PROCEEDINGS OF SCIENCE

e-EVN monitoring of M87

M. Giroletti[*a], **G. Giovannini**[a,b], **C. Casadio**[a], **M. Beilicke**[c], **A. Cesarini**[d], **and H. Krawczynski**[c]
[a] *INAF Istituto di Radioastronomia, via Gobetti 101, 40129 Bologna (Italy)*
E-mail: giroletti@ira.inaf.it
[b] *Dipartimento di Astronomia, via Ranzani 1, 40127 Bologna, Italy*
[c] *Department of Physics, Washington University, St. Louis, MO 63130, USA*
[d] *School of Physics, National University of Ireland, University Road, Galway, Republic of Ireland*

M87 is a privileged laboratory for a detailed study of the properties of jets, owing to its proximity (D=16.7 Mpc, 1 mas = 0.080 pc), its massive black hole ($\sim 6.0 \times 10^9 M_\odot$) and its conspicuous emission at radio wavelengths and above. We started on November 2009 a monitoring program with the e-EVN at 5 GHz, in correspondence of the season of Very High Energy (VHE) observations. Indeed, two episodes of VHE activity have been reported in February and April 2010. We present here the main results of these multi-epoch observations: the inner jet and HST-1 are both detected and resolved in our datasets. We study the apparent velocity of HST-1, which seems to be increasing since 2005, and the flux density variability in the inner jet. All in all, the radio counterpart to this year's VHE event seems to be different from the ones in 2005 and 2008, opening new scenario for the radio-high energy connection.

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[*] Speaker.

1. Introduction

The galaxy Messier 87 (M87, or Virgo A) is the host to one of the nearest radio loud Active Galactic Nuclei (AGNs). It is located at the center of the Virgo cluster of galaxies at a distance $d = 16.7\,\mathrm{Mpc}$, resulting in an angular scale of $1\,\mathrm{mas} = 0.081\,\mathrm{pc}$. The estimated mass of the huge black hole at its center is $M_{\mathrm{BH}} = 6.4 \times 10^9 M_\odot$ [9]. Combined with the low distance of the source, this implies a physical scale of $1\,\mathrm{mas} = 140 R_{\mathrm{Schw}}$.

At radio wavelengths, M87 is associated with the bright source 3C 274, characterized by a monochromatic luminosity of $\sim 10^{25}\,\mathrm{W\,Hz^{-1}}$ (at 408 MHz). Its morphology is rather complex, with an extended halo visible on large angular scale [18] and an inner double lobe structure with a prominent one-sided jet. The jet extends for a few kiloparsecs and it is characterized by many substructures and knots. It has been well studied with the VLA, revealing superluminal proper motion of components [6]. At the high resolution offered by VLBI, the inner portion of the jet shows a limb brightened structure [13, 12, 14], while proper motion of components is only detected within the so-called HST-1 complex about 70 pc (projected) downstream [8].

At higher energy, the jet is also resolved by optical (HST) and X-rays (*Chandra*) observations, while gamma-ray telescopes reveal emission consistent with the position of M87 but do not resolve it, neither in the MeV/GeV band from space with *Fermi* [1], nor in the GeV/TeV one with ground based Cherenkov telescopes [4, 3, 5].

Various models have been proposed to explain the multi-wavelength emission and in particular to constrain the site of the VHE emission in M87. The inner jet region seems favoured by the observed short TeV variability timescales [4]. The VHE emission could then be produced in the BH magnetosphere [16] or in the slower jet layer [19], with the spine accounting for the emission from the radio to the GeV band; this would lead to a complex correlation between the TeV and radio components. Later on, the episode of VHE activity observed in 2005 were accompanied by a dramatic increase of flux density in HST-1 at radio, optical, and X-ray energy. Given the compactness and superluminal motions observed in HST-1 itself with the VLBA, it was suggested that the TeV emission from M87 was originated in HST-1 [8, 11]. Finally, a strong TeV flare was detected again from M87 in February 2008, at the same time as a longer time scale increase of the radio flux from the nucleus, thus reintroducing the scenario in which the TeV flares originate in the core region [2].

The need for an additional high resolution coordinated multi-wavelength campaign targeting M87 was then pressing. In this paper, we present the contribution of the EVN to the efforts aimed at solving this puzzle of great astrophysical interest.

2. Observations and Data Reduction

In the above described context, we started a project to observe M87 with VLBI so that we could simultaneously reveal the properties of the M87 core, jet, and HST-1 structure. In order to grant the best possible combination of high sensitivity, good resolution, and large field of view, we used the EVN at 5 GHz. The observations have been carried out in e-VLBI mode, which delivers prompt results and offers a better time sampling than the regular EVN disk based sessions.

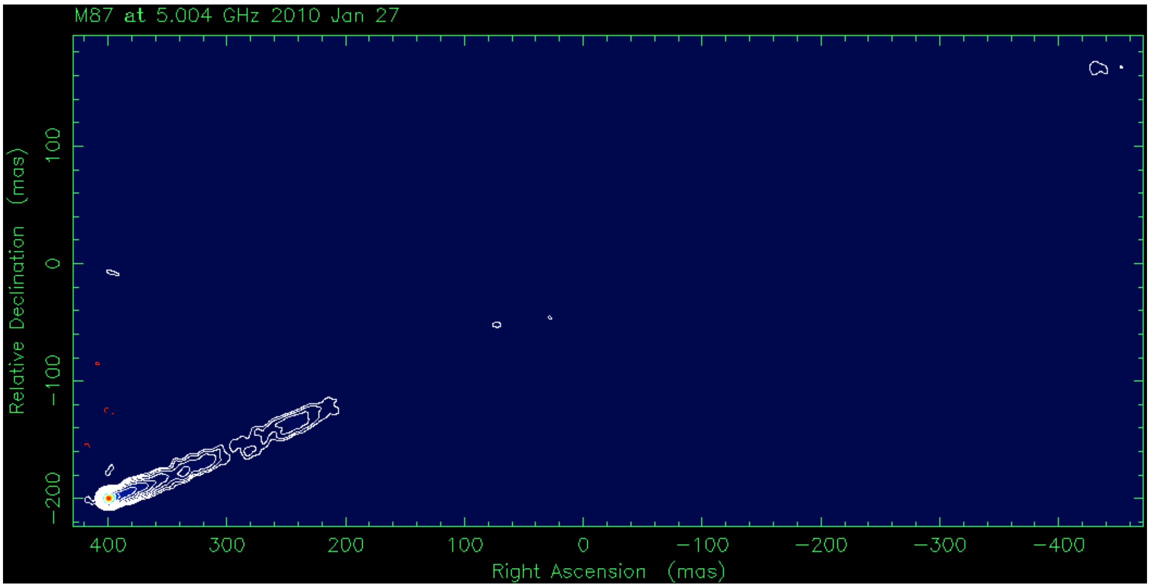

Figure 1: Wide field EVN image of the jet in M87. Contours are traced at $(-1,1,2,4,\ldots)\times 2.0$ mJy beam^{-1}. The peak flux density is 2 Jy beam^{-1}, the restoring beam is 7.1×6.6 mas in PA 43°.

Observations were initially scheduled for 4 epochs, and later extended for a total of 7 observations between 2009 November and 2010 June. A further continuation of the project is also underway. The participating stations are Arecibo, Cambridge, Effelsberg, Jodrell Bank, Medicina, Onsala, Shanghai, Torun, and Westerbork. Data acquired from these telescopes were directly streamed to the central data processor at JIVE, and correlated in real-time. Pipeline calibration was carried out at JIVE and data were downloaded for additional editing and self calibration in AIPS and Difmap.

For observations taking advantage of the long baselines provided by the Arecibo and Shanghai telescopes, our clean beam with uniform weights is about 2.0×0.9 mas in PA $-25°$. As a result of the large bandwidth (a rate of 1 Gbps is sustained by most stations), long exposure (up to 6 hours per epoch), and extended collecting area, the rms noise in our images is mostly dynamic range limited. As an average value, we can quote 0.5 – 0.8 mJy beam^{-1} in the nuclear region and 0.1 – 0.2 mJy beam^{-1} in the HST-1 region.

3. Results

Both the inner jet and the HST-1 region were well detected and imaged with our observational setup. A wide field (900×450 mas) is shown in Fig. 1, while a zoom on HST-1 is presented in Fig. 2. The well known structure of the jet is confirmed, with emission detected for over 300 mas from the core in position angle PA $\sim -65°$. HST-1 is revealed at ~ 920 mas from the core, aligned with the inner jet but oriented in PA $\sim -90°$. HST-1 itself is resolved into several components, the brightest and most compact of which is located upstream the rest of emission.

The observations were scheduled so that they would take place during the season of best conditions for the TeV observatories. Indeed, two episodes of VHE enhanced activity have been reported during our campaign, one on 2010 February 9th [15] and one starting on April 8th [17].

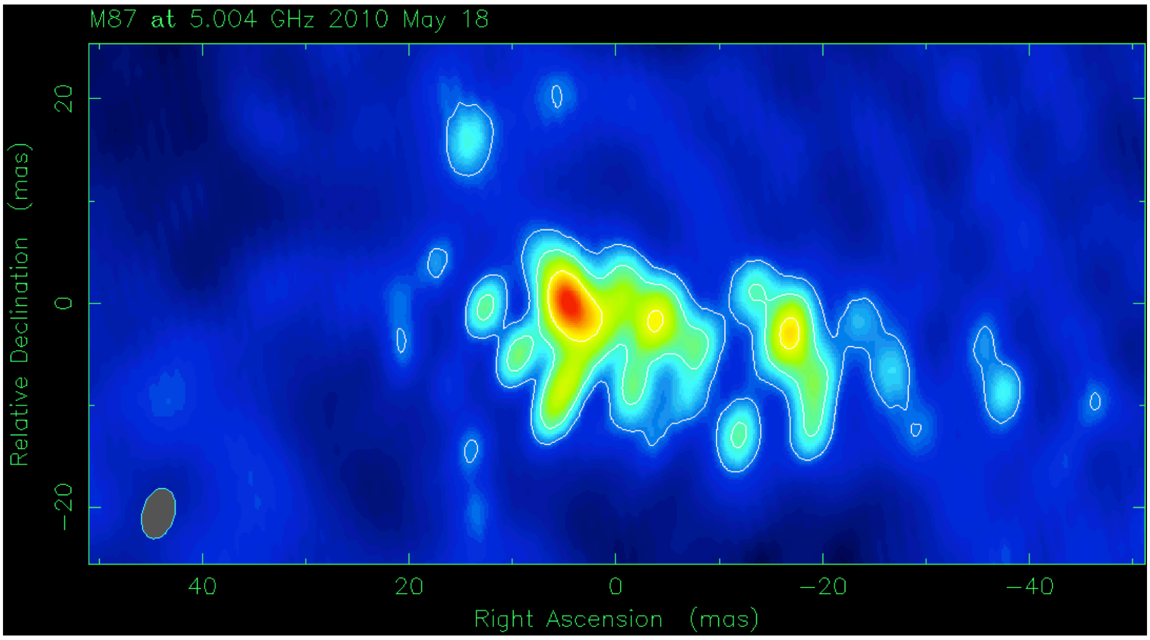

Figure 2: EVN image of the HST-1 region downstream the jet in M87 on 2010 May 18. Contours are traced at $(-0.3, 0.3, 0.6, 1.2)$ mJy beam^{-1}. The peak flux density is 2.0 mJy beam^{-1}, the restoring beam is 5.0×3.1 mas in PA -13°.

Epoch	Core flux (Jy)	HST-1 Peak (mJy beam^{-1})
2009 Nov 19	1.81 ± 0.03	3.5 ± 0.2
2010 Jan 27	1.81 ± 0.03	2.7 ± 0.2
2010 Feb 10 (*)	1.80 ± 0.03	3.0 ± 0.2
2010 Mar 6	1.89 ± 0.03	4.6 ± 0.3
2010 Mar 28 (*)	2.01 ± 0.03	3.4 ± 0.2
2010 May 18	1.93 ± 0.03	2.8 ± 0.2
2010 Jun 9	1.93 ± 0.03	2.6 ± 0.2

Table 1: *Preliminary* core flux density and HST-1 peak brightness at 5 GHz during the EVN monitoring campaign. Epochs marked by an asterisk are those next to reported events of VHE activity (Feb 9th and Apr 8–10 [15, 17]).

The first flare is almost simultaneous (within 24hr) to our third EVN epoch. Our image from that epoch shows that the core and HST-1 structure are still comparable to the pre-flare values and provide a good reference for light curve and proper motion studies of jet substructures with respect to the time of the VHE event [10]. As a matter of fact, even in later epochs both the core and HST-1 have remained on similar values of flux density. A quick summary is reported in Table 1. Even if the values are still somewhat preliminary, it is clear that no dramatic variability is present.

Although the structure of HST-1 is clearly rather complex and overall quite weak, it is still possible to identify and follow epoch by epoch at least the brightest and most compact component. Fixing the core as a reference, we find that the peak is moving with an apparent velocity of $v_{\rm app} \sim 3\,c$

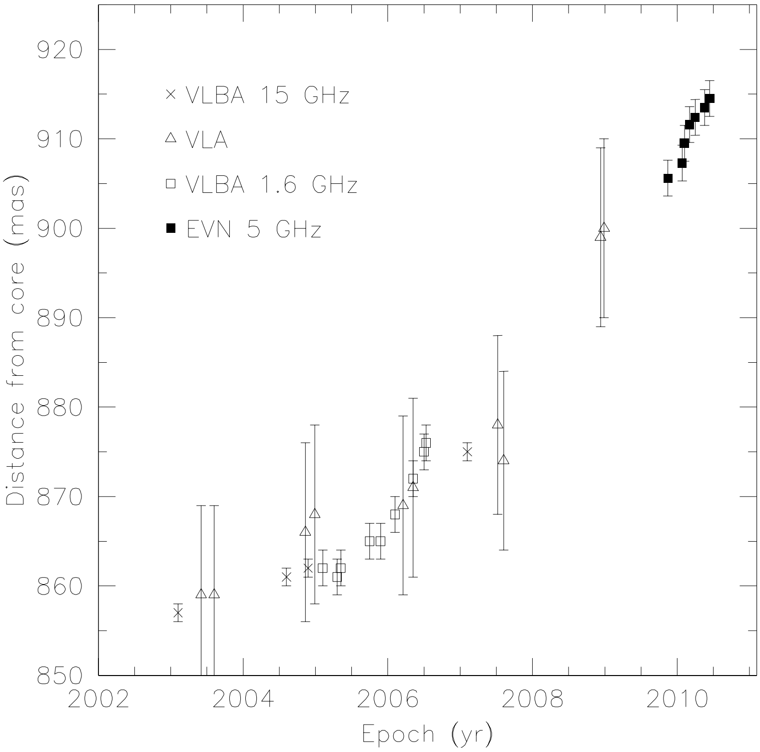

Figure 3: Distance of HST-1 peak from the core in M87, from new EVN data (filled squares) combined with literature VLBA data at 1.6 [8] and 15 GHz [7] and from the VLA archive.

and it is thus superluminal. No stationary component seems to be present in our images.

To put this result in context, we have obtained from the literature [8, 7] and the archives some additional images in which HST-1 is detected. The images have different resolutions and frequency, so a comparison is not trivial. However, it is clear that there is an overall trend of increase in separation between HST-1 and the core, as shown in Fig. 3. The data suggest a change in the proper motion velocity at the epoch $\sim$ 2005.5, coincident with the TeV activity and the peak in the VLA, HST, and *Chandra* light curves of HST-1. In particular, the apparent velocity is $\sim 0.5\,c$ in the time range 2003 – 2005.5, while it becomes $\sim 2.7\,c$ on the period 2005.5 – 2010.25. Further variations could be present, such as a decrease in the apparent velocity in 2007 with a restarted high velocity motion from 2008 (near the time of the high energy flare) up to now. Assuming a jet orientation angle = 25° a proper motion of $2.7\,c$ corresponds to an intrinsic velocity = 0.94c.

4. Discussion and Outlook

Assuming the VHE events in February and April 2010 are representative of the same state of high activity, we have three different episodes to analyse and compare, in 2005, 2008, and 2010. At lower energy, a simultaenous increase of flux density was found in one case in HST-1 (for 2005), in one case in the core (2008), and in neither HST-1 nor the core for the latest event (2010). Indeed, even if it is natural to expect a delay in the 5 GHz data, the images taken as late as June (more than 4 months after the first VHE event) do not reveal any significant enhancement of the radio flux density.

The situation is thus certainly complex; one possibility is that the three events have actually different physical origins. It is however a little surprising that the conditions for such extremely energetic events can be reached from rather different starting conditions. On the other hand, there is the possibility that none of the low energy increase is actually related to the TeV events, which would then be totally unrelated to the radio light curve.

Finally, it is possible that the interplay between the VHE and radio emission is taking place in a more complex way. In this sense, it might be worth considering the hint given by the proper motion study, which suggests that the VHE events could be related to an increase in the apparent velocity of HST-1. Although the current data are still inadequate to support such claim, it could probably be confirmed or disproved with a longer monitoring.

In order to clarify the overall picture, it is thus important to continue to monitor the source from radio to TeV. Moreover, a detailed look at the archives can provide an improved understanding of the behavior of the source in the past.

Acknowledgments

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