HST-1 as a window into the energetics of the jet spine of M 87

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ABSTRACT

We present a new interpretation of the optical knot, HST-1, in the jet of M 87. High-sensitivity 22 GHz Very Large Array images have located HST-1 to within 6 mas of the jet axis immediately upstream. Based on 1.7 GHz Very Long Baseline Array images of a bright flare in 2005, we see that preponderance of emission in the early stages originates from an elongated region that is tilted 12.5° from the jet axis. The superluminal motion, shape, location, and the large jet-aligned optical flare in 2005, we see that preponderance of emission in the early stages originates from an elongated region that is tilted 12.5° from the jet axis. As such, energy flux estimates for HST-1, ~870 mas from the nucleus, published in 2006, indicate that the central engine injected, $Q_{\text{spine}} \approx 2.5 \times 10^{41} \text{ergs s}^{-1}$, into the base of the spine about 200 yr earlier. Furthermore, previous studies have revealed a tubular protonic jet on sub-mas scales that envelopes a low luminosity core, presumably the faint spine base. It was estimated that the central engine injected, $Q_{\text{tubular\ jet}} \approx 6.1 \times 10^{41} \text{ergs s}^{-1}$, about 1.5 yr earlier. If one component of the jet is inherently more powerful, a firm constraint on total jet power in the recent past would then exist. If the emitted jet is inherently dominated by the spine (tubular jet), then the total bilaterally symmetric jet power emitted from the central engine was $<4Q_{\text{spine}} \approx 1.0 \times 10^{42} \text{ergs s}^{-1}$ ($<4Q_{\text{tubular\ jet}} \approx 2.4 \times 10^{42} \text{ergs s}^{-1}$) ~200 (~1.5) yr earlier. Assuming a nearly constant central engine injected jet power for ~200 yr indicates a total jet power of $\lesssim 2 \times 10^{42} \text{ergs s}^{-1}$ in epochs of modern observation or $\lesssim 5\%$ jet production efficiency for an accretion rate of $0.001 M_\odot \text{yr}^{-1}$. Seemingly, the focus of Event Horizon Telescope Collaboration (EHTC) numerical models should be biased toward jet powers of $\lesssim 2 \times 10^{42} \text{ergs s}^{-1}$, as opposed to larger estimates from ejections many centuries or millennia earlier.

Key words. black hole physics – galaxies: jets – galaxies: active

1. Introduction

The nearby galaxy M 87 ($\sim 16.8 \text{Mpc}$ distant) is host to the most studied astrophysical jet. A bright optical knot was found with the Hubble Space Telescope (HST) ~870 mas from the nucleus (Biretta et al. 1999). It is the most superluminal feature ever witnessed in the jet that was typified by subluminal motion at that time. Thus, it experienced tremendous observational attention. In early 2005, it flared in the optical/UV and X-ray to end up becoming brighter than the nucleus (Harris et al. 2006). It was a likely candidate to be the source of a TeV flare in this epoch (Abramowski et al. 2012). HST-1 has been described in terms of a re-collimation shock (Stawarz et al. 2006), however, the current work offers an alternative explanation of its origins, namely, that of a dissipative region of the relativistic central spine of the jet.

The notion of a sheath and a highly relativistic spine has been used to understand high-energy phenomena in blazars (and M 87, in particular) that were difficult to reconcile with single-zone models (Ghisellini et al. 2005; Tavecchio & Ghisellini 2008). However, direct observations of the physical nature and dynamics of the spine has been elusive. On sub-mas scales, cross-sections of the jet in the highest sensitivity images (as of 2022) with 43 GHz and 86 GHz Very Long Baseline Interferometry (VLBI), in 2013 and 2014, respectively, detected a predominantly double-ridged (edge brightened) morphology (Hada 2017; Walker et al. 2018; Punsly 2022). Analyses of the large (ridge) peak to central trough intensity ratios in cross-sectional slices require a source that is a bright thick-walled tubular jet. This jet would then envelop a nearly invisible core or spine at 0.35 mas $< z < 0.65 \text{mas}$, where $z$ is the axial displacement from the nucleus (Punsly 2022). New high-resolution, 86 GHz VLBI with the Global Millimetre VLBI Array, the phased Atacama Large Millimetre/submillimetre Array and the Greenland Telescope in 2018 detected a very narrow central feature that points back towards the vicinity of the ring of emission surrounding the black hole (Lu et al. 2023). Curiously, the detected feature is bright enough that it should have been detected in the 2013 and 2014 cross-sections (even with lower resolution), but it was not apparent (Punsly & Chen 2021; Punsly 2022). Thus, it seems to be a variable feature that is not modeled in the numerical simulation library of the Event Horizon Telescope Collaboration (EHTC hereafter, Porth et al. 2019). An order of magnitude farther out, there is observational evidence of faint disjoint narrow features along the axis, but these do not connect to the region close to the source (Asada et al. 2016; Hada 2017). The dynamics of the spine within an arc-second of the source is unknown. This has motivated efforts to find direct observational evidence of strong spine dissipation that might reveal its energetics and composition.

Previously published VLBI images that clearly resolve the jet from HST-1 in the axial direction have not been sensitive enough to detect jet emission that extends continuously to HST-1. There is a detection gap, from $z \sim 400 \text{mas}$ to HST-1, $z \sim 870 \text{mas}$, even with low frequency Very Long Baseline Array (VLBA) observations, 1.7 GHz and 327 MHz (Cheung et al. 2007),
Rampadarath et al. (2009). In Sect. 2 of this paper, we use new sensitive high dynamic range images from archival Very Large Array (VLA) data at 22 GHz to resolve HST-1 from the jet in the axial direction and trace the jet direction continuously in the gap. There is a mild bend of the jet northward, so that HST-1 lies along the jet centerline or “spine”. We argue in Sect. 3 that the flare in HST-1 that began in 2005 might be a “spinal disruption event”. This flare is ideal for the purposes of determining energetics. We note that there is a wealth of observations over many epochs and frequency (Harris et al. 2006, 2009; Perlman et al. 2011)\(^1\). In Sect. 4, previous equipartition models of the flare in 2005 from Harris et al. (2006) are interpreted in the context of the spine. In Sect. 5, estimates of the energy fluxes of the spine and the surrounding tubular jet from sub-mas scales are combined to make up a unified picture of the jet over the last 200 yr. The jet power in recent epochs is crucial to the EHTC of the spine. In Sect. 5, estimates of the energy fluxes of the jet powers considered by the EHTC is a factor of few hundred to two thousand of the parallel cross-cuts is an iterative process. The intensity peaks are found and a “line of centroids” fitted. The cross-cut PA is varied until the fitted line of centroids is perpendicular to the cross-cuts. Figure 1 shows two epochs in order to see if the jet direction found is independent of observation. The contours were chosen to be approximately evenly spaced in the coordinate plane. Each fit has the same number of points. The process is not completely uniform or perfect. There is always one spacing per fit that is approximately twice as large as the others when using the log scale option for the contour spacing. The points that are chosen for the fit lay on the extremum of the coordinate of the contour and correspond to the location where the cross-cut is tangent to the contour. Since, the fit and the radio image are created with two different softwares, this choice of points facilitates a very accurate overlay (alignment) of the fit on the radio image. Therefore, obtaining an accurate fitted jet axis with its uncertainty on the radio image itself. The range of fits (the red lines) is indicated by the standard error of the regression (Reed 1989). 2005 has a smaller spread in the standard error of the fit because HST-1 was fainter and it did not skew the centroid of the flux density beyond 700 mas (i.e., there is an additional, closer, reliable centroid in the linear fit). The standard error from the best fit line is maximal at the endpoints of the fitted region, reaching \(\approx 3\) mas. Based on a short extrapolation of the fit, the primary result is that the position of HST-1 aligns with the jet axis that is immediately upstream to within \(< 6\) mas in 2003. Figure 1 traces the jet trajectory with three linear pieces. The inner jet, \(z < 400\) mas, is indicated by a black dashed line with the traditional PA = \(-67^\circ\) (Hada et al. 2016). The outer dashed black line is an “eyeball” fit to the faint trajectory beyond HST-1. It is significant that the jet which appears to be very straight for 870 mas makes an abrupt bend at HST-1, as illustrated in Fig. 1. This occurs before the flare and persists during the flare. This would need to be an integral part of any physical description of HST-1.

2. Imaging the adjacent jet upstream of HST-1

The 1.7 GHz VLBA observations are not sensitive enough to detect emission in the gap 400 mas < \(z < 870\) mas (Cheung et al. 2007). Thus, they cannot determine the local jet direction just upstream of HST-1. The best observations for imaging this region are 22 GHz VLA, due to the sensitivity that can be achieved. The synthesized beam is about two to three times the jet width based on extrapolating the outer edges of the 1.7 GHz VLBA jet from Fig. 1 of Cheung et al. (2007). Some 22 GHz images were previously published (Chen et al. 2011). Yongjun Chen graciously recreated the image FITS files for two of these observations with improved signal-to-noise ratio (S/N) for the purposes of this article. An inspection of the residual images associated with the 2011 paper showed a significant emission structure pattern that was morphologically similar to the original structure. This means there was still some emission left in the residual image. This suggests that more “cleaning” was required to create a new residual image that looks like the noise distribution over the whole field, thereby improving the S/N. An earlier version of the 12/31/2004 image appeared in Chen et al. (2011). In spite of the modest resolution, intensity cross-sections orthogonal to the jet determine the centroid of the local jet emission to \(\approx 1/10\) of the synthesized beam width for a \(S/N > 5\) (Cotton et al. 1998). The centroids of the cross-sections define the jet direction. This is achieved by linear fitting these centroids over the range, \(z \approx 400\) mas to \(z \approx 700\) mas, using least squares with uncertainty in both variables (Reed 1989). Since the beam is considerably wider than the jet, the peak intensity will represent the centroid position. The uncertainty of the peak position is \(1/10\) the synthesized beam, unless the maximum is achieved at more than one point. The cross-section can be tangent to the contour over a finite range of points which can be noticed with large magnification of the image. In this circumstance, the uncertainty is the distance between the maxima added in quadrature with 1/10 of the synthesized beam. Finding the position angle (PA) was chosen throughout.

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\(^1\) A line of sight to the jet (LOS) of 18\(^\circ\) was chosen throughout.
(optical and UV), the Faraday rotation that is prominent at radio frequencies is minimal since the rotation angle scales inversely with the frequency squared (Chen et al. 2011). Consequently, the observed polarization direction should represent the intrinsic polarization of the emitted radiation at its source. Thus, we would expect very large optical and UV polarization aligned with the jet direction when the spine radiates (Gabuzda 2018).

By comparison, HST-1 is a historically bright superluminal knot in the M 87 from $P$-band to X-rays, as observed 2005. It is located within 6 mas of the jet center-line. The initial configuration of the luminous ejection in 2005 is very elongated and almost parallel to the local upstream jet axis. It has been noted that the ejections in the complex as well as the direction of the parsec scale jet change direction over time (Giroletti et al. 2012; Ro et al. 2023). However, the initial elongation of the flaring knot, HST-1, is closely aligned with the jet direction. It has a high (25%–40%) optical and UV polarization that is aligned within a few degrees of the local jet axis (Perlman et al. 2011). This is either a group of strong coincidences or the 2005 flare of HST-1 arises from the dissipation of the spine. The primary tenet of this paper is based on the notion that there are too many coincidences to ignore.
The next three columns are the magnetic field, \( B \), and the Lorentz factor, \( \Gamma \). Table 1 is arranged as follows. Everything in bold face is new and the other is data from Harris et al. (2006). Equation (1) indicates a narrow range of \( \delta \) and \( \beta \) that are associated with \( \delta = 1/|\Gamma(1 - \beta \cos \theta)| \).

The next three columns are the magnetic field, \( B \), the plasmaoid from the models described, respectively, in the plasmoid in the variability time scale, and the energy stored in the plasmoid from the models described, respectively, in Harris et al. (2003, 2006). In Col. 5, \( Q_{\text{app}} = E_{\text{app}}/T \) is the energy flux required to fill the plasmoid in the variability time scale, \( T \) (Harris et al. 2006). \( T \) was estimated by Harris et al. (2006) from the 2005 X-ray light curve. The next two columns are the velocity and Lorentz factor in the M 87 frame. The remaining columns are new. They are motivated by the fact that the spine is believed to be a Poynting jet, where \( B \) in Col. 2 is an ordered magnetic field. From the angular momentum conservation, \( B \) is almost purely toroidal, and \( B^\theta \approx \Gamma B \) in the M 87 frame (Punsly 2008). The poloidal Poynting power, \( S^\phi \), in perfect MHD and approximate azimuthal symmetry is Punsly (2008):

\[
S^\phi = \frac{c}{4\pi} \int -B^\theta E^\phi \text{d}A, \quad E^\phi \approx -\beta B^\phi, \\
S^\phi = 2c \int \Gamma^2 \beta U_p \text{d}A, 
\]

for \( \phi \) is the orthogonal direction to \( z \) and \( \phi \) (azimuthal angle) and the normal cross-sectional area element is \( \text{d}A \). Also, \( U_B \) and \( U_p \) are the energy densities of the field and particles in the jet rest frame. \( E^\phi \) and \( S^\phi \) are tabulated inCols. 8 and 9, respectively. Column 10 is the particle energy flux in the M 87 frame, \( \mathcal{K} \). The total jet power in Col. 11 is:

\[
Q_{\text{total}} = S^\phi + \mathcal{K} = \int U_p \Gamma^2 \beta \text{d}A, \quad U_p = U_B. 
\]

where \( Q_{\text{total}} \) is larger than \( Q_{\text{fill}} \) in the range of \( \delta \) relevant to HST-1 in 2005.

### 4. Energy flux estimates of HST-1 in 2005

In this section, the previous equipartition model of HST-1 in Harris et al. (2006) is revisited in the context of the energetics of the spine. One of the big unknowns in that work was the apparent velocity of the ejected material that formed the predominant contribution to the luminosity of HST-1 in 2005. It was subsequently shown with 1.7 GHz VLBA that a powerful knot of emission emerged in 2005.04 (the component c shown in Fig. 2) and traveled downstream at \( \beta_{\text{app}} = v_{\text{app}}/c = 1.14 \pm 0.14 \) (Cheung et al. 2007). So, \( \beta_{\text{app}} \) constrains the range of viable models in Harris et al. (2006).

From Rees (1966) and Ginzburg & Syrovatskii (1969), we have:

\[
\beta_{\text{app}} \equiv \frac{v_{\text{app}}}{c} = \frac{\beta \sin \theta}{1 - \beta \cos \theta},
\]

where \( \theta \) is the LOS (chosen to be 18° here) and \( \beta \) is the velocity of HST-1 viewed in the cosmological rest frame of M 87 with \( \theta = 90° \) (M 87 frame hereafter). Table 1 is arranged as follows. Everything in bold face is new and the other is data from Harris et al. (2006). Equation (1) indicates a narrow range of Doppler factors, \( \delta \), in Col. 1 that are associated with \( \beta_{\text{app}} \).

\[
\delta = 1/|\Gamma(1 - \beta \cos \theta)|. 
\]

The next three columns are the magnetic field, \( B \), the plasmoid radius from time variability arguments, and the energy stored in the plasmoid from the models described, respectively, in Harris et al. (2003, 2006). In Col. 5, \( Q_{\text{app}} = E_{\text{app}}/T \) is the energy flux required to fill the plasmoid in the variability time scale, \( T \) (Harris et al. 2006). \( T \) was estimated by Harris et al. (2006) from the 2005 X-ray light curve. The next two columns are the velocity and Lorentz factor in the M 87 frame. The remaining columns are new. They are motivated by the fact that the spine is believed to be a Poynting jet, where \( B \) in Col. 2 is an ordered magnetic field. From the angular momentum conservation, \( B \) is almost purely toroidal, and \( B^\theta \approx \Gamma B \) in the M 87 frame (Punsly 2008). The poloidal Poynting power, \( S^\phi \), in perfect MHD and approximate azimuthal symmetry is Punsly (2008):

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S^\phi = \frac{c}{4\pi} \int -B^\theta E^\phi \text{d}A, \quad E^\phi \approx -\beta B^\phi, \\
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\]

where \( \phi \) is the orthogonal direction to \( z \) and \( \phi \) (azimuthal angle) and the normal cross-sectional area element is \( \text{d}A \). Also, \( U_B \) and \( U_p \) are the energy densities of the field and particles in the jet rest frame. \( E^\phi \) and \( S^\phi \) are tabulated inCols. 8 and 9, respectively. Column 10 is the particle energy flux in the M 87 frame, \( \mathcal{K} \). The total jet power in Col. 11 is:

\[
Q_{\text{total}} = S^\phi + \mathcal{K} = \int U_p \Gamma^2 \beta \text{d}A, \quad U_p = U_B. 
\]

where \( Q_{\text{total}} \) is larger than \( Q_{\text{fill}} \) in the range of \( \delta \) relevant to HST-1 in 2005.

### 5. Discussion and conclusion

In Sect. 2, we show that HST-1 lies along the central axis of the jet. In Sect. 3, we argue that the superluminal motion, shape, location, and the large, axis-aligned, optical/UV polarization strongly support an identification with the relativistic spine of the jet. In Sect. 4, the equipartition models in Table 1 indicate an energy flux of \( Q_{\text{spine}} \equiv Q_{\text{total}} \approx 2.5 \times 10^{41} \text{ ergs s}^{-1} \). As mentioned in the introduction, the spinal disruption analysis provides an alternative to re-collimation shock models of HST-1. As such, it is not intended as a critique of the otherwise common interpretation that HST-1 might be a re-collimation shock.

A possible explanation of the sudden spine dissipation is given by the data shown in Fig. 1. The jet slowly drifts a few degrees for \( z < 870 \text{ mas} \) and there is nothing that makes it dissipate violently as it propagates. At HST-1, the jet suddenly bends by \( \sim 16° \). The bend seems to have disrupted the propagation, causing the spine to dissipate, making it conspicuous for the first time along its flow. It is possible that an obstruction may have caused the jet deflection. This is supported by the HST detection of an ionized disk of gas \( \Omega \approx 25 \text{ from the nucleus} \) (Ford et al. 1994). As there are density enhancements near the jet axis, an obstruction is certainly plausible.

In order to assess the estimated value of \( Q_{\text{spine}} \), it is useful to provide the context of the surrounding tubular jet. In the region of 0.35 mas < \( z < 0.65 \text{ mas} \) (in 2013 and 2014) it is a mildly relativistic, protonic tubular region that comprises \( \sim 58\% \) of the total jet volume (Punsly 2022). Each arm of the bilaterally symmetric tubular jet of radius, \( R \), and wall thickness, \( W \), transports \( Q_{\text{tubular, jet}} \approx (W/0.25R)^{0.46}[5.3 \times 10^{41}] \text{ ergs s}^{-1} \) (Punsly & Chen 2021). The wall thickness of the jet in this region was estimated to be \( W \approx 0.35R \) (Punsly 2022). This implies a tubular jet power of \( Q_{\text{tubular, jet}} \approx 6.1 \times 10^{41} \text{ ergs s}^{-1} \).
in the spine and $\beta_{app} = 1.14 \pm 0.14$ (4.5 mas yr$^{-1}$) is consistent with this. An ejection time of 1.5 yr before the observation of the tubular jet on sub-mas scales was estimated in Fig. 2 of Punsly (2021). New high-resolution VLBI images indicate that the tubular jet emerges from the central engine thick-walled, namely: it is not a Kelvin-Helmholtz instability generated boundary layer of the spine created farther downstream (Lu et al. 2023). If we assume that the fundamental physical process in the central engine that launches the two component jet is the same for $\sim 200$ yr, then it reasonable to assume that it would preferentially channel most of its jet power into either the spine or tubular jet for $\sim 200$ yr. If the spine (tubular jet) is more powerful, $Q(M^{87})$ emitted from the central engine was $Q(M^{87}) < 4Q_{\text{spine}} \approx 1.0 \times 10^{42}$ ergs s$^{-1}$ ($Q(M^{87}) < 4Q_{\text{tubular jet}} \approx 2.4 \times 10^{42}$ ergs s$^{-1}$) $\sim 200$ yr before the observation. The weakest conclusion that can be asserted is a value of $Q(M^{87}) < 2.4 \times 10^{42}$ ergs s$^{-1}$ at some instance at a time within the last $\sim 200$ yr, provided that the equipartition assumption of the Harris et al. (2006) models is not grossly inaccurate (the tubular jet power estimate does not rely on this assumption). Alternatively, assuming a nearly constant central engine injection jet power for $\sim 200$ yr indicates a total jet power of $Q(M^{87}) \lesssim 2 \times 10^{42}$ ergs s$^{-1}$ (i.e., typical of a Fanaroff-Riley 1 radio galaxy) in epochs of modern observation. This analysis indicates that the spine has not served as a powerful hidden reservoir for jet energy in the last 200 yr. Additionally, $Q(M^{87})$ found here is a factor of 30$^\pm 10$ less than estimates based on features ejected from the nucleus many hundreds to millions of years earlier (Owen et al. 2000; Forman et al. 2005; de Gasperin et al. 2012). The bolometric luminosity, $L_{\text{bol}}$, of the inner jet is a consistency check. Before the EHT image, the inner jet emission was inseparable from disk emission in $L_{\text{bol}}$ estimates (Prieto et al. 2016). Subtracting the EHT millimeter disk flux density in Event Horizon Telescope Collaboration (2019a) from lower resolution, quasi-simultaneous broadband data indicates $L_{\text{bol}}(\text{observed}) \approx 5 \times 10^{41}$ ergs s$^{-1}$ for $z < 0.4$ arcseconds, even during a flare state (Punsly, in prep.). From Eqs. (1) and (2), we know that $L_{\text{bol}}$ in the M87 frame will be Doppler de-boosted. However, the region producing the peak of the SED is unresolved and the relevant $\beta$ (and de-boosting) is unknown. Regardless, $Q \sim 2 \times 10^{42}$ ergs s$^{-1}$ is a sufficient energy budget to support $L_{\text{bol}}$. The jet efficiency, $\eta_{\text{jet}}$, is defined by $Q(M^{87}) \lesssim 2 \times 10^{42}$ ergs s$^{-1} = \eta_{\text{jet}} M c^2$, where $M$ is the accretion rate, $\eta_{\text{jet}} \leq 0.035 [0.001 M_\odot \text{yr}^{-1}] / M$. Here, $M$ must be larger than the mass flow rate of the sub-mass tubular jet, $\approx 0.00014 [0.35 R_\odot ^{0.46} M_\odot \text{yr}^{-1}]$ (Punsly & Chen 2021). For example, EHTC has estimated $M \approx 2.7 \times 10^{-3} M_\odot \text{yr}^{-1}$ in the single-zone approximation (Event Horizon Telescope Collaboration 2019b). Alternatively, if most of the accreted mass is ejected in the jet, then we have $\eta_{\text{jet}} \leq 0.25$. Apparently, there is no requirement of black hole spin as a power source – unless all the accreted mass is ejected in the jet and in this case, it is likely needed. The requirement that the jet needs a black hole spin power source might be an artifact of comparing jet powers in the distant past with current nuclear luminosity.

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Table 1. Parameters of the Harris et al. (2006) equipartition models.

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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>$B$ (G)</td>
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<tr>
<td>Radius (cm)</td>
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<tr>
<td>$E_{\text{min}}$ (ergs)</td>
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