SYNTHETIC SYNCHROTRON EMISSION MAPS FROM MHD MODELS FOR THE JET OF M87

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1. INTRODUCTION

Since its discovery by Curtis (1918), the jet of M87 is the classical prototype for extragalactic jets. Due to its proximity at 16 Mpc (Whitmore et al. 1995; Macri et al. 1999; Tony et al. 2001), M87 is one of the closest radio galaxies, which allows present VLBI instruments to resolve the transversal structure of the jet. Therefore, it is an ideal candidate for testing specific jet formation mechanisms. The jet and its hot spots have been systematically studied across the electromagnetic spectrum from the radio to X-rays, both with ground-based observations and from satellites (for a review see, e.g., Biretta 1996). The initial opening angle is approximately 60° on scales of about 0.04 pc and decreases rapidly until reaching 10° at a distance of 4 pc from the core (Biretta et al. 2002). These observations suggest that the jet of M87 is rather slowly collimated across a length of several parsecs.

The prevailing paradigm for jet formation and collimation is magnetic self-collimation by the Blandford & Payne (1982) mechanism. This view is supported by observations which are consistent with the absence of a nonvanishing toroidal magnetic field component (Asada et al. 2002, 2008; Gabuzda et al. 2004; Zavala & Taylor 2005; Gómez et al. 2008). However, relativistic effects have been shown to decrease the collimation efficiency, i.e., for a given magnetic field configuration at the base of the jet (or rotator efficiency), the fraction of total mass and magnetic flux that is asymptotically cylindrically collimated is lower for a relativistic flow than for a nonrelativistic flow (Bogovalov & Tsinganos 1999; Tsinganos & Bogovalov 2000). Not only is the mass flux fraction lower, but the final opening angle is larger for relativistic outflows due to the decollimating effect of the electric field and the effective inertia of the plasma (Bogovalov 2001), which both counteract the pinching by the toroidal magnetic field. However, this is true only for initially radial magnetic field structures, as opposed to extended magnetic field configurations such as disk winds. See, for example, Fendt & Memola (2001), Vlahakis & Königl (2004), and Komissarov et al. (2007) for efficiently collimating MHD disk wind models.

In a series of papers, Gracia et al. (2005) and Tsinganos & Bogovalov (2005, 2002) suggested a steady state two-component MHD model. The model consists of an inner relativistic outflow, which is identified with the observed jet, and an outer nonrelativistic disk wind. While the inner relativistic jet is not expected to collimate well through magnetic self-collimation, the very same process operates efficiently in the outer nonrelativistic disk wind. It is expected that at least for a part of the available parameter space, collimation in the outer disk wind is so efficient that it might resist the decollimating inertia of the inner relativistic plasma and channel the jet into a narrowly confined beam. Gracia et al. (2005) have shown that such two-component models could easily account for the narrow appearance of the beam of extragalactic jets by reproducing the observational measurement of the opening angle distribution as a function of angular distance from the core (Biretta et al. 2002). Since in these models the jet, i.e., the relativistic inner outflow, is strictly speaking not magnetically self-collimated, but rather confined by the outer disk wind, the authors prefer to talk of collimation by magnetic confinement.

However, Gracia et al. (2005) could not fit the opening angle distribution with a unique MHD model. Instead, various sets of parameters reproduce the observations with similar accuracy.

In deriving the opening angle of their model, Gracia et al. (2005) made a simple but crucial assumption. They identified the observed jet with the inner relativistic outflow of their two-component model. More specifically, the boundary of the jet was assumed to coincide with the shape of a specific field line $\Psi_a$, which separates the relativistic inner region from the nonrelativistic outer disk wind at the base or the launching...
surface of the outflow. So, the observed opening angle was fitted by the shape of a single magnetic field line.

However, observations do not measure the plasma state directly, i.e., in terms of velocity, temperature, or magnetic field strength. Instead, they register photon flux as a function of position on the plane of the sky. As such, from an observational point of view, the width of the jet is defined by the emission dropping below the detection limit or a small fraction of the luminosity of the ridge line of the jet. So, the question is how well did Gracia et al. (2005) measure the width of the jet in terms of observational quantities? Or more generally—do MHD models explain the appearance of AGN jets? This paper answers this question by adopting the point of view of an observer. Assuming that the main radiation mechanism is synchrotron emission, we translate the steady state MHD model into a synthetic emission map and measure the width of the jet using only these data.

The outline of the paper is as follows. In Section 2, we summarize the two-component MHD model for extragalactic jets and discuss some of its properties relevant to this work. In Section 3, we present compact expressions for the calculation of synchrotron emission and apply these to our numerical MHD models for the jet of M87. Finally, we discuss our results in Section 4 and draw some conclusions in Section 5.

2. MHD MODEL

We adopt the model and notation of Gracia et al. (2005) and refer the reader to that paper for details. A simple illustration of the model is shown in Figure 1. It consists of two distinct zones: an inner outflow, which is dominated by relativistic dynamics, and an outer nonrelativistic outflow. Both outflows originate from a spherical launching surface located at a distance $r_0$ from the black hole. The launching surface is threaded by a helical magnetic field; the poloidal component is initially perpendicular to the launching surface. The two zones are separated by a specific field line $\Psi_\alpha$, where $2\alpha$ is the initial angular width or opening angle of the inner relativistic outflow. In the following, we will refer to these two distinct zones by relativistic jet and (nonrelativistic) disk wind, respectively.

This two-component model is motivated by a similar two-component structure of the underlying accretion flow consisting of an outer standard disk (Shakura & Sunyaev 1973) and an inner hot plasma, which could be either an advection-dominated accretion flow (Narayan & Yi 1994; Peitz & Appl 1997; Gracia et al. 2003), or the final plunging region near the black hole where relativistic dynamics dominate through, e.g., frame-dragging or the Blandford–Znajek process.

We impose two different sets of boundary conditions in the two distinct zones along the launching surface. If the launching surface is located beyond the fast magnetosonic surface, i.e., in the hyperbolic MHD regime, the steady state problem reduces to an initial-value Cauchy-type problem and the steady state equations can be integrated directly in terms of conserved integrals of motion as described by Tsinganos & Bogovalov (2002). We stress that beyond the launching surface, we solve the axisymmetric steady state problem self-consistently, including the magnetic field structure, as a function of the boundary values alone. However, we do not solve the problem inside the launching surface, which is a much more complicated exercise. A self-consistent solution of the problem needs to take into account the dynamics of the accretion flow, something which is beyond the scope of this paper.

This procedure yields a set of quantities as a function of space in the comoving frame of the jet. The separating field line $\Psi_\alpha$ perfectly divides the relativistic from the nonrelativistic outflow. Inside of $\Psi_\alpha$ the plasma is highly relativistic, both in terms of its bulk Lorentz factor, $\Gamma \gg 1$, and of its thermal energy, $T \gg m c^2$, while outside the plasma is cold, $T \ll m c^2$, and moving at nonrelativistic speeds, $\Gamma = 1$. Also, the magnetic field strength peaks close to the separating field line where field lines (and poloidal flowlines) of the inner outflow are strongly compressed laterally and confined to a narrow sheet by the field lines of the outer disk wind, thus forming a natural interface between both zones.

Gracia et al. (2005) used the shape of the separating field line $\Psi_\alpha$ to fit the observed opening angle (Biretta et al. 2002) as a function of distance from the core, however, without taking into account projection effects, i.e., they assumed implicitly that the jet of M87 was in the plane of the sky. There is an ongoing discussion on the inclination angle of the M87 jet (see, e.g., Owen et al. 1989; Reid et al. 1989; Biretta et al. 1999; Ly et al. 2007). In this paper we assume that the jet of M87 is oriented at an angle $\theta_{los} = 40^\circ$ from the line of sight as a compromise of values discussed in the literature.

Unfortunately, the parameter space of the MHD model is degenerated in the sense that very different sets of parameters yield equally good fits or even almost identical opening angle distributions. Then, to constrain the model parameters further, we shall invoke the radiation signatures of each model and compare them with the corresponding observations. In this way, we may pin down a small number of acceptable models which simultaneously satisfy the constraints of the MHD model and also reproduce the observed distribution of the emitted radiation.
We have run 2600 axisymmetric steady state MHD models and calculated synthetic synchrotron maps for them. Here, we discuss the four models that evaluate best under different criteria. See Table 1 for their parameters. Figure 2 compares the opening angle as defined by the separating field line $\Psi_\alpha$, projected under an angle of $\theta_{\text{los}} = 40^\circ$, with the observational measurements. Note that all our models fail to fit the jet width at large distances close to the optical knot A at $\sim 900$ pc and also at small distances close to the jet's origin where there are some uncertainties, as discussed in the last section. Models with large initial opening angle matching the first data point, e.g., model C, have difficulties reproducing the opening angle distribution. It is in general very difficult to make the curve more concave. Models with initial opening angles falling slightly short of the measured value (as models A, B, and D) may easily reproduce the rest of the measurement and yield quite good fits. The quality of agreement between the observed opening angle distribution and the theoretical curve is measured by a simple $\chi^2$, i.e., the sum of squares of the difference over all the available data points. Model D best fits the opening angle at $\chi^2 = 2.9$, but does not reproduce the morphological structure of the radiomaps particularly well as discussed in the next section. However, the overall best model A reproduces the morphological structure and still fits the opening angle data reasonably well with $\chi^2 = 7.8$. Note that both models show a clear kink at $\sim 100$ pc due to recollimation toward the axis.

Typically, models that fit the observed opening angle well are moderately relativistic, both in terms of the initial outflow velocity $\Gamma_j \sim 2$–3 and the initial plasma internal energy $T_j \sim 3$ meV. In these models, the plasma velocity increases along the flow to values up to $\Gamma \sim 5$–10. However, the plasma may decelerate and reaccelerate sharply at the recollimation shock. Strong gradients of the plasma velocity may generally be present across the jet as seen in Figure 3. It is, therefore, very difficult to assign a typical Lorentz factor to the whole jet.

3. SYNCHROTRON MAPS

3.1. Calculation of Synchrotron Maps

The calculation of the radio emissivity is done according the relativistic generalization of expressions presented by Laing (1981) and Pacholczyk (1970). It is assumed that the radiating region is optically thin with a uniform and isotropic distribution of electrons

$$N'(E') \propto E'^{-(2\alpha_e+1)}$$

(1)

giving rise to radiation with a spectral index $\alpha_e = 1$, i.e., $S'_e \propto \nu^{-\alpha_e}$. Note that primed quantities are measured in the comoving frame of the plasma, while unprimed quantities refer to the lab frame or are independent of the frame of reference.

We assume, furthermore, that the fraction of electron number density to proton number density is constant throughout the emitting volume. Then the number density of electrons $n_e = \frac{\rho'}{\Gamma} = \frac{\rho}{\Gamma}$

\begin{align*}
\rho' & = \frac{\rho}{\Gamma}, \\
B' & = \frac{1}{\Gamma} B + \frac{\Gamma}{\Gamma + 1} \frac{\nu}{c^2} (\nu \cdot B),
\end{align*}

(4)
for a compact notation and exploited the fact that in ideal MHD
\[ \Gamma \]

Figure 3. Lorentz factor along the flow for model A. Contour levels are shown at \( \Gamma = 2, 4, \ldots, 12 \). The relativistic inner jet initially has Lorentz factors \( \Gamma \sim 2-3 \), but accelerate up to \( \Gamma \sim 10-12 \). Strong gradients may be seen across the jet and near the recollimation shock, if present.

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

\[ \hat{n}'_{los} = D \hat{n}_{los} - (D + 1) \frac{\Gamma}{\Gamma + 1} \frac{v}{c}. \]  
(5)

We have introduced the Doppler factor \( D = (\Gamma(1-v \hat{n}_{los}/c))^{-1} \) for a compact notation and exploited the fact that in ideal MHD Ohm's law holds as \( E = -v \times B \) in both frames of reference.

The emissivity in the lab frame \( \epsilon \) appears Doppler boosted as

\[ \epsilon = D^\alpha \epsilon'. \]  
(6)

The amount of relativistic beaming strongly depends on the line of sight angle, i.e., the angle between the jet axis and the direction to the observer, which we fix at \( \theta_{los} = 40^\circ \). Finally, the flux in the plane of the sky, \( I \), is given by integration along the line of sight

\[ I = \int \epsilon \, d\ell_{los}. \]  
(7)

The synthetic synchrotron maps are convolved with a Gaussian beam to qualitatively match the finite resolution of observed maps. However, since our synthetic maps span more than four orders of magnitude in distance from the core, the width of the Gaussian beam is not kept constant. Typical radiomaps have a spatial resolution corresponding to a couple of observing beams across the width of the jet. We therefore use at each distance along the jet a Gaussian convolution kernel of 1-sigma width equal to one-tenth of the jet radius at that distance, i.e., \( \sigma(Z) = R_{\text{rad}}(Z)/10 \).

The measurements of the opening angle collected by Biretta et al. (2002) typically define the jet radius at distance \( Z \) as the \textit{half-width at quarter-maximum} (HWQM) for the emission across the jet. We adopt this definition and refer to it as the jet width of the radiomap \( 2R_{\text{map}} \), with

\[ I(R_{\text{map}}, Z) = \max(I(R, Z))/4. \]  
(8)

3.2. The Best Model

The synthetic synchrotron emission maps shall qualitatively reproduce two observational constraints: (1) the opening angle defined through HWQM (half-width at quarter-maximum) in terms of small \( \chi^2 \) values, and (2) the pronounced limb brightening in terms of small values for the mean intensity on the axis over intensity on the limb, i.e., \( \langle I_{\text{axis}}/I_{\text{limb}} \rangle \). As a secondary criterion, we favor models showing some degree of enhanced emission close to the nominal position of HST-1 at 70 pc.

We calculated synthetic synchrotron emission maps and evaluated them according to our two criteria. For each of the two criteria we assigned a score between 0 and 1 from a sorted list of values for \( \chi^2 \) and \( \langle I_{\text{axis}}/I_{\text{limb}} \rangle \), respectively, and added those to obtain the total score. A few formally high-scoring models were discarded because they did not show clear sign of increased brightness at distances 70–200 pc that could be identified with the knot HST-1. The first model satisfying all criteria will be referred to as \textit{the best model} or \textit{simply model A}.

The jet in the best model A is launched with a bulk velocity of \( \Gamma_j = 2.74 \) and temperature \( T = 2.85 \text{ mc}^2 \). The separating field line threads the launching surface radially at an angle \( \alpha = 16^\circ \) with an angular velocity \( \omega_0 = 3 \text{ r}_g/c \). The outer cold disk wind is launched with velocity \( \Gamma_d = 1.02 \).

For the best model A, we plotted spatial two-dimensional synthetic synchrotron emission maps (Figure 5), the intensity measured on the jet axis as a function of distance from the core (Figure 4), and the intensity profiles across the jet at various positions along the jet axis (Figure 6).

In Figure 4, we plot the trend along the axis for the best model A and compare it with model C, which shows the highest local brightness enhancement at the position of HST-1 in our sample. The intensity along the axis is well described by a power law in projected distance. Both models have similar power-law indices \( \sim -2.5 \). The model jets dim out faster than the observed jet whose power-law index can be estimated to \( \sim -1.5 \) from
Figure 5. Convolved synthetic synchrotron map. To increase contrast, the map has been divided by the trend along the jet axis (Figure 4). The two lines near the edge of the jet indicate the jet width as defined by the separating field line (the inner black line) and the HWQM of the map (the outer white line). The three horizontal lines indicate the position of cuts across the jet shown in Figure 6. (A color version of this figure is available in the online journal.)

the contrast of several published intensity maps. However, this discrepancy is not surprising as our model does not take into account any microphysics in order to reenergize the electron distribution. Both models show a rise of luminosity around 70 pc over the local power law by a factor of ~3 and ~10, respectively. The location of this bright spot coincides with the location of strong recollimation shocks where density and magnetic field strength increase.

Figure 5 shows the synthetic synchrotron map. In order to increase the contrast we divided the map by the trend along the jet axis, i.e., \( I(R, Z)/I(0, Z) \). The jet beam is well defined, showing large opening angles close to the core and becoming almost conical at large distance. At the position of the recollimation shock, the jet width decreases and forms a visible neck.

The synthetic synchrotron maps show strong gradients of intensity across the jet. These are more clearly visible in Figure 6 where cuts across the jet are shown. For comparison, we also show profiles for model C which has the most pronounced limb brightening.

The best model A shows limb brightening already at a distance of ~0.2 pc from the core. In the limb bright region \( \langle I_{\text{axis}}/I_{\text{limb}} \rangle = 0.76 \) on average before convolution. After convolution, the ratio rises to typically 0.85. Model C bifurcates at ~0.5 pc and has \( \langle I_{\text{axis}}/I_{\text{limb}} \rangle = 0.67 \) and 0.80 before and after convolution, respectively. These values agree with those observed by Ly et al. (2007) ~ 0.63, Kovalev (2008) ~ 0.6, and Kovalev et al. (2007, and private communication) 0.6–0.8, depending on jet region and resolution. We note, however, that the limb brightness as well as the bifurcation distance depends on the details of convolution as discussed later on.

Figure 7 compares the opening angle derived from the synthetic maps \( R_{\text{map}} \) with the observations. Model B fits the observations best with \( \chi^2 = 5.7 \), but fails to reproduce the limb brightening. The best model A has \( \chi^2 = 14.6 \), which we consider acceptable, in particular, if one considers the figure.

Finally, we compare the width of the jet from the MHD models, \( R_\alpha \), with the jet width of the synthetic synchrotron maps, \( R_{\text{map}} \). Both curves are superimposed on the synthetic map in Figure 5. For many models in our sample, these two curves are virtually indistinguishable. However, for our overall best model, these two curves are noticeably different, even if they run almost parallel. For this particular model, \( R_\alpha \) underestimates the opening angle by ~20% for all the length of the jet, i.e., \( R_{\text{map}} \sim 1.2 R_\alpha \). For other models in our sample, the difference is typically not more than 30%–40%.

3.3. The Origin of Limb Brightening

The synthetic emission map of the best model A in Figure 5 shows clear limb brightening from a distance of ~0.5 pc up to the location of the recollimation shock at ~70 pc and, to a lesser extent, even beyond. This can be seen more clearly in Figure 8 which shows the synchrotron emissivity \( \epsilon \) in the midplane of the jet. It is worth noting that close to the origin the whole jet body emits synchrotron radiation. Further down the jet—and certainly beyond 0.2 pc projected distance from the core—the emission is dominated by a thin shell at the outer edge of the jet, while the inner region close to the axis remains relatively dark by a factor of more than a hundred. Within our model this is easily explained noting that the synchrotron emissivity Equation (2) is roughly proportional...
Figure 7. Comparison of the opening angle calculated from synthetic maps and the observational data for M87. The lines show opening angle profiles as given by the HWQM contour $R_{\text{HWQM}}$ of the overall best model A (the solid line) and model B (the dashed line) which fits the opening angle data best. Models C (dotted) and D (dot-dashed) are shown for comparison. Various symbols represent observational measurements. The data points marked by filled circles were taken into account in the fitting procedure. The innermost and outermost measurement (open circles) were disregarded as explained in the text.

Field lines within the relativistic jet start out radially from the launching surface, but are soon deflected by the outer cold disk wind. This leads to strong concentration of magnetic flux, and therefore high field strength in a narrow region at the interface between both components of the MHD model. The simultaneously occurring increase of density plays only a minor role.

Further down the flow at around 60 pc, the emissivity within the jet body increases again significantly and edge brightening is less pronounced. This region coincides well with the location of the recollimation shock, where the topology of the magnetic field and the distribution of plasma across the jet significantly change. Beyond the recollimation shock, the emissivity is almost homogeneous across the jet.

However, the full picture is more complicated than that, since the orientation of the highly nonhomogeneous velocity field relative to the line of sight is at least equally important. Not only does the poloidal velocity vary from one magnetic flux surface to the next, but the jet plasma is also rotating. Together, this makes the Doppler factor and the angle to the line of sight in the comoving frame highly variable even along the circumsphere of the emitting plasma shell. Cross-sections perpendicular to the apparent axis of the jet reveal that the emissivity along the line of sight may be highly asymmetric with respect to fore- and background halves of the jet.

4. DISCUSSION

Limb brightening strongly constrains the parameters of MHD models for the jet of M87. It is difficult not only to find parameters resulting in a pronounced limb brightening in terms of low $<I_{\text{axis}}/I_{\text{limb}}>$, but also to reproduce the spatial extent of the limb bright region. Depending on frequency and resolution, radiomaps for M87 show limb brightening from large distances almost right down to the core (Cheung et al. 2007; Kovalev et al. 2007). However, the bifurcation distance, i.e., the location where the jet morphology transits from center bright to limb bright, seems to depend strongly on the frequency of a particular observation. It is not clear a priori to what extent this is due to intrinsic different emission properties at different observing frequencies, or due to spatial resolution effects. Y. Y. Kovalev (private communication) has analyzed the deep 15 GHz VLBA image of the inner jet in M87 (Kovalev et al. 2007). The distance from the core at which the bifurcation becomes detectable changes from 5 mas at the original 15 GHz resolution to more than 100 mas for a tenfold larger beam corresponding to 1.5 GHz. We conclude that variable resolution can, in principle, account for different bifurcation distances at different frequencies.

Limb brightening is often explained by stratified jets consisting of a fast spine and a slow sheath (see, e.g., Aloy et al. 2000; Ghisellini et al. 2005). In those models the slow sheath brightens up in comparison to the spine because of Doppler boosting into the $1/\Gamma$ cone. For the given large line of sight angle of the M87 jet, the fast spine is seen from well outside of the Doppler-boosted cone and its emission deboosted. Here, we suggest an alternative explanation for limb brightening in AGN, in particular M87. In our model, the limb brightens up due to the concentration of magnetic flux at the interface between the relativistic jet and the confining nonrelativistic disk wind. The synchrotron emissivity is therefore already intrinsically higher in the comoving frame and limb brightening does not rely on relativistic aberration alone. Incidentally, as seen in Figure 3 in our models the velocity fields is strongly stratified including rotating which will counteract limb brightening for large inclination angles.
The exact value of the line of sight angle for the jet of M87 is still under debate. In this study, we have assumed an angle \( \theta_{\text{los}} = 40^\circ \) which brings it into the upper end of the suggested range of values. In order to study the effect of the line of sight angle on limb brightening, we have calculated synthetic maps for model A under an angle \( \theta_{\text{los}} = 30^\circ \). In comparison to the original map, the bifurcation distance moves out to 0.5 pc, limb brightening is more pronounced, and the recollimation shock is brighter with regard to the trend along the axis. At the same time, this obviously enlarges the apparent opening angle along the jet and brings the recollimation shock closer to the core in disagreement with observations. The simplest way to bring the opening angle curve back down and move the recollimation shock out is to decrease the model’s initial opening angle \( \alpha \). However, models with lower \( \alpha \) tend to show weaker limb brightening and dimmer recollimation shocks (if present at all). It may therefore be challenging to construct models that reproduce all criteria for smaller inclination angles.

Under the assumption that jet and counterjet are intrinsically identical, one can in principle constrain the inclination angle by measuring the jet-to-counterjet brightness ratio \( I_+ / I_- \) given by

\[
I_+ / I_- = \left( \frac{1 + \beta \cos \theta_{\text{los}}}{1 - \beta \cos \theta_{\text{los}}} \right)^{\alpha + 2},
\]

where \( \beta = v/c \) is the velocity in units of the speed of light, and \( \alpha \) is the electron distribution power-law index. Kovalev et al. (2007) estimated this ratio to be of the order 10–15, while Ly et al. (2007) measured \( I_+ / I_- = 14.4 \) and constrained the bulk flow velocity to \( \beta \sim 0.6-0.7 \). We calculated a synthetic synchrotron map for the best model A pointing in the opposite direction, i.e., the counterjet at \( \theta_{\text{los}} = 220^\circ \), and estimated \( I_+ / I_- \sim 13 \) from the on-axis intensities close to the core on either side of it (see Figure 9). The agreement is remarkable, in particular taking into account that one would naively expect a much higher value (>200) from the model’s initial Lorentz factor \( \Gamma_j = 2.74 \), i.e., \( \beta_j = 0.93 \), given in Table 5. However, Equation (9) assumes a homogeneous velocity field along the axis and identical intrinsic emissivities on either side of the core. Stratification of the jet beam and rotation of the plasma about the axis, as is the case in our models, can therefore lead to serious misinterpretation if not taken into account.

While fitting the opening angle to the observational measurements collected by Biretta et al. (2002), we disregarded the outermost data point close to the optical knot A at 900 pc. All our models fail to reproduce this measurement and disregarding it made the least-squares fit more reliable and robust for the remaining data points. However, we argue that at such large distances the interaction between the environment and the jet, which cannot be taken into account by our numerical MHD solver, begins to dominate the jet dynamics, and thus renders our model insufficient. We have also disregarded the innermost data point of 60°. This old measurement has recently been challenged. Ly et al. (2007) state that the opening angle at the jet base is larger than 15° and therefore consistent with Biretta et al. (2002) old measurement, but then interestingly continue to repeat arguments that it might be an overestimation. Maps presented by Krichbaum et al. (2008) and Walker et al. (2008) seem to leave room for smaller opening angles at the base. In general, the initial opening angle measured from our synthetic emission maps can easily be higher than 40°.

Most of our models that reproduce the measured opening angle as a function of distance as well as the limb brightening do at the same time exhibit a recollimation shock, showing some degree of locally enhanced emission. We identify this recollimation shock with the bright knot HST-1. In most of our models, the emission at the bright knot does not increase by more than a factor of 10 compared to the general trend, while for the real HST-1 the increase in emission level is probably higher. However, this is not surprising, since our MHD model does not include any microphysics, e.g., particle acceleration, which could be responsible for further enhancing the emission level. It is still noteworthy that the conditions in the vicinity of the recollimation shock of the best model A are similar to those postulated from SSC models in order to fit the TeV emission in M87. In particular, Harris et al. (2003) recently presented an SSC model assuming that the TeV emission was originating from HST-1. In our model, the Doppler factor in the vicinity of the recollimation shock is rather low \( D \sim 1-2 \). For those Doppler factors, Harris et al. (2003) calculated a magnetic field strength of \( B' = (13-3.7) \) mG, which matches very well with \( B' \sim 10 \) mG in our model.

5. SUMMARY AND CONCLUSIONS

We have calculated self-consistent global MHD models and synthetic optically thin synchrotron maps with the aim to reproduce the reported opening angle distribution as well as the morphological structure, in particular limb brightening, of the jet of M87. We have applied different criteria to quantify the agreement between models and observations. All criteria can be satisfied to high degree by individual models in our database. However, no model does satisfy simultaneously all criteria exceedingly well. We identified a best model as compromise between the opening angle distribution and the high degree of
limb brightening. This model satisfactorily meets our criteria, but does not perform best in any single one.

Gracia et al. (2005) used the shape of the field line separating the two regions on the boundary surface to define the opening angle. As shown in this work, this particular field line and flux contours of synthetic maps are parallel for a wide range of models and distances along the jet. However, the first method may underestimate the opening angle for some parameters by typically 30%.

The morphological structure across the jet can be reproduced in principle. A wide range of models show limb brightening away from the core. The transition from center-bright to limb-bright, the bifurcation of the jet generally occurs well below 1 pc projected distance. A quantitative comparison with specific observations, however, requires careful modeling of the convolving beam and may require including opacity effects, i.e., optically thick emission. Both effects are frequency dependent.

In our models, limb brightening is due to a strong increase of the comoving frame synchrotron emissivity in a relatively thin shell near the outer edge of the visible jet as a result of concentration of magnetic flux at the interface between the relativistic outflow and the nonrelativistic disk wind, i.e., the environment. In contrast to other models limb-brightening here is not an immediate result of a slowly moving sheath being boosted into the 1/T cone; in fact the “sheath” in our models is typically Doppler-deboosted due to the presence of a stratified azimuthal velocity component.

The optical knot HST-1 has received much attention. Most MHD models with acceptable fits to the opening angle distribution feature a shock at the distance 70–200 pc. This is particularly true for models with large initial opening angle $\alpha$. The shock is due to the fact that the jet is not in lateral force equilibrium at the launching surface and overexpands. Later, it is forced back toward the axis by magnetic hoop stress and produces a recollimation shock (Bogovalov & Tsinganos 2005). In all cases, the shock is visible as a bright spot in the synthetic maps.

We performed our parametric studies unbiased toward the existence of a recollimation shock. All high-ranking models have a recollimation shock. Only after ranking our models, we favored for illustrative purposes models with pronounced brightness increase at some point along the axis. We therefore conclude that the optical bright knot HST-1 is a general feature of all models matching our selection criteria and cannot be seen independently from them. In particular, we suggest that any physical model explaining the opening angle and morphological structure will simultaneously account for HST-1.

In addition, our best-fitting model is consistent with a number of observational constraints such as the magnetic field in the knot HST-1 and the jet-to-counterjet brightness ratio.

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