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A multi-band flare in the M 87 jet 80 pc away from the central engine

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Abstract. The radio-loud active galactic nucleus M 87 hosts a powerful jet fueled by a super-massive black hole in its center. A bright feature 80 pc away from the central engine of M 87, namely HST-1, has shown a multi-band flare that peaked in 2005. Early radio, optical and X-ray observations have suggested that HST-1 is superluminal, and is possibly related to the TeV flare observed by HESS around 2005. Therefore, it was suggested that HST-1 has blazar-like activity. To examine the blazar-like nature for this superluminal knot in the M 87 jet, we analyzed VLBA 2 cm data of 15 epochs from 2000 to 2009. HST-1 is successfully detected with milliarcsecond resolution from 2003 to 2007, and our findings do not support that HST-1 has a blazar-like nature.

Key words. Radio continuum: galaxies – Techniques: high angular resolution – Techniques: interferometric – Galaxies: active – Galaxies: jets

1. Introduction

M 87 (Virgo A) is an active galactic nucleus (AGN) located in the Virgo cluster. It hosts a relativistic one-sided jet (Shklovsky 1964) emanating from the central supermassive black hole (Harms et al. 1994), and different projected jet apparent speeds were reported from 0.25 c to 6 c, based on multiband observations in the radio (e.g., Ly et al. 2007, Acciari et al. 2009; Kovalev et al. 2007, and Lister et al. 2009b) and in the optical (Biretta et al. 1999) bands. We are interested in the nature of a bright superluminal knot in the M 87 jet, which was firstly discovered by the *Hubble Space Telescope* (*HST*) in 1999 (Biretta et al. 1999). This bright knot, named HST-1, is located 1″ (80 pc) away from the core, and it is very active from the radio to the X-ray band.

In 2005, a TeV flare from M 87 was detected by the HESS telescope (Aharonian et al. 2006), and the multiwavelength observations of M 87 core and HST-1 show that the origin of the TeV emission could be in the HST-1 region. The TeV light curve of HST-1, with a peak in 2005, shows the same trend as ob-

Send offprint requests to: C. S. Chang served in the near ultraviolet band with the *HST* (Madrid 2009), in the soft X-ray band with *Chandra*, and in the radio band at 2 cm with the VLA (Harris et al. 2006; Cheung et al. 2007). Therefore, it was suggested that the TeV emission from M 87 might be generated from the HST-1 region, and that the HST-1 has a blazar nature (Harris et al. 2008). To examine this hypothesis, we re-imaged the VLBI observations of M 87 at 15 GHz from 2000 to 2009, and we applied wide-field imaging techniques to search for the HST-1 feature.

2. Data analysis

Since 1994, M 87 has been monitored at 15 GHz using the VLBA by the 2 cm Survey (Kellermann et al. 2004) and the MOJAVE program[1] (Lister et al. 2009a). We reanalyzed 12 epochs of observations from these monitoring program obtained after late 2001, together with three targeted observations of M 87 in 2000.

We applied 2D wide-field imaging technique to the HST-1 region. The HST-1 lies 80 pc (~800 beamwidths at 15 GHz) away from the VLBA core, and time or frequency data averaging would cause smearing in the HST-1 region. Therefore, we do not apply any averaging to the data in order to prevent smearing effects. Furthermore, based on earlier VLBA 1.5 GHz and VLA 15 GHz observations of HST-1 (Cheung et al. 2007), we expected the total flux density of HST-1 would be much weaker than the total flux density of the inner jet. To detect HST-1, we need to image the very extended structure of the inner jet region in order to remove the sidelobes which affect the HST-1 region. Therefore, we applied natural weighting and (u, v)-tapering to the whole dataset. The resultant beam size after tapering and natural weighting is $\sim$1.9 mas $\times$1.2 mas (position angle between -3° and -17°) with a slightly variations due to data conditions in each observing epochs. Furthermore, we degraded the resolution to a larger beam size of 8 mas $\times$3.4 mas with a position angle of 0°. We chose the beam size to be the same as at of in the VLBA 1.5 GHz observations (Cheung et al. 2007), in order to compare both results and to perform spectral analysis. Here we denote the smaller beams (obtained with tapering and natural weighting) as beam A, and the larger beams (8 mas $\times$3.4 mas) as beam B.

[1] `http://www.physics.purdue.edu/MOJAVE/`

3. Results

We completed the wide-field imaging of 15 epochs of observations on M 87 at VLBA 15 GHz obtained between 2000 and 2009. Each epoch was imaged using beam A and beam B. of thel 15 epochs, HST-1 was detected in six epochs from 2003 to early 2007. Figure 1 shows M 87 images of the inner jet and the HST-1 regions obtained in different frequencies. In Figure 1, we show the 4 epochs of HST-1 images with the most significant detections from 2004.61 to 2005.85 in beam A (green panel), and we show one epoch of HST-1 in beam B (red panel); we also show the inner jet of M 87 imaged in beam B (yellow panel). The HST-1 feature had a total flux density that varied between 4 mJy and 24 mJy, and a peak surface brightness that varied from 1 mJy to 4 mJy beam^{-1} (beam A) and 2 mJy to 10 mJy beam^{-1} (beam B) during 2003 and 2007. By comparing our HST-1 images (beam B) with the 1.5 GHz maps (Cheung et al. 2007 and Cheung, priv. comm.), we derived an average spectral index of $\alpha \sim -0.78$ ($S_\nu \propto \nu^{+\alpha}$). We fitted the peak of HST-1 and the M 87 core in the image plane with a Gaussian component using `IMFIT` in AIPS. By linear-fitting the relative position between the peak of HST-1 and the M 87 core in the six epochs of HST-1 detection, we derived the apparent projected speed of HST-1 to be $\beta_{\rm app} = 0.61 \pm 0.31$.

4. Conclusions

By analyzing our VLBA 15 GHz data from 2000 to 2009, we have detected HST-1 during the period 2003 to 2007, which covered the multi-band flaring period of HST-1. We obtained a slow motion of HST-1 ($\beta_{\rm app} = 0.61 \pm 0.31$ at 15 GHz), and we measured a steep spectrum of $\alpha \sim -0.78$ in this region.

The intensity of HST-1 reached a maximum in different wavebands in 2005, and the

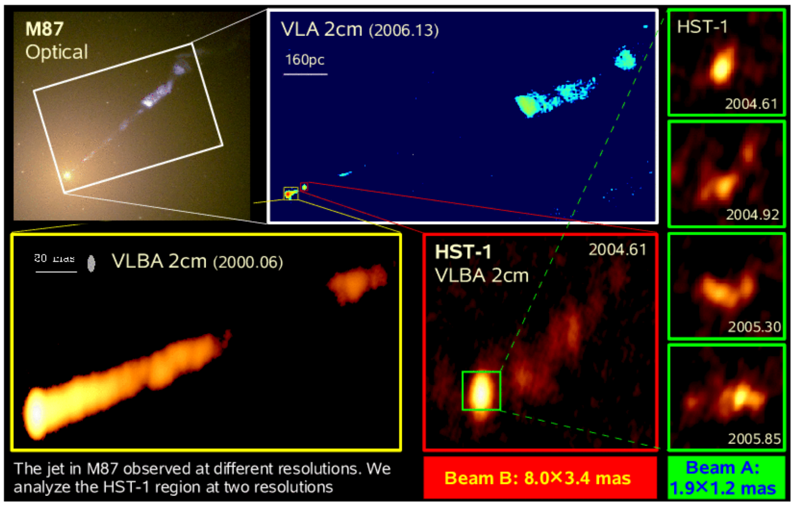

Fig. 1. M 87 and HST-1 observed in different bands. This figure illustrates the size scale of M 87 and HST-1 observed in different wavelengths. The panels in yellow, red, and green show the results of our observations. The optical image of M 87 was obtained by the *HST*, and the VLA 2 cm image was produced from the NRAO archival data.

light curves from the VLA 15 GHz, VLBA 1.5 GHz, near ultraviolet, and X-ray observations all show the same tendency (Harris et al. 2009; Madrid 2009). Our results are consistent with the other observations, that HST-1 brightened during the multiband flare in 2005. However, we see that HST-1 is extremely extended on parsec-scales, and it has a steep spectrum. There was no compact feature with a brightness temperature higher than $9{\times}10^6$ K present in the 15 GHz VLBA observations of the HST-1 region. Although we cannot completely exclude the possibility that the HST-1 was the source of the TeV flare in 2005, our results do not support that the HST-1 has a blazar nature.

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