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The unique case of the active galactic nucleus core of M87: a misaligned low-power blazar?

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ABSTRACT

M87 hosts one of the closest jetted active galactic nuclei (AGN) to Earth. Thanks to its vicinity and to the large mass of its central black hole, M87 is the only source in which the jet can be directly imaged down to near-event horizon scales with radio very large baseline interferometry. This property makes M87 a unique source to isolate and study jet launching, acceleration, and collimation. In this paper, we employ a multizone model designed as a parametrization of general relativistic magnetohydrodynamics (GRMHD); for the first time, we reproduce the jet’s observed shape and multiwavelength spectral energy distribution simultaneously. We find strong constraints on key physical parameters of the jet, such as the location of particle acceleration and the kinetic power. However, we underpredict the (unresolved) gamma-ray flux of the source, implying that the high-energy emission does not originate in the magnetically dominated inner jet regions. Our results have important implications both for comparisons of GRMHD simulations with observations and for unified models of AGN classes.

Key words: radiation mechanisms: non-thermal – galaxies: individual: M87 – galaxies: jets.

1 INTRODUCTION

Active galactic nuclei (AGN) are accreting supermassive black holes residing at the centre of galaxies; the gravitational energy released by accretion on to such compact objects makes them the brightest non-transient sources in the sky at all wavelengths. Over the years, many classes of AGN have been identified on the basis of their accretion rates, viewing angle, and the presence or lack of collimated, relativistic outflows called jets (e.g. Antonucci 1993; Urry & Padovani 1995). While the basic physics of the AGN phenomenon is fairly well understood (e.g. Shakura & Sunyaev 1973; Blandford & Znajek 1977; Blandford & Königl 1979; Blandford & Payne 1982; Narayan & Yi 1994; Blandford & Begelman 1999; Abramowicz & Fragile 2013), a complete picture of accretion, outflow formation and ejection, and how these are coupled is still missing. A full understanding of the energy output of AGN is necessary to quantify the impact that supermassive black holes have on their environment, which, in turn, is needed to correctly predict galaxy formation and evolution (e.g. Silk & Rees 1998; Di Matteo, Springel & Hernquist 2005; Silk 2013).

One of the most well known and remarkable AGN discovered to date is the one hosted in M87, a giant elliptical galaxy in the Virgo cluster. It hosts a remarkably massive black hole ($M_{bh} = 6.5 \times 10^9 M_{\odot}$, EHT Collaboration 2019c). With this mass, the gravitational radius $R_g = GM_{bh}/c^2 = 9.7 \times 10^{14}$ cm, making 1 pc $\approx 3 \times 10^3 R_g$. The source is located at a distance of $D = 16.7 \pm 0.6$ Mpc, estimated through applying the surface brightness fluctuation (SBF) method using the Hubble Space Telescope Advance Camera for Surveys Virgo Cluster Survey (ACSVCS, Blakeslee et al. 2009), and emits a modest bolometric luminosity of $L_{bol} \approx 2.7 \times 10^{42}$ erg s$^{-1}$, which fluctuates by about 20 per cent due to the AGN variability between the radio and X-ray bands (Prieto et al. 2016). These properties combined make M87 an excellent source to study AGN in the low-luminosity regime (LLAGN), in which the in-falling material is believed to be underluminous (e.g. Narayan & Yi 1994; see also Yuan & Narayan 2014 for a recent review), and parsec-scale collimated jets are more likely to be formed and launched (e.g. Nagar, Falcke & Wilson 2005). The viewing angle of the forward jet is estimated to be between 10° and 20° (e.g. Biretta, Sparks & Macchetto 1999; Mertens et al. 2016; Kim et al. 2018; Walker et al. 2018).

Unlike many LLAGN, the jet of M87 is easily detected on a variety of physical scales: Its radiative output is believed to dominate the spectral energy distribution (SED) of the AGN core (e.g. Nemmen, Storchi-Bergmann & Eracleous 2014; Prieto et al. 2016), and the outflow extends up to kpc scales (e.g. Biretta et al. 1999; Owen, Eilek & Kassim 2000; Wilson & Yang 2002). The proximity of the source allows observations mapping the jet on parsec and subparsec scales with an accuracy beyond that achievable for more distant sources. M87 is the only source whose jet has been...
resolved over multiple spatial scales, from \( \approx 10^3 R_g \), with arcsec-accuracy instruments like *Hubble and Chandra* (e.g. Biretta et al. 1999; Wilson & Yang 2002; Cheung, Harris & Stawarz 2007), down to \( \approx 10^4 - 10^5 R_g \) with radio very large baseline interferometry (VLBI) at \( \approx 2-86 \) GHz (e.g. Hada et al. 2011, 2013, 2016; Asada & Nakamura 2012; Nakamura & Asada 2013; Mertens et al. 2016; Walker et al. 2018). Higher frequency VLBI observations at \( 230 \) GHz by Doelman et al. (2012) imply very small scales (\( \approx 10 R_g \)) for the base of the jets, and observations with the full Event Horizon Telescope (EHT) array have successfully resolved the shadow of the black hole itself (EHT Collaboration 2019a). The only three other sources for which a similar study of the jet collimation profile has been conducted, albeit with a lower angular resolution and dynamic range in observations, are Cygus A (Boccardi et al. 2016), 3C 84 (Giovannini et al. 2018), and NGC 4261 (Nakahara et al. 2018).

This wealth of high-quality, high-resolution VLBI data makes M87 a unique source for isolating the physics of jets in accreting black holes. The general picture that has emerged over the years is that the jet is highly collimated and parabolic in shape up to around \( 10^4 R_g \), after which it transitions to a conical profile (Blandford & Königl 1979; Asada & Nakamura 2012). The inner core is likely to be magnetically dominated (Kino et al. 2014; Hada et al. 2016), and while in the inner parsec and subparsec scale regions only subluminal or mildly superluminal speeds are observed (e.g. Mertens et al. 2016), the plasma ejected from the HST-1 knot complex (located at a deprojected distance of \( \approx 5 \times 10^5 R_g \) downstream of the core) has shown superluminal speeds up to \( 6c \) (Biretta et al. 1999). Taken together, these observations imply that the jet is magnetically dominated near the base, and accelerated up to large scales of \( \approx 10^7 R_g \) by converting the initial high magnetic field into bulk kinetic energy, in agreement with general relativistic magnetohydrodynamics (GRMHD) simulations (e.g. Komissarov et al. 2007; Chatterjee et al. 2019).

Along with extensive radio monitoring, the jet of M87 has also been studied in-depth in the high-energy regime. The X-ray emission of both the core and kpc-scale jet knots (which can be resolved by the *Chandra X-ray Observatory*, hereafter *Chandra*) is well reproduced by a featureless absorbed power law; the core emission is thought to be dominated by the jet (e.g. Wilson & Yang 2002; de Jong et al. 2015; Prieto et al. 2016) rather than the accretion flow. Remarkably, HST-1 has shown a strong flaring activity in the past, even for the outshining the core emission (Harris et al. 2003, Cheung et al. 2007; Sun et al. 2018). The source is spatially unresolved in the gamma-ray band, but it has been detected both by *Fermi-LAT* (Abdo et al. 2009) and atmospheric Cherenkov telescopes (e.g. H.E.R.A: Aharonian et al. 2003, H.E.S.S.: Aharonian et al. 2006; Albert et al. 2008; Abramowski et al. 2012b; Aliu et al. 2012, VERITAS: Acciari et al. 2011, MAGIC: Abramowski et al. 2012a). While the *Fermi-LAT* data cannot easily constrain variability, very high energy (VHE) observations have found variability on remarkably short time-scales of a few days. The 2005/2006 VHE flare detected by H.E.S.S. (Aharonian et al. 2006), coincided with the period of increased activity and knot ejection in HST-1, leading Cheung et al. (2007) to suggest that at least part of the high-energy emission may not originate near the black hole. Recent work by Ait Benkhali, Chakrabarty & Rieger (2019) shows that both the shape of the gamma-ray spectrum and detailed analysis of the variability imply that the high-energy photons are likely produced in multiple components.

Despite such a complex behaviour, the overall shape of the SED has been found in the past to be consistent with a standard one-zone synchrotron self-Compton (SSC) model (e.g. Abdo et al. 2009; de Jong et al. 2015), with the caveat that the implied bulk speed of the jet is far lower than that inferred from modelling blazar SEDs, in contrast with AGN unification models (Henri & Saugé 2006). One possible solution to this inconsistency, which is common for single-zone models, has been proposed by Tavecchio & Ghisellini (2008), who proposed that the jet is composed of an inner, relativistic spine and of a slower moving, outer sheath. The different velocities of the two components lead to enhanced inverse-Compton emission, and the different Doppler factors of the spine and the sheath as a function of the line of sight can reconcile the differences in inferred bulk speeds for aligned and misaligned sources.

The critical drawback of both single-zone and spine/sheath models is their inability to predict both the jet’s shape and/or radio emission, because in these models the synchrotron self-absorption frequency is typically \( \approx 10^{11} \) Hz (e.g. Tavecchio, Maraschi, Ghisellini 1998). The aim of this paper is to investigate whether this limitation also applies to inhomogeneous, multizone models by building on the work of Prieto et al. (2016), who fitted the radio through X-ray SED of M87 with the multizone anjet model developed by Markoff, Nowak & Wilms (2005). For the first time, we use a semi-analytic model to reproduce both the jet shape, inferred from VLBI imaging, and the SED of an AGN jet, using the bjet model first presented in Lucchini et al. (2019, hereafter Paper I). By using both constraints at the same time, we show that we have a little degeneracy in our model, and can put strong constraints on the origin of the gamma-ray emission of the source.

This paper is structured as follows: In Section 2, we build an updated multiwavelength SED with an improved X-ray coverage, in Section 3, we present the model used and apply it to the M87 core emission, in Section 4, we discuss the implications of our modelling, and in Section 5, we summarize our findings. Throughout this paper, we assume a luminosity distance to the source of 16.8 Mpc, a black hole mass of \( 6 \times 10^8 M_\odot \) as in EHT Collaboration (2019a), and a viewing angle of \( \theta = 14^\circ \). At the assumed distance, an angular resolution of 0.4 arcsec corresponds to a physical size of \( \approx 35 \) pc.

### 2 DATA ANALYSIS

We compile a new multiwavelength SED of M87 by complementing the quiescent state, 0.4 arcsec data at radio, submillimetre/millimetre, infrared, and optical frequencies of Prieto et al. (2016) (in which the details of the data selection and reduction are reported) with an additional X-ray and gamma-ray coverage.

We looked for *Chandra* observations coinciding as closely as possible (within a period of a few months) with the ALMA observations of 2012 June. We also take the *Fermi-LAT* gamma-ray spectrum from the 3FGL catalogue (Acero et al. 2015) as representative of the source’s steady-state high-energy emission.

#### 2.1 Chandra data reduction

The following *Chandra* observations were available between 2011 December and 2013 March: 13964, 13965, 13515, 14973, and 14974. The *Chandra* observations of M87 were extracted using Ciao 4.9 using the standard pipelines. First, the CIAO script chandra_repro was run to update calibrations. As a second step, ACIS observations were extracted using specextract and d9-generated regions. One observation, ID 13515, was taken with the High Resolution Camera (HRC), and no spectra were extracted for this source. specextract was run with the psf correction, to correct the ARF for the small (sub-PSF) extraction region. We extracted spectra for the core...
region, *HST*-1, the kpc-scale jet, as well as a background region. Finally, we also extracted a spectrum to the south of the jet in order to get a spectrum of the gas in the host galaxy surrounding the jet. The gas spectrum is used as a background for the spectra of the AGN components (core, *HST*-1, and kpc-scale jet).

All extraction regions are reported in Table 1 and shown in Fig. 1.

### 2.2 X-ray spectral modelling

We fit both phenomenological and physical models to the data using the Interactive Spectral Interpretation System (ISIS) software package (Houck & Denicola 2000), version 1.6.2-35, which enables the statistical modelling of multiwavelength spectra using custom models. All models are folded through the detector response matrices of X-ray satellites; at all other wavelengths, the instrument response is assumed to be an identity matrix, which represents the response of a detector with an effective area \( A = 1 \text{ m}^2 \). *Chandra* spectra are binned to a signal-to-noise ratio of 4.5 in order to be able to use \( \chi^2 \) statistics when fitting. Each fit is performed by running the subplex \( \chi^2 \) minimization algorithm, after which we refine the fit and explore parameter space by using the *emcee* implementation of a Markov chain Monte Carlo (MCMC) routine, based on *emcee* developed by Foreman-Mackey et al. (2013). The routine initializes an ensemble of walkers (we use 100 for each free parameter), which at each iteration move through the parameter space; depending on the \( \chi^2 \) values in the new and old positions, the move may be accepted or rejected. We evolve the chain for 5000 iterations and discard the first 1500 as the ‘burn-in’ period of the chain. In this way, the MCMC routine identifies the global minimum in the parameter space, along with possible degeneracies among parameters. The final distribution of walkers allows us to estimate the best-fitting values of the global minimum, and uncertainties of the fitted parameters. These are defined, respectively, as the peaks in the fitted parameters. These are defined, respectively, as the peaks in the best-fitting values of the global minimum, and uncertainties of the fitted parameters. These are defined, respectively, as the peaks in the fitted parameters.

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other. Each spectrum was fitted with an absorbed power law (termed as `powerlaw`); in all cases, the power-law model is in excellent agreement with the data ($\chi^2 = 1.05$ for the combined data set). The fits did not show any statistical improvement if we let the column density vary between spectra, so we tied the normalization (°2) across the entire data set; our best-fitting values show a small excess (by a factor of about 3) above the Galactic value of 1.94 $\times$ 10°2 cm$^{-2}$. The best-fitting values are shown in Table 2, and the spectra and residuals are shown in Fig. 2.

The spectra at all epochs are consistent with each other with the exception of Obs ID 14974. In this epoch, we find that the flux of both the core and HST-1 is lower by a factor of $\approx$2, while the spectral indices and kpc-scale jet remain unchanged. We do not believe this to be a physical change caused by the source's variability. This is because, in order for the variability to be physical, both the core and HST-1 would have to vary by the same amount over the same period, which is extremely unlikely. Instead, the discrepancy in flux measurements is likely caused by the difficulty in separating the core and HST-1 components in ACIS images, as shown in the right-hand panel of Fig. 1. Because of these systematics, we neglect the core and HST-1 spectra from Obs ID 14974 in the following analysis.

### 3 MODELLING THE M87 CORE EMISSION

In this section, we model the core SED with the `bljet` leptonic multizone model; the full details are contained in Paper I, and references therein. Briefly, the model assumes that a fraction $N_f$ of the black hole’s Eddington power is injected in a highly magnetized nozzle of radius $r_0$ and aspect ratio $h = 2r_0$, which can be thought of as related to a magnetized corona or wind (see e.g. Markoff et al. 2005). We define the initial magnetization as $\sigma_0 = (U_b,0 + P_b,0)/(U_e,0 + U_b,0 + P_e,0) \approx 1$, where $U_b,0$, $U_e,0$, and $P_b,0$ are the initial energy densities of the magnetic field, electrons, and protons in the jet, $P_b,0$ and $P_e,0$ are the pressure of the magnetic field and electrons, and the protons are assumed to be non-relativistic and thus have a negligible pressure. The jet accelerates up to a terminal Lorentz factor $\Gamma_m$ up to a distance $z_{acc}$ by converting the initial magnetic field into bulk kinetic energy until the outflow becomes matter-dominated ($\sigma_{acc} \leq 1$). The bulk Lorentz factor of the outflow is assumed to scale with the distance from the black hole $z$ as a power law: $\Gamma(z) \propto z^{1/\alpha}$, with $\alpha \approx 0.5$. The jet-opening angle is inversely proportional to the Lorentz factor: $\theta(z) = \Gamma(z)\theta_0$, where $\theta_0$ is a proportionality constant taken to be less than 1. The resulting jet profile is roughly parabolic in shape in the bulk acceleration region, and conical in the outer region.

The leptons in the jet are assumed to be thermalized and relativistic up to a distance $z_{acc}$ from the base (which we took to be equal to $z_{acc}$ in Paper I, though this need not be the case), at which point 10 per cent of the particles are injected in a power-law tail with slope $\beta$. At the dissipation region, the particle distribution is also assumed to be heated, parametrized by increasing the temperature of the relativistic Maxwellian by a fixed factor $f_{heat}$. The energy of the cooling break in the non-thermal particle distribution is controlled by the free parameter $f_c$, which regulates the importance of adiabatic losses with respect to radiative losses. The maximum energy reached by the particles is parametrized by the dimensionless parameter $f_c$, which sets the time-scale of the acceleration mechanism. In preliminary fits, we found that the magnetization at the acceleration region $\sigma_{acc}$ has a negligible effect on the SED as the bulk of the emission is generated fairly close to the jet base ($z \leq 10^2 R_g$) in highly magnetized regions where $\sigma \gg 1$, and therefore we fix it to $\sigma_{acc} = 1$. Unlike in Paper I, we also found that the SED was well matched by assuming an isothermal jet with constant temperature $T_\nu$, and that the break energy of the particles was consistent with the value calculated from equating adiabatic and synchrotron time-scales: $E_b(z) = (3\beta(z)m_e^2c^3)/(4\pi(z)\sigma_T U_b(z))$, where $z$ is the distance along the jet, $\beta(z)$ is the speed of the jet in units of $c$, $m_e$ is the mass of the electron, $r(z)$ is the radius of the jet, $\sigma_T$ is the Thomson cross-section, and $U_b(z)$ is the magnetic field energy density along the jet. We therefore fixed both $f_{heat}$ and $f_c$ to unity.

Finally, we have expanded the inverse-Compton calculation in the code to include the host galaxy’s stellar photon field. Following, e.g. Stawarz et al. (2006), we assume that the radiation energy density...
in the galaxy core is $U_{\text{rad}} = 10^{-9}$ erg cm$^{-3}$ and peak temperature $T = 3200$ K. The main parameters of the model are summarized in Table 3.

### 3.1 Matching the jet collimation profile

Before performing spectral fits with bljet, we match the jet geometry to the available VLBI observations of the source. The quality of the imaging data limits the allowable range of the parameters of bljet, particularly $\alpha$, $\Gamma_{\text{acc}}$, and $\rho$. In Paper I, we took fixed values for these parameters; in this section, we will show that these values allow the shape predicted by the model to match the observation fairly well. We stress that because our collimation profile model is relatively simple, our goal is to find a set of parameters that qualitatively produces a jet similar to that of the M87 fit, rather than perform a quantitative statistical fit of the jet's collimation and acceleration.

We first combine the imaging observational constraints by fixing the radius of the jet nozzle $r_0$ to $3R_g$, which ensures that the computed jet width never exceeds the observed value, and the distance of the bulk collimation/acceleration region $z_{\text{acc}}$ to $2.5 \times 10^8 R_g$ (e.g. Asada & Nakamura 2012; Hada et al. 2013), which fixes the location of the parabolic to conical transition in the jet profile. We then vary the values of $\alpha$, $\rho$, and $\Gamma_{\text{acc}}$ and check their impact on the predicted jet shape. The resulting profiles are shown in Fig. 3. In general, highly collimated jets (corresponding to low values of $\alpha$ and $\rho$) predict a jet that is too narrow near the base; less collimated shapes (large values of $\alpha$ and $\rho$) instead overpredict the jet width on larger scales. Similarly, fast jets are narrower than slow jets.

As shown in Fig. 4, taking $\alpha = 0.5$, $\rho = 0.18$, and $\Gamma_{\text{acc}} = 15$ provides a reasonable agreement with the imaging data, with the exception of the inner $\approx 500R_g$; we, thus, keep these values unchanged and assume a constant geometry throughout the spectral-fitting procedure. In principle, an even better agreement with the imaging data could be obtained by assuming, for example, that $\rho$ also changes with distance (the right-hand panel of Fig. 3, for instance, suggests that $\rho$ is around 0.3 at the base, decreasing to 0.18 farther out). Imposing a wider collimation profile in the initial segments of the jet would lower the number density in these regions, while the strength of the magnetic field and total number of particles would remain unchanged. As a result, the synchrotron emission in the final SED would remain unchanged, but the inverse-Compton component would be suppressed slightly. As we will discuss in the next section, we do not expect the inverse-Compton emission to contribute meaningfully to the core’s emission from radio to X-rays, and, thus, our conclusions are unaffected by the mismatch in the inner jet collimation profile.

### 3.2 Broad-band spectral modelling: a synchrotron-dominated inner core

The constraints imposed by the imaging data on the jet shape leave only five of the fitted parameters in bljet to be free: the injected jet power $N_j$, location of the particle acceleration region $z_{\text{acc}}$, electron temperature $\gamma_e$, slope of the non-thermal distribution $\rho$, and particle acceleration efficiency $\epsilon_{\text{acc}}$.

We find that the data require an excess in the optical/near-infrared bands, which we model as a single blackbody. The model syntax assigned in ISIS to the full SED is `tblackx(bljet+bbody)`.

Our best fit of the SED is shown in Fig. 5, and the best-fitting parameters and uncertainties are reported in Table 4. The radio and X-ray emission is mainly due to non-thermal synchrotron, while the ALMA band is dominated by thermal synchrotron emission from the jet nozzle, and the optical/infrared emission shows a prominent thermal bump. The model is in excellent agreement with the data up through the X-ray band; furthermore, after running emcee we do not find any significant degeneracy in any of the free parameters, which are all very well constrained. However, the model predicts a gamma-ray flux of $\approx 10^{-14}$ erg s$^{-1}$ cm$^{-2}$, far below the Fermi/LAT spectrum; we discuss the implications of this finding in Section 4.

### 3.3 Broad-band spectral modelling: SSC-dominated regime

Unlike the synchrotron-dominated regime, we could not find a satisfactory fit to the data in a regime in which the X-rays are produced through SSC near the base of the jets. This is because of the combination of constraints imposed by direct imaging of the jet collimation profile, combined with the main assumption underlying bljet (while the jet is accelerating, it is magnetically dominated). A highly magnetized base for a given synchrotron luminosity (fixed by the radio/submillimetre fluxes) implies a low lepton number density, which, in turn, results in a suppression of the SSC flux. The only way to offset such an offset is to assume a much higher temperature ($\langle \gamma_e \rangle \approx 100$) for the radiating particles in the jet base. Our best attempt to fit the data in such a regime is shown in Fig. 6; as shown in the figure, such a high temperature causes the nozzle’s...
Figure 3. Jet profile in bljet for different parameters compared with VLBI data in the inner parabolic region. Left-hand panel: jet acceleration profile ($\Gamma(z) \propto z^{\alpha}$); middle panel: jet terminal Lorentz factor; right-hand panel: jet opening angle [$\theta(z) = \rho(z) \Gamma(z)$]. The model is in good agreement with the data by taking $\alpha = 0.5$, $\Gamma_{\text{acc}} = 15$, and $\rho = 0.18$, with the exception of the inner $\approx 500R_g$.

Figure 4. Top panel: jet profiles overlaid on top of the VLBI imaging data. Orange shows the jet profile assumed during the spectral fits with bljet; dark blue shows a broken power-law fit of the VLBI data ($\rho_{\text{bljet}} \approx 0.18$ in the inner region, $\rho_{\text{bljet}} \approx 1.0$ in the outer region). Bottom panel: model residuals for the bljet.

emission to vastly exceed the sub/mm and infrared data, while still not successfully matching the X-ray flux of the source. Therefore, we rule out SSC from the magnetically dominated inner jet spine as the radiative mechanism responsible for the emission detected by Chandra.

4 DISCUSSION

The first result emerging from our combined imaging/spectral fit is that the 3FGL spectrum cannot be matched by the model for the compact jet; the predicted gamma-ray flux of the core is only $\approx 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, two to three orders of magnitude below the data. The main contribution to the core’s limited gamma-ray flux is due to inverse-Compton scattering of the host galaxy’s starlight, rather than SSC. This conclusion is mainly driven by matching our model’s jet dynamics and shape with those inferred from the direct imaging of the outflow through VLBI.

The second result of the fit is that the location of particle acceleration occurs very close to the black hole ($z_{\text{acc}} = 97 R_g$); such a distance is far closer to the central engine than the acceleration distance inferred from the jet speed and collimation profile. Interestingly, high-resolution VLBI 86-GHz images of the jet show a ‘pinching’ of the outflow around this distance (Hada et al. 2016), which was also observed at this scale in GRMHD simulations (e.g. McKinney 2006; Barniol Duran, Tchekhovskoy & Giannios 2017; Nakamura et al. 2018; Chatterjee et al. 2019); we tentatively suggest that the initial injection of particle acceleration in the jet may be influenced by this pinching region.

The third result is that, assuming that the magnetically dominated jet creates most of the observed X-rays, the radiating leptons need to be accelerated to very high Lorentz factors ($\approx 10^7 - 10^8$), varying slightly along the length of the jet) in order to extend the synchrotron spectrum up to the Chandra energy range. Such high particle energies can be achieved by assuming a very high particle acceleration efficiency $f_{\text{sc}}$. Prieto et al. (2016) modelled a similar SED with agrjet but instead found a matter-dominated jet base, in which the soft X-ray photons are produced by the SSC emission from the jet nozzle. We cannot reproduce such a solution because in bljet the base of the jet is always magnetically dominated, thus suppressing the SSC flux; this assumption leaves non-thermal synchrotron as the only radiative mechanism in the jet capable of matching the X-ray data.

The fourth result is that the particle distribution in the jet is consistent with being isothermal even beyond the dissipation region (in our model, this corresponds to $f_{\text{heat}} = 1$), and the temperature of the relativistic Maxwellian ($T_\gamma = 4.2^{+1.0}_{-0.3} \times 10^7$) is well constrained by the submillimetre ALMA data, which form a clear bump. The finding that the particle distribution in the jet is isothermal differs from our findings in Paper I, in which we showed that it was necessary to increase the temperature ($f_{\text{heat}} > 1$) of the particle distribution at $R_{\text{diss}}$ (fig. 12 in Paper I). One likely explanation for this discrepancy is in the difference in jet kinetic powers between the two sources. In PKS 2155–304, the higher kinetic power ($N_j = 9^{+0.7}_{-0.5} \times 10^{-5} L_{\text{Edd}}$) could drive stronger shocks in the jet, allowing for additional energy to be transferred to the radiating particles, while in M87 ($N_j = 3.2^{+0.5}_{-0.3} \times 10^{-5} L_{\text{Edd}}$) this amplification does not seem to be necessary.

The optical/infrared thermal bump was interpreted by Prieto et al. (2016) as a tracer of an optically thick, geometrically thick accretion disc, with an inner radius of $R_j$ and temperature of 3200 K; when fitting a Shakura–Sunyaev disc to the data, we recover similar parameters. However, this combination of inner radius and
that in M87 bulk acceleration continues up to large scales of \( \approx \) the observed trend of increasing bulk motion up to galaxy. cau

The transition in the jet shape from parabolic to conical, as well as the observed trend of increasing bulk motion up to \( \approx \) the blackbody contribution, and the dashed blue line represents the inverse-Compton emission. The black solid line shows the total model flux and includes the effects of absorption. The data cannot be reproduced with an SSC-dominated inner jet.

Figure 6. Radio through X-ray SED of M87 with an attempt at an SSC-dominated fit. The dashed pink line represents thermal synchrotron emission from the jet base, the dot–dashed green line represents the de-absorbed, non-thermal synchrotron emission, the double dot–dashed yellow line represents the the blackbody contribution, and the dashed blue line represents the inverse-Compton emission. The black solid line shows the total model flux and includes the effects of absorption. The data cannot be reproduced with an SSC-dominated inner jet.

Table 4. Best-fitting synchrotron-dominated parameters and relative uncertainties.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (± uncertainty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injected power ( N_p (10^{-5} L_{\text{Edd}}) )</td>
<td>3.2 (±0.5)</td>
</tr>
<tr>
<td>Dissipation distance ( r_{\text{dis}} (r_g) )</td>
<td>9.7 (±0.3)</td>
</tr>
<tr>
<td>Electron temperature ( T_e (y_e) )</td>
<td>4.7 (±0.3)</td>
</tr>
<tr>
<td>Non-thermal power-law slope ( p )</td>
<td>2.34 (±0.01)</td>
</tr>
<tr>
<td>Acceleration efficiency ( f_a )</td>
<td>1.0 (±0.2)</td>
</tr>
<tr>
<td>BB normalization ( 10^{-5} L_{39}(D_{10kpc})^2 )</td>
<td>5.1 (±0.7)</td>
</tr>
<tr>
<td>BB temperature (eV)</td>
<td>0.28 (±0.03)</td>
</tr>
</tbody>
</table>

Note. *Best fit consistent with the allowed upper limit.

temperature results in an accretion rate of \( \approx 10^{-7} \dot{M}_{\text{Edd}} \). At such a low accretion rate, the disc should be in the advection-dominated (ADAF) state, and therefore its emission should not resemble a blackbody (or a superposition of blackbodies). Furthermore, such a low accretion rate is two orders of magnitude below the estimated jet power. These findings suggest that the origin of the thermal bump may not be related to the accretion disc, and, instead, be caused by a residual starlight contribution in the inner 32 pc of the galaxy.

The observations of increasing bulk motion up to \( \approx \) the blackbody contribution, and the dashed blue line represents the inverse-Compton emission. The black solid line shows the total model flux and includes the effects of absorption. The data cannot be reproduced with an SSC-dominated inner jet.

Figure 5. Top panel: radio through X-ray subarcsec core SED of M87 with our best synchrotron-dominated fit. The dashed line represents the thermal synchrotron emission from the jet base/corona; the dot–dashed green line represents the de-absorbed, non-thermal synchrotron emission, and the double dot–dashed yellow line represents the blackbody contribution, approximating the host galaxy contribution. The black solid line shows the total model flux and includes the effects of absorption. Bottom panel: radio through gamma-ray SED of M87. The inverse-Compton contribution of the jet base, the dot–dashed green line represents the de-absorbed, non-thermal synchrotron emission from the jet base, the dot–dashed green line represents the de-absorbed, non-thermal synchrotron emission, the double dot–dashed yellow line represents the blackbody contribution, and the dashed blue line represents the inverse-Compton emission. The black solid line shows the total model flux and includes the effects of absorption. The data cannot be reproduced with an SSC-dominated inner jet.

the jet is the dissipation of magnetic field into bulk kinetic energy in a highly magnetized region, this implies that the outflow remains magnetically dominated (\( \sigma \geq 1 \)) up to these large scales; high \( \sigma \), in turn, implies a relatively low lepton number density required to match the synchrotron spectrum, and such a low lepton number density naturally results in a suppression of the inverse-Compton flux. The inefficiency of the inverse-Compton process in the source remains unchanged by taking lower values of \( \sigma \): the regions near the dissipation region \( R_{\text{dis}} \) (responsible for the radio and X-ray emission) are always highly magnetized, thus automatically setting a relatively low number density of particles throughout the outflow. Increasing the inverse-Compton flux would require both taking a low \( \sigma \) and increasing the jet power, which would, in turn, cause the synchrotron emission to exceed the radio/submillimetre data. Our findings are in contrast to previous modelling efforts of M87 (e.g. Abdo et al. 2009; de Jong et al. 2015), which reproduced the SED of the source with a standard homogeneous one-zone SSC model. The parameters explored in both these works require the plasma emitting in the core region to be strongly particle dominated, with \( U_c/U_b \geq 100 \), in order to produce a meaningful high-energy flux; this is in contrast with VLBI data, which favour a magnetically dominated core (\( 10^{-1} < U_c/U_b < 10^{-4} \), Kino et al. 2014; Hada et al. 2016).

Recently, coupling radiation with GRMHD simulations has also been used to model the inner jet of M87 in place of simple semi-analytic models (e.g. Mościbrodzka, Falcke & Shiokawa 2016; Chael, Narayan & Johnson 2019). Both these works find that the bulk of the X-ray emission is due to SSC rather than optically thin synchrotron, in contrast to our work here. However, this conclusion depends very strongly on the assumptions made in the post-processing of the radiation in the simulations due to two main factors. First, in GRMHD simulations, the radiating electrons are assumed to be predominantly located in the outer sheath of the jet, thus restricting the emitting region to a more matter-dominated region than the jet base of our model. Secondly, the particle distribution in both the above works is assumed to be only a relativistic Maxwellian, which prevents the optically thin synchrotron spectrum from extending above the submillimetre band. Finally, it is worth...
noting that if SSC were the dominant mechanism producing X-rays in M87, it would no longer be consistent with a low-power blazar when oriented face-on (see Section 4.2). Because of these differences, a direct comparison of the spectra predicted from these simulations and from our model is not straightforward. Including more realistic particle distributions that account for non-thermal leptons (Davelaar et al. 2018) in simulations will facilitate such a comparison in the future.

EHT Collaboration (2019b) used the X-ray flux as a constraint of several GRMHD models by (conservatively) rejecting all the solutions whose SSC emission overpredicts the data. Our work, instead, suggests that more GRMHD models could be rejected by the observations, as we expect the bulk of the X-ray radiation to originate from non-thermal synchrotron emission.

4.1 The origin of the gamma-ray emission

Our work shows for the first time that in the context of a leptonic model based on an MHD-driven, magnetically accelerated outflow, the gamma-ray emission of M87 likely does not originate in the magnetically dominated inner jet regions. In this section, we explore alternative mechanisms for the high-energy emission, and discuss the implications of each.

One possible way of increasing the efficiency of inverse Compton is if the jet is structured, with an inner, fast spine surrounding a slow-moving sheath, as commonly found in GRMHD simulations (e.g. McKinney 2006; Hardee, Mizuno & Nishikawa 2007; Penna, Narayan & Sadowski 2013; Nakamura et al. 2018; Chatterjee et al. 2019). In this case, the synchrotron emission from the spine/layer is boosted in the comoving frame of the sheath/spine, resulting in an increase of the inverse-Compton flux (Ghisellini, Tavecchio & Chiaberge 2005). Indeed, such a model was applied to M87 by Tavecchio & Ghisellini (2008), who showed that the TeV emission could be well matched, thanks to the spine/sheath contribution to the seed photon fields. However, an additional inverse-Compton contribution would reduce the radiative cooling time-scale of high-energy particles, which are needed to match the Chandra data, thus requiring extremely short acceleration time-scales. A similar issue was also pointed out by Costamante et al. (2018) for the case of hard-TeV BL Lacs.

Alternatively, the high-energy bump could be due to hadronic processes. The main caveat to this scenario is the high power requirement typically associated with hadronic models. Our estimated jet power, driven mainly by the radio fluxes, is assumed a black hole. This power assumes one cold proton (carrying the jet’s bulk kinetic energy) per electron. Such an estimate is consistent with, but on the lower end of, independent measures obtained by studying the internal pressure exerted by the kpc-scale jet knots (e.g. Bicknell & Begelman 1996; Owen et al. 2000; Stawarz et al. 2006) or estimating the required heating in the galaxy’s X-ray halo (e.g. Churazov et al. 2002; Forman et al. 2005; Allen et al. 2006; Russell et al. 2013); all of these find a range of . Requiring that the power in the halo/outter jet and core be roughly of the same order of magnitude, these constraints on the jet’s energetics leave relatively little room for a population of relativistic protons in the outflow (unless the core has recently entered a phase of renewed activity). However, implementing an energetically dominant population of relativistic/protons would cause the underlying assumptions of to fail (see Paper I), and is therefore beyond the scope of this work.

A third possibility is that the high-energy emission does not originate in the core, but in the kpc-scale jet (Stawarz, Sikora & Ostrowski 2003; Hardcastle & Croston 2011), due to a combination of inverse Compton with synchrotron, stellar, and cosmic microwave background photons. The recent hints of variability on monthly time-scales found in the Fermi/LAT light curve of the source (Ait Benkhali et al. 2019) as well as the fast TeV variability (Aharonian et al. 2006) would disfavour such an interpretation. Cheung et al. (2007), however, showed that the inferred size of the HST-1 complex at VLBI scales is compact enough that it could indeed be the source of the TeV emission; furthermore, flaring activity on yearly time-scales has been detected in X-ray kpc-scale jets of Pictor A (Marshall et al. 2010) as well as M87 itself (Harris et al. 2003). Because of all these arguments, we conclude that HST-1 or the kpc-scale jet cannot be ruled out as the sites of a significant portion of M87’s gamma-ray emission.

In addition to the limited variability, Ait Benkhali et al. (2019) found that the source shows a complex spectrum likely originating from multiple components, of which at least one is variable. Such a complex behaviour could be reproduced if, on top of a steady-state component (such as the large-scale jet), a secondary highly variable region is also present. One possible candidate in such a scenario would be magnetospheric gap acceleration in the black hole’s ergosphere (e.g. Nerovn & Aharonian 2007; Rieger & Aharonian 2008; Levinson & Rieger 2011; Mościbrodzka et al. 2011; Broderick & Tchekhovskoy 2015).

In conclusion, while the location of the gamma-ray emission is still unclear, our work rules out a one-zone SSC model originating in the magnetized core, as such a mechanism implies plasma conditions in strong disagreement with theoretical expectations.

4.2 What kind of misaligned blazar is M87?

Fig. 7 shows a comparison between our best-fitting model rescaled to a viewing angle of and a sample of SEDs from nearby blazars. We built the sample by selecting all blazars in the ROMABZCAT catalogue (Massaro et al. 2015) with known redshift between 0 and 0.025, corresponding to a luminosity distance of about 110 Mpc. This search returned 16 sources, listed in Table 5. One of these sources (5BZU J1325−4301) is the misaligned radio galaxy Centaurus A, and, thus, we excluded it from the sample. Out of the remaining 15 sources, 10 are listed as galaxy-dominated BL Lacs and 5 as blazars of uncertain type; three are detected by Fermi/LAT (5BZG J0153+7115, 5BZU J0319+4130, 5BZU J1632+8232) and two are detected in radio, infrared, and optical, but not in X-rays or gamma rays (5BZG J1148+592, 5BZG J1945−5520). The data of this sample are from Myers et al. (2003), Healey et al. (2007), Dixon (1970), Jackson et al. (2007), Condon et al. (1998), White et al. (1997), Gregory & Condon (1991), Nieppola et al. (2007), White & Becker (1992), Kuehr et al. (1981), McConnell et al. (2012), Wright & Otrupcek (1990), Mauch et al. (2003), Wright et al. (1994, 2009, 2010), Murphy et al. (2010), Moshir et al. (1990), IRAS Joint Science (1994), Gregory et al. (1996), Planck Collaboration VII (2011), Planck Collaboration XXVIII (2014), Planck Collaboration (2015), Bianchi et al. (2011), Warwick et al. (1981), Levine et al. (1984), Evans et al. (2014), Rosen et al. (2016), Saxton et al. (2008), Voges et al. (1999), Boller et al. (2016), Elvis et al. (1992), Evans et al. (2010), Forman et al. (1978), Verrecchia et al. (2007), Hiroi et al. (2011), Hiroi et al. (2013), D’Elia et al. (2013), Cusumano et al. (2010a,b), Ajello et al. (2012), Bird et al. (2010), Baumgartner et al. (2013), Piccinotti et al. (1982), Hartman et al. (1999), Acero et al. (2015), Abd et al. (2010), Nolan et al. (2012), Giommi et al. (2012), and Bartoli et al. (2013). Finally, we included the averaged
of kpc and terminates in well-developed lobes (Owen et al. 2000). These inherently more powerful sources.

of a typical gamma-ray bright HBL like Mrk 421 or PKS 304, which face-on is clearly far more faint than that of gamma-ray bright HBLs. Out of all sources in our sample, we found that the most similar blazar SED to our aligned model is that of 5BZG J0709+501.

Figure 7. Comparison between our model for M87 (orange line), the same model but rescaled to a viewing angle of 5°, our sample of nearby blazars (grey points), and Mrk 421 (black stars). The Fermi/LAT-detected sources are represented by squares (5BZG J0153+7115), asterisks (5BZU J0319+4130), and plusses (5BZU J1632+8232), respectively. The SED of 5BZG J0709+501 is shown by the blue diamonds. The SED of M87 seen face-on is clearly far more faint than that of gamma-ray bright HBLs. Out of all sources in our sample, we found that the most similar blazar SED to our aligned model is that of 5BZG J0709+501.

SED of Mrk 421 from Abdo et al. (2011) to compare our model to a prototypical high-peaked BL Lac (HBL).

When rescaled to a face-on geometry, the SED predicted by our model shifts to qualitatively resemble a BL Lac. The increase in beaming in the outer jet regions causes the synchrotron peak to shift from the far-infrared to the X-ray band, and the Compton peak luminosity almost matches the synchrotron luminosity. Despite this increase in beaming, the SED remains more faint by three orders of magnitude more faint than the other Fermi-detected sources in our sample. Instead, the predicted SED resembles the more faint, galaxy-dominated sources of the sample, which are detected in radio and X-ray surveys but not at higher energies. In particular, our face-on model is in remarkably good agreement with the radio and X-ray data of 5BZG J0709+501.

The reason for the low luminosity is the available energy budget in the jet inferred from our model, which is far lower than that we found for PKS 2155–304 (\(P_{\text{jet,M87}} \approx 3 \times 10^{-5} L_{\text{Edd}} \approx 2.9 \times 10^{43} \text{ erg s}^{-1}\) against \(P_{\text{jet,PKS}} \approx 9 \times 10^{-3} L_{\text{Edd}} = 1.25 \times 10^{35} \text{ erg s}^{-1}\), see Paper I). This finding implies that M87 is not the misaligned counterpart of a typical gamma-ray bright HBL like Mrk 421 or PKS 304, which are inherently more powerful sources.

Despite the low energy budget, radio images of M87 display a typical Fanaroff–Riley type I morphology: The jet extends for tens of kpc and terminates in well-developed lobes (Owen et al. 2000). The ability of a low-power jet to produce such an extended structure suggests that the surrounding environment of the galaxy, rather than the central engine, may be the main driver for the formation of the large-scale radio structure (e.g. Tchekhovskoy & Bromberg 2016).

5 CONCLUSION

In this paper, we have for the first time combined constraints from VLBI imaging and spectral data to model the jet from the M87 radio galaxy, using our multizone jet model, bjet. We find that bjet can reproduce both the jet morphology and the SED from the radio to the hard X-ray band. Furthermore, the strong constraints imposed by the data ensure that a single degeneracy is present in the model, and that the free parameters are well determined. In particular, we find that the jet power near the core is \(P_{\text{jet,M87}} \approx 3.2 \times 10^{-5} L_{\text{Edd}} = 2.9 \times 10^{43} \text{ erg s}^{-1}\), in agreement with previous independent estimates. Deriving such good constraints highlights the importance of combining spectral modelling with additional information such as direct VLBI imaging when modelling AGN jets.

In the gamma-ray regime, we find that the inner magnetically dominated jet predicts too little flux to reproduce the Fermi/LAT 3FGL spectrum. This is because the high magnetization at the base, combined with the radio flux constraints, implies a low lepton number density, resulting in a very low inverse-Compton flux. Our findings are in contrast with single-zone SSC models, which can match the high-energy SED but only if the plasma is highly matter-dominated (e.g. Abdo et al. 2009; de Jong et al. 2015). Such a strongly matter dominated emitting region is unlikely to exist in the magnetically dominated inner jet, but might exist in the outer sheath of the jet (Tavecchio & Ghisellini 2008). Additional mechanisms that could allow for an enhanced gamma-ray emission are particle acceleration in the vicinity of the black hole (either the ergosphere, e.g. Neronov & Aharonian 2007; Rieger & Aharonian 2008; Levinson & Rieger 2011, or the stagnation surface, Broderick & Tchekhovskoy 2015), or inverse-Compton scattering of the host galaxy’s starlight, and/or of the cosmic microwave background in the large-scale jet (Stawarz et al. 2003).

When rescaling our best-fitting model to a face-on viewing angle of 5°, we find that while the SED roughly resembles that of a BL Lac, the predicted luminosity remains far lower than a prototypical HBL like Mrk 421. The main reason is that the increased beaming does not offset the low available jet power. This finding implies that the jet of M87 is not powerful enough to be the misaligned counterpart.
of a gamma-ray bright BL Lac, instead resembling more a faint, galaxy-dominated source.

The main caveat of our model is that it focuses on probing the inner magnetically dominated spine, neglecting the emission from the (more particle dominated) outer jet sheath. On one hand, limb-brightening is clearly observed in the radio imaging of M87 (e.g. Mertens et al. 2016; Hada et al. 2016), and, in principle, the sheath brightening is clearly observed in the radio imaging of M87 (e.g. McKinney 2006; Tchekhovskoy, Narayan & McKinney 2010; Nakamura et al. 2018; Chatterjee et al. 2019), implying that our assumed shape for the spine is consistent with the observed shape of the (edge-brightened) jet. Secondly, our synchrotron-dominated core model, when rescaled to a face-on geometry, resembles a low-power BL Lac, in agreement with AGN unification models (Antonucci 1993; Urry & Padovani 1995). This would not be the case if the bulk of the X-rays were produced in the slower outer sheath, as the Doppler factor would not be expected to vary significantly between the two viewing angles. Therefore, while our model cannot fully capture the physics of the system, it seems to provide a good overall description of the source beyond simpler single-zone models.

Our results are particularly important in light of the upcoming observations of M87 with the Event Horizon Telescope (e.g. EHT Collaboration 2019a), which provides even more detailed imaging of the regions near the black hole. These state-of-the-art observations will require further improvements in the modelling of jets, for example, by explicitly solving the relativistic MHD equations in the presence of gravity (e.g. Polko, Meier & Markoff 2010, 2013, 2014; Ceccobello et al. 2018) to derive the jet dynamics. We plan to couple these more physically consistent MHD solutions to observables in future works.

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