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# The jet in M87 from e-EVN observations

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**Abstract.** One of the most intriguing open questions of today's astrophysics is the jet physical properties and the location and the mechanisms for the production of MeV, GeV, and TeV gamma-rays in AGN jets. M87 is a privileged laboratory for a detailed study of the properties of jets, owing to its proximity, its massive black hole, and its conspicuous emission at radio wavelengths and above. We started on November 2009 a monitoring program with the e-EVN at 5 GHz. We present here results of these multi-epoch observations and discuss the two episodes of activity at energy E>100 GeV that occured in this period. One of these observations was obtained at the same day of the first high energy flare. We added to our results literature data obtained with the VLBI and VLA. A clear change in the proper motion velocity of HST-1 is present at the epoch ∼2005.5. In the time range 1998 – 2005.5 the apparent velocity is subluminal, and superluminal (∼2.7c) after 2005.5.

**Keywords.** Galaxies: jets, Galaxies: M87, Galaxies: active

## 1. Introduction

The giant radio galaxy Messier 87 (M87), also known as 3C 274 or Virgo A, is one of the best studied radio sources and a known $\gamma$-ray-emitting AGN. It is located at the center of the Virgo cluster of galaxies at a distance = 16.7 Mpc, corresponding to an angular conversion 1 mas = 0.081 pc. The massive black hole at the M87 center has an estimated mass = $6 \times 10^9$ solar masses, with a scale of 1 mas = 140 $R_S$. The bright jet is well resolved in the X-ray, optical, and radio wave bands.

The jet is characterized by many substructures and knots. In 1999 HST observations revealed a bright knot at about 1" from the core, named HST-1. This feature is active in the radio, optical, and X-ray regimes. It was discussed by Perlman *et al.* 1999, who compared optical and radio images. Biretta *et al.* 1999 measured in the range 1994–1998 a subluminal speed = 0.84c for the brightest structure (HST-1 East), which appears to emit superluminal features moving at 6c. However this motion was measured in regions on a larger scale with respect to the VLBI structures discussed here. In this time range HST-1 in the radio band was a faint jet structure (a few mJy/beam, see Fig. 1), but starting from 2000 it increased by more than a factor 50 and it reached a flux density ∼100 mJy in 2005 (See Fig. 2 and Harris *et al.* 2009).

VLBI observations of the M87 inner region show a well resolved, edge-brightened jet structure. At very high resolution (43 and 86 GHz) near to the brightest region the jet has a wide opening angle, and we refer to the many published papers which discuss the possible presence of a counter-jet and the location of the radio core; see e.g. Junor *et al.* 1999, Krichbaum *et al.* 2005. After a few milliarcsec (mas) the jet appears well collimated and limb-brightened.

Very High Energy (VHE) $\gamma$-ray emission was reported by the High Energy Gamma-Ray Astronomy (HEGRA) collaboration in 1998/99 (Aharonian *et al.* 2003), confirmed by the High Energy Stereoscopic System (HESS) in 2003–2006 (Aharonian *et al.* 2006), and by VERITAS in 2007 (Acciari *et al.* 2008). Coordinated intensive campaigns have permitted to detect the source again in 2008 (Acciari *et al.* 2009) and as recently as February and April 2010 (Mariotti *et al.* 2010). Steady emission at MeV/GeV energies has also been detected by *Fermi*/LAT (Abdo *et al.* 2009).

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 was favoured by the observed short TeV variability timescales according to Aharonian *et al.* 2006. The VHE emission could then be produced in the BH magnetosphere (Neronov *et al.* 2007) or in the slower jet layer (Tavecchio *et al.* 2008), 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.

However, VLBA observations at 1.7 GHz by Cheung *et al.* 2007 resolved HST-1 in substructures with superluminal components. Aharonian *et al.* 2006 discussed that HST-1 cannot be excluded as a source of TeV $\gamma$ rays, however they conclude that the more promising possibility is that the site of TeV $\gamma$-ray production is the nucleus of M87 itself. Comparing multifrequency data Harris *et al.* 2008 suggested that the TeV emission from M87 was originated in HST-1.

Finally, Acciari *et al.* 2009 reported rapid TeV flares from M87 in February 2008, associated by an in increase of the radio flux from the nucleus, while HST-1 was in a low state, thus concluding that the TeV flares originate in the core region.

In this context we started at the end of 2009 a program to observe with the e-EVN M87 at 5 GHz to study the properties of the M87 core, jet, and HST-1 structure.

## 2. Observations and Data Reduction

The observations have been carried out in e-VLBI mode, with data acquired by EVN radio telescopes, directly streamed to the central data processor at JIVE, and correlated

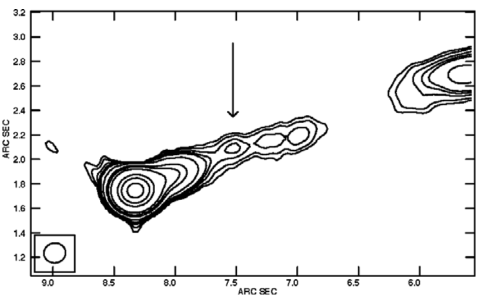


**Figure 1.** M87 jet obtained on March 1998 at 15 GHz with the VLA in A configuration. An arrow indicates the HST-1 position. Levs are: -3 1.5 2 3 4 5 10 30 50 100 500 1000 2000 mJy/beam. The HPBW is 0.16”

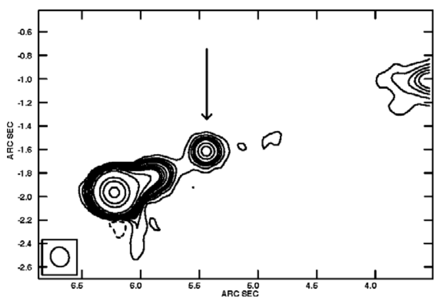


**Figure 2.** M87 jet obtained on June 2003 at 15 GHz with the VLA in A configuration. An arrow indicates the HST-1 position. Levs are: -3 2 4 6 8 10 15 20 30 50 100 500 1000 2000 mJy/beam. The HPBW is 0.16”

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in real-time. The observing frequency of 5 GHz was chosen to simultaneously grant a large field of view and a high angular resolution. For observations taking advantage of the long baselines provided by the Arecibo and Shanghai telescopes, our clean beam with uniform weights is about $2.0 \times 0.9$ mas in PA $-25°$.

We obtained 6 epochs at 5 GHz, namely on 2009 November 19, 2010 January 27, February 10, and March 28, and as Target of Opportunity on 2010 March 6, May 18, and June 9.

As a result of the large bandwidth (a rate of 1 Gbps was 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. We present here preliminary results. Data reduction was carried out in the standard mode using the AIPS and CalTech package.

## 3. Results

### 3.1. *The inner jet region*

The jet orientation and velocity has been discussed in many papers comparing observational data on the jet brightness and proper motion. Recently Acciari *et al.* 2009 assumed as a likely range $\theta = 15 - 25$ deg.

Because of the very similar uv-coverage, we used our images to search for evidence of a possible proper motion, comparing different epoch position of jet substructures and subtracting images at different epochs (with the same grid, angular resolution and similar uv-coverage) to look for possible systematic trends. No evidence was found in anycase.

We find a marginal evidence of a nuclear flux density increasing in the last three epochs.

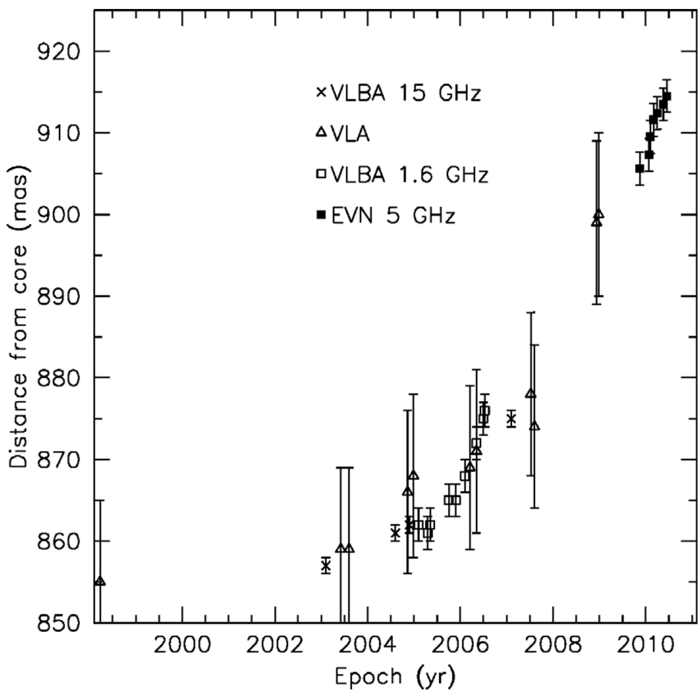


**Figure 3.** Distance of HST-1 brightest peak from the M87 core at different epochs

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In these epochs we have an increase of the core flux density and of the inner jet (within ∼8 mas) flux density. The data analysis is still in progress since it is not easy to separate the core and jet flux density because of the source structure.

### 3.2. *HST-1*

In our observations HST-1 is clearly resolved. It is oriented in E-W direction forming an angle of ∼20° with the jet axis. The HST-1 size is in agreement with a very small (∼0°) jet opening angle confirming the high jet collimation in the sub-arcsecond region.

To better study the dynamic of this structure we searched archive VLA data at high resolution (A configuration) and high frequency (U, and Q bands). We refer to Harris *et al.* 2009 for a discussion of the flux density variability. Here we only want to compare different epochs to derive the HST-1 dynamic.

We started to analyze data from 1998, even if HST-1 is very faint before of 2003. Starting from 2003.6 the HST-1 structure is well evident (see e.g. Fig. 2 obtained on June 2003) and well separated by the jet structure near the core.

We estimated from e-EVN and VLA data the distance of HST-1 from the core. In e-EVN data we measured the distance between the core and the brightest knot in HST-1, in VLA images we used the HST-1 peak, being this structure unresolved. Adding the values obtained at 1.5 and 15 GHz by Cheung *et al.* 2007 and Chang *et al.* 2010, respectively, we can study the HST-1 proper motion with a good statistic from 2003 to present epoch. The apparent proper motion of HST-1 is shown in Fig. 3.

A clear change in the proper motion velocity is present at the epoch ∼2005.5, coincident with the TeV $\gamma$-ray activity and the maximum radio/X-ray flux density of HST-1. In the time range 2003 – 2005.5 the apparent velocity is 0.5c – 0.6c; in the time range 2005.5 – 2010.25 the apparent velocity is ∼2.7c. We note also a possible 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 2.7c corresponds to an intrinsic velocity = 0.94c.

## 4. Summary

With our new e-EVN data we have obtained images of the nuclear region of M87 and of the jet substructure HST-1.

The radio core flux density is constant in the first three epochs with an average flux density ∼1805 mJy and slightly increasing in the last three epochs: 2013 mJy in 2010.25.

The HST-1 structure is well resolved in many substructures. A complex proper motion is clearly present. Comparing e-EVN data with archive VLA data and published VLBA data at 1.7 and 15 GHz we find a strong evidence that in 2005.5 HST-1 increased its velocity from an apparent velocity ∼0.5c to 2.7c. With present data it is not possible to discuss if this change in velocity is related to the M87 VHE activity and/or to the maximum radio/X-ray flux density of HST-1 at this epoch. A more regular and longer monitor and a multi-frequency comparison is necessary to clarify this point.

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## Discussion

MEIER: Cheung *et al.* (2007) claim that HST-1 is a complex of components, with one quasi-stationary and others moving up to $4.3\,c$. Please, comment on the differences between your data and Cheung *et al.*'s.

GIOVANNINI: We collected new anda archive data from 1998 to now. The data show a clear HST-1 proper motion with a shift in position larger than the HST-1 size, therefore, all the structure is moving. We agree with Cheung *et al.* (2007) that HST-1 is complex with many sub-structures, variable in flux density and position. However, in our data we do not see a stationary component. All the structure is moving at about the same velocity, the same velocity of the brightest sub-component.

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