VLBI OBSERVATIONS OF THE JET IN M 87 DURING THE VERY HIGH ENERGY $\gamma$-RAY FLARE IN 2010 APRIL

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ABSTRACT

We report on the detailed radio status of the M 87 jet during the very high energy (VHE) $\gamma$-ray flaring event in 2010 April, obtained from high-resolution, multi-frequency, phase-referencing Very Long Baseline Array observations. We especially focus on the properties of the jet base (the radio core) and the peculiar knot HST-1, which are currently favored as the $\gamma$-ray emitting sites. During the VHE flaring event, the HST-1 region remains stable in terms of its structure and flux density in the optically thin regime above 2 GHz, being consistent with no signs of enhanced activities reported at X-ray for this feature. The radio core shows an inverted spectrum at least up to 43 GHz during this event. Astrometry of the core position, which is specified as $\sim 20 R_\odot$ from the central engine in our previous study, shows that the core position is stable on a level of 4$\sigma$. The core at 43 and 22 GHz tends to show slightly ($\sim 10\%$) higher flux level near the date of the VHE flux peak compared with the epochs before/after the event. The size of the 43 GHz core is estimated to be $\sim 17 R_\odot$, which is close to the size of the emitting region suggested from the observed timescale of rapid variability at VHE. These results tend to favor the scenario that the VHE $\gamma$-ray flare in 2010 April is associated with the radio core.

Key words: galaxies: active – galaxies: individual (M 87) – galaxies: jets – gamma rays: galaxies – radio continuum: galaxies

Online-only material: color figures

1. INTRODUCTION

The location and the physical properties of very high energy (VHE) $\gamma$-ray emission from relativistic jets are some of the most intriguing questions in astrophysics. The nearby radio galaxy M 87 is a well-known VHE $\gamma$-ray emitter since the first identification of TeV emission by HEGRA in 1998/1999 (Aharonian et al. 2003). Thanks to its proximity ($D = 16.7$ Mpc, $z = 0.00436$; Jordán et al. 2005) and a large black hole mass ($M_{\text{BH}} \approx \frac{3}{6} \times 10^9 M_{\odot}$; Macchetto et al. 1997; Gebhardt & Thomas 2009), the jet structure can be resolved under close to 100 Schwarzschild radii scale ($R_\odot$) with very long baseline interferometry (VLBI) observations (Junor et al. 1999; Ly et al. 2007; Asada & Nakamura 2012; Hada et al. 2011, hereafter H11), providing a unique opportunity to probe the connection between the VHE $\gamma$-ray and the relativistic jet by isolating the detailed substructures.

Recently, there have been three remarkable VHE flares from M 87: the events in 2005, 2008, and 2010. In the 2005 event (Aharonian et al. 2006), the VHE flare was accompanied by radio-to-X-ray flares from HST-1, a peculiar knot located at a de-projected distance of at least $\sim 120$ pc downstream of the nucleus (Harris et al. 2006), with the emergence of superluminal ($\sim 4 c$) radio features (Cheung et al. 2007). These lead to the strong argument that the VHE emission originates in HST-1 (e.g., Stawarz et al. 2006; Cheung et al. 2007; Harris et al. 2008, 2009), although there are still some debates on this interpretation (e.g., Georganopoulos et al. 2005). In the case of the 2008 event, on the other hand, the Chandra X-Ray Observatory detected an enhanced X-ray flux from the nucleus, while HST-1 maintained a comparatively constant flux. In addition, synchronized Very Long Baseline Array (VLBA) observations at 43 GHz revealed a strong flux increase from the radio core that lasted the subsequent $\sim 2$ months. These provide evidence that the VHE flare in 2008 originates in the core (Acciari et al. 2009).

The third flare occurred more recently, in 2010 April, where the VHE flare was clearly detected during the joint monitoring campaign by H.E.S.S. VERITAS, and MAGIC (Ong & Mariotti 2010; Aliu et al. 2012; Abramowski et al. 2012, hereafter A12). The detected flare displays a smooth rise and decay in flux with a peak around MJD 55296 (2010 April 9 and 10), reaching a historic high state of about 20% of the flux of the Crab Nebula. Interestingly, Chandra observations taken $\sim 3$ days after the peak of the VHE flare detected an enhanced flux from the nucleus, whereas HST-1 remained in a low state (Harris et al. 2011). Short timescales of variabilities observed at VHE and X-ray suggest that the size of the emitting region is of the order of a few light days times the Doppler factor $\delta$, which corresponds to less than $\sim 10 \delta R_\odot$. We note, however, that a detailed study on HST-1 by Giroletti et al. (2012, hereafter G12) confirmed a recurrence of this structure and its possible connection with the VHE activity.

While the broadband light curve is studied in A12, in this paper we report on the detailed radio status of the M 87 jet during...
Figure 1. Summary of VLBA images of the M 87 jet during the VHE γ-ray flare in 2010 April. The main (global) image at 2 GHz was obtained by combining the data on 2010 April 8 and 18. The bottom right inset indicates a close-up view toward the HST-1 region. The nomenclatures of the two main features (comp1 and comp2) are based on G11. The upper left inset indicates a 43 GHz image for the core and the inner jet (also obtained by averaging both epochs). The beam sizes at 2/43 GHz are 7.5 × 3.9 mas in P.A. −54° (bottom right in the inset of HST-1) and 0.43 × 0.21 mas in P.A. −16° (bottom right in the 43 GHz image), respectively. For each image, contours start from −1, 1, 2... times 3σ image rms levels (3σ = 1.0/3.5 mJy beam−1 at 2/43 GHz) and increasing by factors of 1.4.

The 2010 VHE flaring event obtained from high-resolution VLBA observations. We especially focus on the multi-frequency observations which successfully synchronized with this event, providing a wealth of information for HST-1 and the inner jet during the flare on a milliarcsecond scale. The data and the analysis are described in the next section. We then show the results in Section 3. In the final section, we discuss the results obtained and give a summary. In the present paper, the spectral index α is defined as $S(\nu) \propto \nu^{\alpha}$.

2. OBSERVATIONS AND DATA REDUCTION

M 87 was observed with the VLBA at 2, 5, 8, 15, 22, and 43 GHz on 2010 April 8 and 18 (MJD 55294 and 55304), which are just before and just after the date of the maximum flux of the VHE flare (MJD 55296). These data, which were not presented in A12 except for the results of the HST-1 flux at 2 GHz, are identical to those presented in H11, where we investigated the core shift of M 87 using the phase-referencing technique relative to the nearby radio source M 84. The details of the observations and the data reduction processes including the astrometric analysis are described in H11. For this paper, we partly reanalyzed the data in order to properly examine the radio status of M 87 including the HST-1 region, which is located ∼900 mas away from the phase-tracking center. The data were averaged only to 5 s in time and individual channels (1 MHz width) were kept separated before the imaging process to avoid time/bandwidth smearing effects at the location of HST-1.

In addition, we also analyzed many available VLBA archival data at 43 and 22 GHz to investigate the light curve of the inner jet region around the VHE flare (see Section 3.2). These consist of the data on January 18 (22 GHz), April 4 (22 GHz), May 1 (22 GHz), May 15 (22 GHz), and May 30 (22 and 43 GHz) 2010, which were not included in A12.

Images were created in DIFMAP software with iterative phase/amplitude self-calibration. Several weighting schemes were used depending on the target region. In Figure 1, we summarize representative images of the M 87 jet obtained from our observations.

3. RESULTS

3.1. The HST-1 Region

The HST-1 region was detected at both epochs at 2 and 5 GHz on a level of 12σ and 7σ image rms, respectively. At 8 GHz, the analysis combined for both epochs with a relatively strong $\nu\nu$-tapering detected this region with ∼8σ. The feature was not detected at 15, 22, and 43 GHz due to the image sensitivity limit. Some of the HST-1 properties in these epochs (i.e., the distance from the core and the position angle, P.A., of the HST-1 region at 2 GHz) have already been reported in G12 in the context of the long-term kinematic study of this feature.

The overall structure observed in these epochs is similar to that in 2010 January, the image for which is presented in G12. The HST-1 region is resolved into two main subfeatures with an overall extension of ∼40 mas at 2 GHz. Model fitting with two Gaussian components yields the sizes of these features as ∼18 mas (1.5 pc, $2.5 \times 10^{3} R_{S}$) and ∼16 mas (1.3 pc, $2.2 \times 10^{3} R_{S}$) for the upstream/downstream components, respectively. While the emergence of a new component upstream from HST-1 is discovered in the later epochs of 2010 (G12), such a feature is not found in our observations on April 8 and 18. The brightness temperature for the brightest component is estimated to be $\sim 1 \times 10^{7} K$, which is similar to the upper limit of $9 \times 10^{6} K$ derived in the previous study at 15 GHz (Chang et al. 2010).

In Figure 2, we show the integrated radio spectrum of the HST-1 region in these epochs. The HST-1 region shows a steep spectrum with an averaged spectral index of $\alpha \sim -1.2$, indicating that the emission region is optically thin. This radio spectral index seems to be slightly steeper than the values for the optical bands ($\alpha_{O-UV} \lesssim -0.7$; Perlman et al. 2011), which were measured between 2002 and 2007. The spectral shapes are quite similar between these two epochs and no significant
flux variation was found within the errors. The magnitudes of the flux densities in these epochs appear to follow the long-term, monotonically decaying trend that continues since the maximum phase in 2005. These observational characteristics at radio frequencies are consistent with no signs of enhanced activities in HST-1 at X-ray during 2010 (A12; Harris et al. 2011).

3.2. The Core and the Inner Jet Region

The inner jet region was clearly detected at all frequencies during the VHE flaring phase. This region is characterized by the compact core with the edge-brightened structure as seen in the 43 GHz image in Figure 1. Similar images are obtained when images are created separately for April 8 and 18.

In Figure 3, we show the light curve of the inner jet region at 43 and 22 GHz around the 2010 flaring event. This is an updated version of the 43 GHz light curve presented in A12, which did not include the data points analyzed here. Based on Acciari et al. (2009) and A12, the fluxes for three different regions are provided: (1) the peak flux when convolved with a beam of 0.43 × 0.21 mas in P.A. −16° at 43 GHz or 0.54 × 0.27 mas in P.A. −10° at 22 GHz, (2) the nucleus (the deconvolved flux in the circular region of radius 1.2 mas = 0.1 pc, centered on the intensity peak), and (3) the flux integrated along the jet between distances of 1.2 and 5.3 mas from the intensity peak. We assign 5% errors to all of the data points because the amplitude calibration of the VLBA is typically accurate within ±94% both at 22 and 43 GHz compared with the other epochs. This is in contrast to the event in 2008, where the 43 GHz core underwent a remarkable flux increase (up to ~30%) lasting the subsequent ~two months together with a flux enhancement from the X-ray core (Acciari et al. 2009).

In Figure 4, we next show the radio spectra of the inner jet on April 8 and 18 for the three regions. Note that, regarding the peak fluxes at 22 and 43 GHz, the data have all been convolved with a 22 GHz beam to match the spatial resolutions. The spectra of each region look quite similar between April 8 and 18. We found the following spectral characteristics as a function of the measured region: the spectra gradually change from steep to flat toward the upstream side (α ~ −0.7 at (3) to ~ −0.1 at (2)), and the spectrum of the innermost region (1) becomes slightly inverted between 22 and 43 GHz with α ~ 0.1, indicating that region (1) is optically thick at these frequencies. This is consistent with the detection of the core shift reported in H11, because this effect occurs only when the core represents an opaque part of the synchrotron emission at each frequency. For some other radio sources, their inverted radio cores are caused by foreground free–free absorption (e.g., Kellermann 1966; O’dea 1998), but that does not seem to be the case for M 87 (Ly et al. 2007). The measured frequency dependence of the core shift ν~0.94±0.09 by H11 is in good agreement with ν~1, which is typically expected when the core is dominated by synchrotron self-absorption (SSA; e.g., Blandford & Königl 1979; Königl 1981; Lobanov 1998).

In Figure 5, we finally show the difference in the core shift (in right ascension, R.A., direction) between these two epochs (i.e., r_{core,v}(t = MJD55304)−r_{core,v}(t = MJD55294)). Because...
Figure 4. Radio spectra of the central region of M 87 on 2010 April 8 and 18. The peak fluxes at 22 and 43 GHz were estimated with the synthesized beam at 22 GHz (0.54 × 0.27 mas in P.A. –10°).

(A color version of this figure is available in the online journal.)

Figure 5. Astrometry of the core positions. (Top panel) Detected core shifts in R.A. direction on April 8 and 18 (Hada et al. 2011). (Bottom panel) Difference in the core position (in R.A. direction) between April 8 and April 18 at each frequency (the positions on April 18 minus the ones on April 8). Positive direction indicates the jet direction.

4. DISCUSSION AND SUMMARY

The location and the physical properties of the VHE \( \gamma \)-ray emission of M 87 are still under hot debate. The core and HST-1 are currently favored as the emitting sites based on the multi-band correlations detected in the 2005 and 2008 events, respectively. In the case of the 2010 flare discussed here, Chandra detected an enhanced X-ray flux from the nucleus during the VHE flare, while HST-1 remained in a low state (Harris et al. 2011). This is reminiscent of the 2008 case. The observed timescales of short variability at VHE/X-ray suggest that the size of the emitting region is less than \( \sim 10 \delta R_s \). This leads to the argument that the 2010 VHE flare probably originates in the innermost jet region, at least within the resolution element of Chandra (0.6 \( \sim \) 50 pc; A12).

At the radio bands, we did not find remarkable activities either in the inner jet or HST-1 during this event. However, the results obtained tend to favor the above interpretation rather than the HST-1 origin. For the HST-1 region, we did not find any compact sub-components that could account for the small emitting volume suggested from the rapid VHE/X-ray variabilities. From the observed optically thin radio spectra of HST-1, one can expect simultaneous correlation between radio and VHE if the 2010 event originates in this feature, but instead the radio flux is constantly decreasing. The discovery of a new component upstream of HST-1 in 2010 is particularly intriguing (G12), but the timing of its appearance seems to be slightly offset from the VHE event. The radio core, on the other hand, remains very compact during this period. Gaussian model fitting to the 43 GHz visibility data indicates a deconvolved size of the radio core \( \sim 0.12 \) mas (17 \( R_s \)), which is close to the size of \( \lesssim 10 \delta R_s \). Moreover, the observed optically thick nature of the radio core possibly hides or weakens the VHE-related activity at the radio bands, which could be related to the relatively moderate evolution of the radio core flux. A possibility that the

the detected core shifts on April 8 and 18 are quite similar to each other, we did not find any significant time evolution of the core position over the all observed frequencies. The result at 43 GHz, where the measurement attains the highest position accuracy, indicates that the core position remains stable on a level of 4 \( R_s \) (projected scale on the sky) during this period. A similar result is reported during the VHE flare in 2008 (not more than \( \sim 6 \) \( R_s \); Acciari et al. 2009).
jet between the core and HST-1 is the γ-ray emitting source is not completely ruled out because Chandra does not resolve this region. However, this scenario seems to be problematic because this region is relatively extended compared with the suggested emitting volume, and maintains optically thin radio spectra with constant flux density during the VHE flare.

It should be noted that the core shift measurements obtained in these observations locate the 43 GHz radio core position at ∼20 R_s from the central engine (H11). This implies that the site of the VHE γ-ray associated with the core is not more distant than ∼20 R_s from the black hole. In this case, the ambient radiation field, such as from the accretion flow, could absorb the emitted TeV photons due to the process of photon(VHE)–photon(IR) pair creation (Neronov & Aharonian 2007). However, M 87 has only a weak IR nucleus (νL_ν ∼ 10^{40–41} erg s^{-1}; Perlman et al. 2001), so this allows the γ-ray photons up to ∼20 TeV to escape even from within 20 R_s of the black hole (Brodatzki et al. 2011).

If the VHE flare in 2010 really originates in the core, one should explain the reason for the distinct behavior of the radio-to-γ-ray correlation between 2008 and 2010. One possibility is the difference of the opacity at the radio bands between 2008 and 2010 due to the change of magnetic field strength. Assuming that the emitting plasma is spherical and uniformly magnetized, one can estimate the magnetic field strength through the condition of SSA as B = 3.2 × 10^{-3} ν_b^2 S_m^2 ρ^{-1/2} (1 + z)^{-1} Gauss, where ν_b, S_m, and ρ give the angular size of the emitting region in mas, the SSA turnover frequency in GHz, the flux density at ν_m in Jy (Kellermann et al. 1981). Adopting ρ ∼ 0.12 mas, ν_m ∼ 43 GHz, S_m ∼ 0.7 Jy, δ ⩾ 1, B is estimated to be ⩾2.0 G. In the case of the 2008 flare, on the other hand, a time-dependent modeling of the 43 GHz core light curve based on SSA indicates a relatively moderate magnetic field strength ∼0.5 G (Acciari et al. 2009). If we assume that the other parameters maintain roughly the same values between 2010 and 2008, this yields ν_m ∼ 35 GHz, resulting in the 43 GHz core being partially optically thin in 2008. Thus, more of the radio emission can escape from the γ-ray emitting site, leading to the stronger radio/VHE correlation in the 2008 case.

The radiative cooling due to synchrotron emission may also contribute to the weaker activity of the radio core in 2010 because of its relatively stronger magnetic field. The timescale of the synchrotron cooling at a frequency ν_c can be estimated as t_{sync} ∼ B^{-3/2} ν_c^{-1/2}, where ν_{sync}, B, and ν_c are measured in years, Gauss, and GHz (Scheuer & Williams 1968).

The cooling timescale of the 43 GHz emission, t_{sync,43GHz} under B ⩾ 2.0 Gauss results in t_{sync} ∼ 20 days. This timescale is comparable to the duration of the possible decaying pattern of the radio core flux (seen for the region (1) between MJD 55295 and MJD 55332).

While various γ-ray production models for the black hole vicinity/jet formation region have been proposed (Reimer et al. 2004; Neronov & Aharonian 2007; Lenain et al. 2008; Tavecchio & Ghisellini 2008; Barkov et al. 2010), it is not easy to discriminate between such models on the basis of these observations alone. To constrain the exact location and match the γ-ray emission process to a specific model, the use of higher frequency VLBI (Doelman et al. 2012) is promising; this will provide higher transparency to the γ-ray emitting region with an event horizon scale resolution.

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