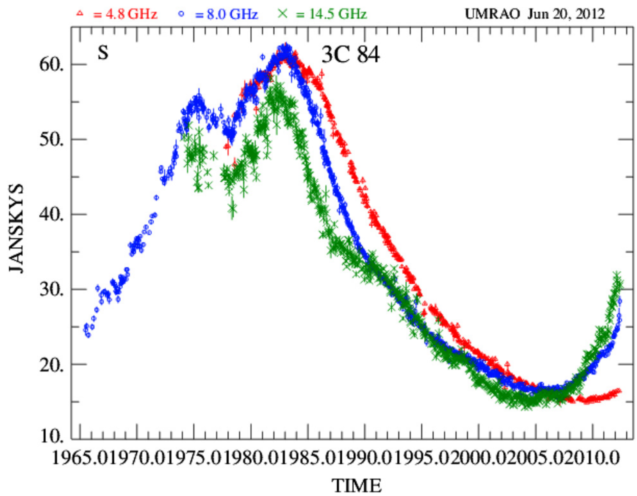

Figure 2. The total flux density of 3C 84 from the University of Michigan Radio Astronomy Observatory (UMRAO) data base at 4.8, 8.0 and 14.5 GHz

Component C3 (see Fig. 3) was first detected on 2003.11 and it is moving from the core with an apparent velocity of about 0.3 - 0.5 c and increasing in flux density. As shown in Fig. 3 it is unrelated to the old component C2 and its motion is at a different Position Angle (PA).

In high resolution VLBI images at 43 and 86 GHz obtained before 2003, the inner structure is dominated by the core C1 and the component C2 at about 1.2 mas. In these images the jet morphology was centrally peaked. In the images obtained a few years later (2005-2007) the new component C3 is well visible and became the dominant component of the inner 3C 84 nuclear structure. Component C3 is advancing with an increasing apparent velocity (0.47c in November 2008). The morphology of the jet connecting C1 to C3 is limb-brightened and the jet PA is $\sim 170\ ^{\circ}$ quite different from the C2 structure.

3C 84 was detected in γ-rays by the Fermi Large Area Telescope (LAT) in Aug. 2008 (Abdo *et al.* 2009). This detection is particularly relevant because 3C 84 was not detected by EGRET (Energetic Gamma Ray Experiment Telescope) of the Compton Gamma Ray

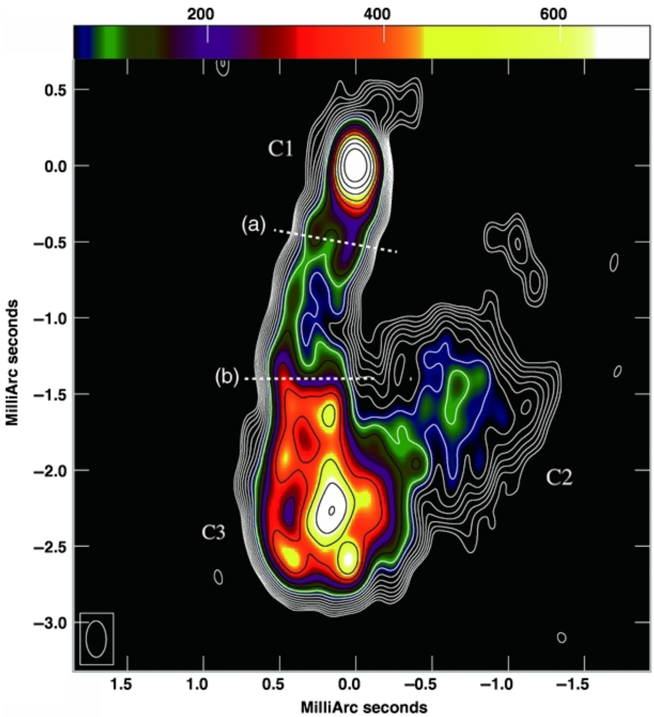

Figure 3. 43 GHz total intensity map of 3C 84. The contours are plotted at the level of 5.43×(1.41, 1, 1.41, 2.83, 4, 5.66, 8, 11.3, 16, 22.6, 32, 45.3, 64, 90.5, 128, 181, 256) mJy/beam. The ellipse shown at the bottom left corner of the image indicates the FWHM of the convolved beam. The FWHM of the convolved beam is 0.24 × 0.13 mas at the position angle 0.69°. The white dashed lines (a) and (b) indicated in the figure are the slice locations, (from Nagai *et al.* 2014).

Observatory in the 1990s (Reymer *et al.* 2003). The γ-ray flux density measured by Fermi is about seven times higher than the upper limit from EGRET observations.

This suggest the presence of two different activities in the nuclear region of 3C84: a first phase with a flux density decreasing, evolution of C2 component, centrally peaked jet structure, and no γ-ray emission and a second phase with an increasing of the flux density, the evolution of new component C3, a limb-brightened jet structure and γ-ray emission.

2. Space VLBI

3C84 was observed by the RadioAstron space radio telescope and an array of 29 ground radio telescopes from September 21, 2013 at 15:00 (UT) to September 22, 13:00 (UT). Observations were obtained in the C- and K-band. Observations were obtained during a perigee passage with projected space baselines from 0.2 to 10.4 Earth diameters. Here I am presenting only K band data. A positive signal was detected up to 8 Earth Diameters corresponding to 0.027 mas fringe spacing (for more details see Giovannini *et al.* 2018.

Figure 4 presents our 22 GHz space-VLBI image of the innermost parsec of 3C 84 at the angular resolution of 0.10 × 0.05 mas in PA 0°.

The bright and compact emission at about 2.2 mas north of the image reference center is identified with the radio core, from where a faint and short counter-jet and a 3-mas-long jet depart, in N-S direction. The main jet ends in a bright spot with a surrounding

https://doi.org/10.1017/S1743921318007226 Published online by Cambridge University Press

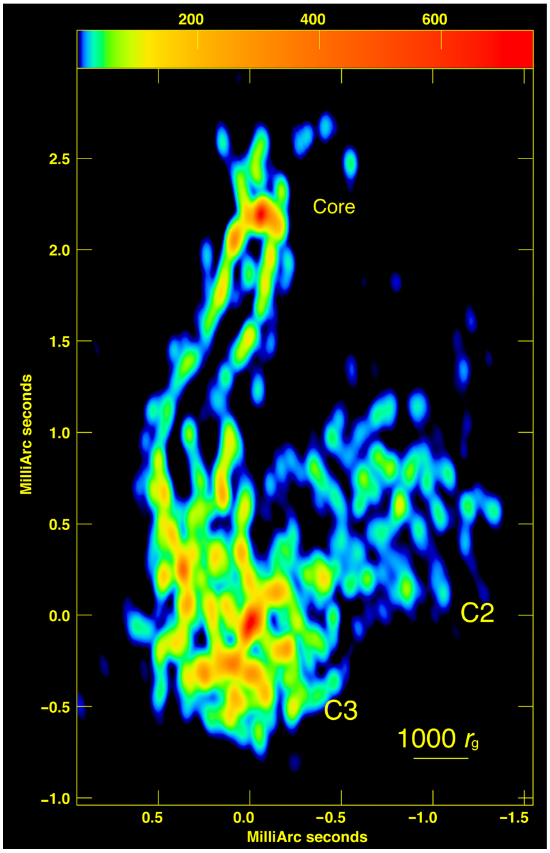

Figure 4. Radio image of the central parsec in 3C84 obtained with the space VLBI array. The x and y axes show the distance (in mas) from the image reference centre. The HPBW is 0.10 × 0.05 mas at PA = 0°. The noise level is 1.4 mJy/beam and the peak intensity is 0.75 Jy/beam.

diffuse emission identified with the emission feature called "C3" (Nagai *et al.* 2014). The diffuse emission feature, called "C2", is visible on the western side of the jet.

Main results from space VLBI images, are discussed below.

2.1. *The jet structure*

The jet is edge-brightened already at 0.03 mas from the core corresponding to 350 gravitational radii (r_g) de-projected. The large intensity ratio between the bright sheath and the central jet spine can be due to a specific velocity structure combination (Komissarov 1990), or by an intrinsic brightness difference, or both (see also Giovannini *et al.* 2018).

2.2. *The jet opening angle*

The limb-brightened jet connecting the core and C3 shows a large initial opening angle (the largest opening angle observed in any astrophysical jet). This large initial opening angle is followed by a rapid collimation to a quasi-cylindrical shape. This quasi-cylindrical structure is already present at a few hundred r_g from the core. This implies a strong jet collimation inside a few hundred r_g from the central engine. If the bright outer jet layer is launched by the BH ergosphere, it has to rapidly expand laterally followed by an almost cylindrical collimation. If this is not the case the jet sheath is likely launched from the accretion disk.

https://doi.org/10.1017/S1743921318007226 Published online by Cambridge University Press

2.3. *Jet evolution and the C3 structure*

The component C3 is advancing with a position angle of $\sim 170°$. This direction is clearly unrelated to that of comonent C2. The limb-brightened jet appears to terminate in the brightest region of C3 component, slightly resolved in our images. The surrounding region rembers the shape of radio lobes in radio galaxies suggesting that is is due to the interaction of the jet with the surrounding medium. This is like a young source in the expanding phase.

Recently, VLBA images at 43 GHz from the Boston University Blazar Program have pointed out that the C3 hotspot is not stable but its position is not only moving out from the core with an apparent sub-luminal velocity but is also 'oscillating' from East to West. Polarization, flux density and morphology are also not constant and possibly these changes are correlated each other (see Nagai *et al.* 2017 and Kino *et al.* 2018). These behaviors suggest a strong interaction between the jet and ambient medium. More detailed studies will allow to derive the physical properties in this region.

3. Conclusions

High resolution space VLBI data have allowed us to study the inner jet region of 3C 84. The data transversely resolve the edge-brightened jet at only 0.03 mas from the core. The jet collimation profile is known from $\sim 10^2$ to 10^4 gravitational radii. A comparison between M87 and 3C84 jets suggests a strong relation with the restarted nature and young age of the 3C84 jet. A comparison with previous activity of 3C 84 shows a change in the jet properties and activity with time. The possibility to follow a young jet activity from its beginning can give a unique record of the early jet evolution in a galaxy.

Acknowledgements

I would like to thank all authors of the letter published on Nature Astronomy (Giovannini *et al.* 2018) for their contribution.

The RadioAstron project is led by the Astro 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 State Space Corporation ROSCOSMOS, in collaboration with partner organizations in Russia and other countries. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities. The European VLBI Network is a joint facility of independent European, African, Asian and North American radio astronomy institutes. The KVN is a facility operated by the Korea Astronomy and Space Science Institute. The KVN operations are supported by the Korea Research Environment Open NETwork, which is managed and operated by the Korea Institute of Science and Technology Information. This research is based on observations correlated at the Bonn Correlator, jointly operated by the Max-Planck-Institut fr Radioastronomie and the Federal Agency for Cartography and Geodesy.

This study makes use of 43 GHz VLBA data from the VLBA-BU Blazar Monitoring Program (VLBA-BU-BLAZAR; http://www.bu.edu/blazars/VLBAproject.html), funded by NASA through the Fermi Guest Investigator Program.

References

Abdo, A. A., *et al.* 2009, *ApJ* 699, 31
Giovannini, G.,, *et al.* 2018, *Nature Ast.*, 2, 472
Kino, M., *et al.* (2018) 2018, arXiv:180808855
Ko missarov (1990) 1990, *Sov. Ast. Lett.* 16, 284
Nagai, H., *et al.* 2012, *MNRAS*, 423, L122

Nagai, H., *et al.* 2014, *ApJ*, 785, 53
Nagai, H., *et al.* 2017, *ApJ*, 849, 52
Preuss, E., Kellerman, K. I., Pauliny-Toth, I. I. K., Witzel, A., & Shaffer, D. B. 1979, *A&A*, 79, 268
Reimer, O., Pohl, M., Sreekumar, P., & Mattox, J. R. 2003, *ApJ*, 588, 155
Romney, J. D., Benson, J. M., Dhawan, V., Kellerman, K. I., Vermeulen, R. C., & Walker, R. C. 1995, *Proc. Natl. Acad. Sci. USA*, 92, 11360
Suzuki, K., *et al.* 2012, *ApJ*, 746, 140
Venturi, T., Readhead, A. C. S., Marr, J. M., & Backer, D. C. 1993, *ApJ*, 411, 552
Walker, R. C., Dhawan, V., Romney, J. D., Kellerman, K. I., & Vermeulen, R. C. 2000, *ApJ*, 530, 233