SUPERLUMINAL RADIO FEATURES IN THE M87 JET AND THE SITE OF FLARING TeV GAMMA-RAY EMISSION

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ABSTRACT

Superluminal motion is a common feature of radio jets in powerful γ-ray–emitting active galactic nuclei. Conventionally, the variable emission is assumed to originate near the central supermassive black hole where the jet is launched on parsec scales or smaller. Here we report the discovery of superluminal radio features within a distinct flaring X-ray–emitting region in the jet of the nearby radio galaxy M87 with the Very Long Baseline Array. This shows that these two phenomenological hallmarks—superluminal motion and high-energy variability—are associated, and we place this activity much farther (≥120 pc) from the “central engine” in M87 than previously thought in relativistic jet sources. We argue that the recent excess very high energy TeV emission from M87 reported by the H.E.S.S. experiment originates from this variable superluminal structure, thus providing crucial insight into the production region of γ-ray emission in more distant blazars.

Subject headings: galaxies: active — galaxies: individual (M87) — galaxies: jets — radio continuum: galaxies — radiation mechanisms: nonthermal

1. INTRODUCTION

The proximity of M87 (D = 16 Mpc; Tonry 1991) makes it one of the best systems to study relativistic jets at high linear resolution (Fig. 1). Our observations with the Chandra X-Ray Observatory isolated short (month) timescale variability (Harris et al. 2006) in a jet region previously dubbed “HST-1,” which is separated by 0.86° (60 pc, projected) from the central “active” supermassive black hole (SMBH). The variability culminated in a factor >50 X-ray outburst, making HST-1 the brightest X-ray source in the galaxy for a few years. Figure 2 shows a light curve from 2000 to the end of 2006.

Observations with the Hubble Space Telescope (HST) and the Very Large Array (VLA) show comparable activity in the optical and at radio frequencies (Perlman et al. 2003; Harris et al. 2006). After the detection of appreciable radio flux in HST-1 from our first season of VLA observations (in 2003), we began to monitor the jet at higher (subparsec) resolution with the NRAO’s Very Long Baseline Array (VLBA) at three frequencies (0.33, 0.61, and 1.7 GHz) commencing in 2005 January. This was the period at which the X-ray and optical intensities were peaking, and the radio intensity plateaued (Fig. 2). Here we report on the highest resolution (1.7 GHz) observations that resolve dynamic structures within the flaring X-ray region, including the discovery of superluminal motion in multiple knots. The implications for observations of more distant γ-ray–emitting relativistic jets are discussed.

2. DESCRIPTION OF OBSERVATIONS

Each of our nine VLBA runs consisted of six 1 hr integrations of M87 over an 8 hr period, with calibrator observations interleaved. Four adjacent 8 MHz bandwidth channels were used, centered at 1.667 GHz. The full 10 antenna array was used, except in 2005 January (missing Hancock antenna), 2005 May (missing Saint Croix), and 2006 May (missing Pie Town). The data were calibrated using NRAO’s VLBA data calibration pipeline in AIPS and postprocessed with a combination of DIFMAP and AIPS. The rms noise in the VLBA images are within 15% of the theoretically predicted value for the full VLBA (0.053 mJy beam ). The images have been restored with a common beam (Fig. 3) that is within 10% of the uniformly weighted beams of all but the 2005 May epoch.

Over the inner jet, the new sequence of VLBA images shows previously known radio structure out to ~250 mas from the core (Biretta & Junor 1995; Dodson et al. 2006), with additional transversely resolved emission between ~200 and 450 mas (Fig. 1). The central position angle (P.A. ~ 290°) of the first ~100 mas portion of the jet aligns roughly with the large-scale VLA jet. Knot HST-1 is farther downstream and is offset from the central jet by being aligned with the projection of the northern edge of the resolved ~200–450 mas jet (i.e., P.A. ~ 294.5°).

A short 2.3 GHz VLBA observation obtained in 2004 July by the USNO (Fey & Charlot 2000) detected only the two brightest features in HST-1 seen in our early VLBA images, allowing us to trace these structures back by ~0.5 yr before our program commenced. Further archival VLBI observations of varying quality as far back as 2000 (e.g., Dodson et al. 2006) did not give any significant detections of HST-1. We registered the images from the different epochs on the position of the maximum of the radio core (Fig. 1). Based on the stability of the structure of the inner jet (Dodson et al. 2006) over the 10 total epochs of observations, the core position is determined to be aligned to a fraction of the common beam over the 2 yr period.

With the images registered, the upstream (eastern) edge, which we call “HST-1d,” is the dominant feature in the HST-1 complex at the early epochs. The later epoch images reveal the emergence of a radio knot (HST-1c) moving downstream from HST-1d at a rate of 4.48 ± 0.42 mas yr (βapp = 1.14 ± 0.14c) at a P.A. of 279°, and the peak radio surface brightness decays by only ~20% over a 1 yr period. Sometime between 2005 December and 2006 February, knot HST1c evidently splits into two roughly equally bright features: a faster moving component (c; 4.3c ± 0.7c) and a slower moving

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trailing feature (c2; $0.47c \pm 0.39c$). Between the two years, the location of HST-1d is basically stationary to within ~2 mas (i.e., its motion is $<0.25c$) at 860 mas from the core and is the apparent point of origin of the superluminal ejections.

The most distant knot (HST-1a) is well isolated from the other structures in every observation. We observe it moving downstream at $2.49c \pm 0.25c$ at P.A. = $295^\circ \pm 8^\circ$ (basically radial) until 2005 December when it appears to decelerate to $1.41c \pm 0.49c$ at a smaller P.A. of $289^\circ$ (although the P.A. change is apparent in Fig. 4, it is not statistically significant). A fainter feature (HST-1b), identifiable beginning 2005, trails HST-1a at an identical speed ($2.52c \pm 0.14c$) with a nonradial trajectory (a smaller P.A. of $279^\circ \pm 6^\circ$). Feature c1 (see above) actually ends up in 2006 July where HST-1b was first detected in 2005 January.

Fig. 2.—Light curves of the total TeV emission from M87 (taken from Aharonian et al. 2006) and of the jet knot HST-1 (X-ray and two radio bands). The 2 keV and 15 GHz data up to approximately 2005 August were previously published in Harris et al. (2006). Our subsequent observations now show the X-ray intensity of HST-1 declining steeply, similar to the total TeV emission from M87. The 1.7 GHz VLBA points are integrated from the entire HST-1 complex.
a maximum coinciding with the peak of the radio–to–X-ray activity detailed in HST-1 (mid-2005; Fig. 2) suggesting a link between these flares. However, the HST-1 knot was dismissed as a possible production site of the TeV emission (Aharonian et al. 2006) because of the short (days) timescale TeV variability detected on top of the longer timescale variability. Such rapid variations were considered unlikely for HST-1 since they imply (through the causality argument) an emission region size $R_{\text{var}} \approx 0.0028 \text{ pc}$. We can neither claim nor reject the presence of ~1 day timescale variability in our optical or X-ray data for HST-1 due to insufficient sampling. However, the VLBA data show the compact knots in HST-1 to be essentially unresolved with semimajor axes $<0.15 \text{ pc}$, and the current optical/X-ray variability data constrain $R_{\text{var}} \leq 0.0226 \text{ pc}$ (see below), approaching the size limits set by the variability of the TeV emission.

Here we suggest HST-1 as a plausible site for the production of a dominant portion of the detected very high energy (VHE) TeV emission due to inevitable inverse Compton upscattering off ambient photon fields (e.g., starlight) by the electrons producing the flaring synchrotron optical–to–X-ray emission. This was in fact proposed by Stawarz et al. (2006) in discussing earlier (2004 and before) TeV detections of M87. The connection is strengthened by the fact that the maxima of the total TeV flux density from M87 and synchrotron (HST-1 only) flares observed in 2005 were coincident, and that their luminosities are comparable (Fig. 2). In addition, the 0.4–10 TeV emission from M87 at this time is well described by a single power law with spectral index $\alpha_v = 1.2 \pm 0.15 \ (S \propto v^{-\alpha})$, while the optical–to–X-ray power-law slope of HST-1 during the same period is similar: $\alpha_{OV} = 0.99 \pm 0.03$. These observations are consistent with a common origin for the flaring radio through $\gamma$-ray emission from HST-1 as outlined in more detail in Stawarz et al. (2006).

The above conclusion is supported by the lack of any other plausible production site for the VHE $\gamma$-ray emission in M87. For example, the innermost (subparsec scale) jet region is characterized by only small-amplitude optical/X-ray variability (Harris et al. 2006) and only mildly relativistic radio features (Ly et al. 2007). As argued also by Aharonian et al. (2006), this is inconsistent with models for the generation of VHE emission in the unresolved core (Georganopoulos et al. 2005). Instead, Aharonian et al. (2006) considered curvature radiation of ultra–high-energy protons (Levinson 2000; Boldt & Loewenstein 2000) accelerated by a strong magnetic field in the closest vicinity ($<3R_\text{g}$) of the SMBH at the center of M87. However, this interpretation is also problematic due to the fact that the nearest environments of active SMBHs are expected to be opaque to TeV photons as a result of photon-photon annihilation on ambient photon fields such as from the accretion disk.

In M87, the $\gamma$-ray photons in the energy range covered by H.E.S.S. ($\epsilon = 1–10$ TeV) interact mostly with photons emitting at $\nu_0 \sim 2 \times 10^{21}$ Hz (i.e., infrared to optical ones). Quantitatively, the optical depth for the $\gamma\gamma$ annihilation process can be approximated by $\tau_{\gamma\gamma} \approx \tau_{\gamma\text{e}} r_{\text{e}}$, where $\tau_{\gamma\text{e}}$ is the Thomson cross section. The number density $n_{\text{e}}$ of the $h\nu_\text{e}$ nuclear photons within a spherical volume around the SMBH of radius $r$ is related to the monochromatic luminosity $L_\nu$ by $n_{\text{e}} L_\nu = L_\nu / 4\pi r^2$, (the main contributor to the photon energy density is judged to be from the accretion disk). Hence, one can find $\tau_{\gamma\gamma} \approx 2L_\nu \times 10^{10}$ ergs s$^{-1}$($\nu/10^{13}$ Hz)$^{-1}$($r/R_\text{g}$)$^{-1}$. The considered region would be transparent to the TeV photons only if

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3. DISCUSSION AND SUMMARY

The importance of the superluminal motions reported here is twofold. First and foremost, the HST-1 complex is well isolated from the nucleus and the rest of the jet, so the outbursting higher energy (X-ray, optical) emission isolated by $\textit{Chandra}$ and HST can be uniquely attributed to the region resolved by our VLBA observations (Fig. 1). While VLBI detections of superluminal motions are now commonplace in more distant relativistic jet sources (e.g., Kellermann et al. 2004), the physical link to the higher energy activity has not been possible previously because of the lack of comparably high spatial resolution (e.g., Jorstad et al. 2001). Second, contrary to conventional wisdom, this “blazar”-like activity is clearly displaced from the central engine by $\geq 120$ pc (deprojected; see § 3.2). Thus, at least in the case of M87, the observed hallmarks of blazar behavior are not directly associated with the immediate vicinity of the SMBH where the jet is launched (Junor et al. 1999). Without the comparably high linear resolution, an analogous sequence of events in a more distant source would be associated with the base (i.e., subparsec to a few parsec scales) of the jet where the “nonjetted” contribution from the active galactic nucleus (AGN) to the observed X-rays (such as from the accretion disk; Marscher et al. 2002) would contaminate the light curves.

3.1. The Origin of Very High Energy $\gamma$-Ray Emission in M87

At even higher energies, the H.E.S.S. collaboration recently reported flaring TeV emission from M87 (Aharonian et al. 2006). This emission revealed gradual (year timescale) variability, with
3.2. HST-1 as a Recollimation Shock

A natural question to ask is if the position of the HST-1 knot in the M87 jet is “special” in some way. In other words, what determines the location and flaring behavior of this extremely compact and variable feature within the relativistic outflow? The kinematics of the superluminal components (in particular, the 4.3c motion in c1) constrains the jet at the location of HST-1 to be aligned at $\theta \approx 26^\circ \pm 4^\circ$ and requires that $\Gamma \gtrsim (\beta^2 + 1)^{1/2} = 4.4$ and $\delta \approx 2$. The HST-1 region is therefore $\approx 120$ pc (deprojected assuming $\theta \approx 30^\circ$).

For a SMBH with $M_{\bullet} \approx 3 \times 10^9 M_\odot$ (Macchetto et al. 1997), this corresponds to the distance of $\approx 10^3$ Schwarzschild radii ($R_s = G M_{\bullet} / c^2 \approx 4.4 \times 10^{14}$ cm $\approx 1.4 \times 10^{-4}$ pc). At such a large distance from the active center, our X-ray observations establish flux doubling timescales of $0.14$ yr (Harris et al. 2006), which constrain $R_{\text{acc}} < c t_{\text{var}} \delta \approx 0.0226$ pc.

Recently, Stawarz et al. (2006) showed that the position of the HST-1 knot agrees with the expected location of a “reconfinement nozzle” formed within the M87 jet due to a converging shock driven by the interaction of the outflow with the interstellar medium (ISM). In this ambient medium, it was postulated that the gravitational influence of the central SMBH in the inner region of the M87 host galaxy (Lauer et al. 1992) results in an increase of the gas pressure, analogous to the formation of the observed enhanced stellar cusp (Young et al. 1978). For the temperature $k T_{\text{ISM}} \approx 0.8$ keV of hot gaseous ISM (with the number density $n_{\text{now}} \approx 0.17$ cm$^{-3}$) in the inner ($<1$ kpc) parts of the galaxy, the gravitational capture radius is $R_s = G M_{\bullet} / c^2 \approx 100$ pc, where $c$ is the appropriate sound speed (Di Matteo et al. 2003). It turns out that $\approx 100$ pc is the spatial scale of the disk of ionized gas observed in M87 by the HST (Ford et al. 1994). It was the Keplerian rotation of the inner parts of this disk that enabled a precise estimate of the black hole mass in this system (Macchetto et al. 1997).

Thus, one can surmise that a gravitationally perturbed ambient medium leads naturally to the formation of a jet feature like HST-1 at $\approx 100$ pc from a central SMBH. In this scenario, the “stationary” region HST-1d defines the opening of the nozzle. The origins of the different superluminal features can be traced back to this position at $\approx 2004.5$ (HST-1e), 2003.3 (HST-1b), and 2001.9 (HST-1a). The latter two could have originated more recently as they assume the nominal velocities of $2.5c$; the apparent curve in the trajectory and deceleration of HST-1a leads us to believe that it could have been moving faster previously to our first VLBA imaging observations.

The formation of a reconfinement nozzle within the jet is not unique for the hydrodynamical outflow considered by Stawarz et al. (2006). It was previously shown (Tsinganos & Bogovalov 2002) that interactions between a strongly magnetized relativistic outflow with a nonrelativistic collimating magnetohydrodynamical (MHD) wind may lead as well to the formation of a converging shock within the relativistic component. An evaluation of the exact position of this shock from the jet base is extremely model-dependent. Nevertheless, for the jet parameters anticipated by Gracia et al. (2005), who successfully explained the observed gradual collimation of the M87 jet between $10^3 R_s$ and $10^5 R_s$ (Junor et al. 1999) based on the Tsinganos & Bogovalov (2002) MHD model, the expected position is near the location of the HST-1 knot. We speculate that a rapid release of the magnetic energy within the formed nozzle via magnetic reconnection may play an important role in producing the observed high-energy flares and ejection of the relativistic radio blobs, somewhat analogous to coronal mass ejections from the Sun (Pick et al. 2006).

In summary, we have discovered superluminal motions of radio features in the M87 jet at a site remote from the central SMBH. These features appear to be associated with the remarkable flare of 2005 for which the radio, optical, and X-ray flux densities peaked at levels of $>30–50$ times that of a few years earlier. We have argued that the TeV excess intensity of 2005 detected from M87 by H.E.S.S. was a manifestation of the same event. Thus, most of the defining characteristics of blazars have now been shown to occur at a distance $\approx 120$ pc from the SMBH instead of from the immediate environs of the central engine, as is commonly believed to be the case. As we enter the GLAST era, ensuing studies of high-energy flares from blazars should consider such a production site as we have resolved in M87.

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