A two-zone synchrotron model for the knots in the M87 jet

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ABSTRACT

The flux and the spectral index in the X-ray energy band from the knots of the M87 jet as observed by Chandra indicate a possible synchrotron origin but cannot be explained by simple one-zone models with continuous injection of non-thermal electrons. In this Letter we propose a two-zone model to explain the observed spectra of the knots of the M87 jet. We consider the synchrotron emission from a region with a tangled magnetic field where relativistic non-thermal electrons are continuously injected in from an associated acceleration region. The acceleration region is assumed to be a compact zone possibly around a shock front. A power-law distribution of electrons is injected into the acceleration region and accelerated to a maximum energy determined by the acceleration time-scale and the loss processes. With the present model we are able to explain the overall broad-band features of the knots of the M87 jet. Also the present model predicts a change in spectral index at ultraviolet energies, and future observations at these energies, can be used to constrain the parameters involved in the model.

Key words: galaxies: active – galaxies: individual: M87 – galaxies: jets – X-rays: galaxies.

1 INTRODUCTION

M87 is a nearby giant elliptical galaxy (distance = 16 Mpc; Tonry 1991) possessing a one-sided jet with projected distance ≈2 kpc and bright in radio, optical and X-ray energies. The jet structure is very well studied in radio (Owen, Hardee & Cornwell 1989; Birgetta, Zhou & Owen 1995; Sparks, Birgetta & Macchetto 1996), infrared (Sparks et al. 1996; Perlman et al. 2001b) and optical (Meisenheimer, Roeser & Schloetelburg 1996; Sparks, Birgetta & Macchetto 1996) bands. Prior to Chandra, the M87 jet was not very well studied at X-ray energies due to the limited angular resolution of earlier X-ray telescopes, Einstein and ROSAT. However, Chandra due to its better spatial resolution is able to resolve many fainter knots of the M87 jet which were observed only in radio and optical bands earlier. Moreover, the positions of these knots in X-ray energies are nearly coincident with their radio/optical counterparts (Perlman et al. 2001b; Perlman & Wilson 2005). Also M87 is the only radio galaxy [other than CenA (Sreekumar et al. 1999)] which is detected in GeV–TeV energies (Aharonian et al. 2003). Initially it was not well understood whether the TeV gamma-ray emission region is close to the nucleus (Georganopoulos, Perlman & Kazanas 2005) or from the knot HST-1 (Stawarz et al. 2006). However, the detection of M87 by HESS confirmed the high-energy emission from the region close to the nucleus (Aharonian et al. 2006). The recent VERITAS detection of VHE emission from M87 (Benbow 2008) again suggests the emission may not be from HST-1. Considering the fact that the M87 jet is misaligned to the observer, explaining this TeV gamma-ray emission required a modified model other than the one used to explain blazar emission. Neronov & Aharonian (2007) explained TeV gamma-ray emission due to radiative cooling of electrons accelerated by strong rotation induced electric fields in the vacuum gaps in black hole magnetospheres. Lenain et al. (2008) proposed a multiblob model with several plasma blobs moving in the large opening angle of the jet formation zone. TeV gamma-ray emission is explained as Doppler boosted synchrotron self-Compton radiation by the blobs moving close to the line of sight.

The radio-to-optical emission from the knots of the M87 jet is quite well accepted as synchrotron emission due to cooling of relativistic non-thermal electrons by the magnetic field therein (Perlman et al. 2001b). The flux and the spectral indices at X-ray energies indicate a possible continuation of synchrotron emission of the radio-to-optical spectra with the change in the spectral index beyond optical energies (Marshall et al. 2002; Stawarz et al. 2005).

Simple theoretical models, namely the continuous injection model (hereafter CI) (Kardashev 1962; Ginzburg & Syrovatskii 1968; Heavens & Meisenheimer 1987; Meisenheimer et al. 1989) and the one time injection model (Kardashev 1962; Pacholczyk 1970; Jaffe & Perlora 1973) were unable to explain the observed X-ray flux and/or the spectral index. The CI model considers the synchrotron emission from non-thermal electrons injected continuously into a region with tangled magnetic field. But the X-ray flux predicted by this model is more than the observed flux (Perlman & Wilson 2005). In the one time injection model, a burst of electrons are injected at t = 0 and allowed to evolve with (Jaffe & Perlora 1973) or without pitch angle scattering (Kardashev 1962;
Here \( \gamma \) energy-independent (Atoyan & Aharonian 1999) and the electron distribution for an electric field. We treat the present scenario as two zones: one around the shock can be an outcome of an earlier acceleration process. The particles accelerated by the shock cool via synchrotron radiation in a homogeneous magnetic field behind it. The present model is similar to a situation where particles accelerated by an external shock are advected downstream to be accelerated further by an internal shock. Two-zone models were in fact used by various authors to explain the spectral and the temporal behaviour of blazars (Kirk et al. 1998; Li & Kusunose 2000; Bhattacharyya, Sahayanathan & Bhatt 2005). In the next section, the formulation of the present model and the parameters involved are discussed. In Section 3 we discuss the results of the fitting using the present model and compare the present model with the other existing models.

2 THE TWO-ZONE MODEL

We consider the acceleration of a power-law distribution of particles (which may be a relic of a past acceleration process) at a shock front and cooling via synchrotron radiation in a homogeneous magnetic field. We treat the present scenario as two zones: one around the shock front where the particles are accelerated (AR) and the downstream region where they lose most of their energy through the synchrotron process (CR). This model is then used to explain the radio–optical–X-ray–radio spectra of the knots in the M87 jet. We assume the CR to be a spherical blob of radius \( R \) with tangled magnetic field \( B_{\text{CR}} \) and the AR is assumed to be a very thin region with magnetic field \( B_{\text{AR}} \). A power-law distribution of electrons is continuously injected into the AR accelerated by the shock characterized by an acceleration time-scale \( t_{\text{acc}} \). Particles are then accelerated at a rate \( 1/t_{\text{acc}} \) to a maximum energy determined by the loss processes. The AR is assumed to be compact and the emission from the CR mainly contributes the overall photon spectrum.

The kinetic equation governing the evolution of electrons in the AR is given by

\[
\frac{\partial n(\gamma, t)}{\partial t} = \frac{\partial}{\partial \gamma} \left[ \beta_{\text{AR}} \gamma^2 - \gamma \frac{t_{\text{acc}}}{t_{\text{esc}}} \right] n(\gamma, t) - n(\gamma, t) \frac{t_{\text{acc}}}{t_{\text{esc}}} + Q(\gamma),
\]

where \( Q(\gamma) d\gamma = q_0 \gamma^{-p} d\gamma \) for \( \gamma_{\text{min}} < \gamma < \gamma_b \).

Here \( \gamma \) is the Lorentz factor of the electron, \( t_{\text{esc}} \) is the escape time-scale and \( \beta_{\text{AR}} = [\sigma_T/(6\pi\tau e c)]B_{\text{AR}}^2 \).

Equation (1) can be solved analytically using Green’s function (Atoyan & Aharonian 1999) and the electron distribution for an energy-independent \( t_{\text{acc}} \) and \( t_{\text{esc}} \) at time \( t \) is given by

\[
n(\gamma, t) = t_{\text{acc}} \gamma^{-(\alpha+1)} \left( 1 - \frac{\gamma}{\gamma_{\text{max}}} \right)^{u-1} \times \int_{x_0}^{\gamma} Q(x) \left[ \frac{1}{x} - \frac{1}{\gamma_{\text{max}}} \right]^{-\alpha} dx,
\]

where \( \alpha = t_{\text{acc}}/t_{\text{esc}} \) and the lower limit of integration \( x_0 \) is given by

\[
x_0 = \left[ \frac{1}{\gamma_{\text{max}}} + \frac{1}{\gamma} - \frac{1}{\gamma_{\text{max}}} \right]^{-1} \exp(t/t_{\text{acc}}) \cdot \gamma_{\text{max}} = 1/((\beta_{\text{AR}} t_{\text{acc}}) > \gamma_b \) is the maximum Lorentz factor an electron can attain in the AR. For \( t \gg t_{\text{acc}} \) equation (4) can be approximated to be \( \gamma_{\text{min}} \) as the injection term in equation (3) vanishes for \( x \ll \gamma_{\text{min}} \).

The evolution of the electrons in the CR is governed by the equation

\[
\frac{\partial N(\gamma, t)}{\partial t} = \frac{\partial}{\partial \gamma} \left[ \beta_{\text{CR}} \gamma^2 N(\gamma, t) \right] + Q_{\text{CR}}(\gamma),
\]

where

\[
Q_{\text{CR}}(\gamma) \approx q_0 \alpha \gamma^{-(\alpha+1)} \left( 1 - \frac{\gamma}{\gamma_{\text{max}}} \right)^{u-1} \times \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} x^{-p} \left[ \frac{1}{x} - \frac{1}{\gamma_{\text{max}}} \right]^{-\alpha} dx
\]

and \( \beta_{\text{CR}} = [\sigma_T/(6\pi\tau e c)]B_{\text{CR}}^2 \).

The distribution of electrons at the time \( t \) in the CR from equation (5) is given by

\[
N(\gamma, t) = \frac{1}{\beta_{\text{CR}}^2} \int_{\gamma}^{t_{\text{esc}}} Q_{\text{CR}}(x) dx,
\]

where \( t_{\text{esc}} = \gamma/(1 - \gamma \beta_{\text{CR}} c) \).

From equation (3), it can be shown that the injection into the CR (for \( \alpha + 1 > p \)) is a broken power law with index \(-p\) for \( \gamma < \gamma_b \) and \(-(\alpha + 1)\) for \( \gamma > \gamma_b \). The synchrotron losses in the CR introduce an additional break \( \gamma_c \) in the electron spectrum depending upon the age of the CR \( t_{\text{obs}} \) and \( B_{\text{CR}} \):

\[
\gamma_c = \frac{1}{\beta_{\text{CR}} t_{\text{obs}}}.
\]

The electron spectrum in the CR at \( t_{\text{obs}} \) can then have two different spectral shapes depending on the location of \( \gamma_c \) with respect to \( \gamma_b \).

(i) \( \gamma_c > \gamma_b \): The final spectrum will have two breaks with indices

\[
N(\gamma, t_{\text{obs}}) \propto \begin{cases} \gamma^{-p}, & \gamma_{\text{min}} < \gamma < \gamma_b, \\ \gamma^{-(\alpha+1)}, & \gamma_b < \gamma < \gamma_c, \\ \gamma^{-(\alpha+2)}, & \gamma_c < \gamma < \gamma_{\text{max}}. \end{cases}
\]

(ii) \( \gamma_c < \gamma_b \): In this case the indices are

\[
N(\gamma, t_{\text{obs}}) \propto \begin{cases} \gamma^{-p}, & \gamma_{\text{min}} < \gamma < \gamma_c, \\ \gamma^{-(\alpha+1)}, & \gamma_c < \gamma < \gamma_b, \\ \gamma^{-(\alpha+2)}, & \gamma_b < \gamma < \gamma_{\text{max}}. \end{cases}
\]

The synchrotron emissivity \( \epsilon_v \) from the resultant electron spectrum is then calculated by convolving \( N(\gamma, t) \) with the single particle emissivity averaged over an isotropic distribution of pitch angles \( P(\gamma, v) \):

\[
\epsilon_v = \frac{1}{4\pi} \int_{1}^{\infty} N(\gamma, t) P(\gamma, v) d\gamma.
\]

The predicted spectrum by the above model depends on nine parameters, which are \( q_0, \alpha, \gamma_{\text{min}}, \gamma_b, \gamma_{\text{max}}, p, \beta_{\text{CR}}, R \) and \( t_{\text{obs}} \).
\(\alpha\) and \(p\) are estimated from the radio-to-optical and optical-to-X-ray spectral indices; \(q_R\) and \(R_{\text{eq}}\) are constrained using the observed luminosity and equipartition magnetic field. For \(R\) we assume the physical sizes measured in the radio (Hardee 1982). The age of the knot \(t_{\text{obs}}\) is chosen to introduce a break in the observed spectrum at the optical band and \(\gamma_b\) is fitted to reproduce the observed X-ray flux. \(\gamma_{\text{min}}\) and \(\gamma_{\text{max}}\) are used as free parameters and are fixed at 5 and 10\(^8\).

### 3 RESULTS AND DISCUSSION

We applied the above model to explain the knots D, F, A and B of the M87 jet: the results of the fitting are shown in Fig. 1 and the parameters used for the fit are given in Table 1. The spectrum of knot E can be explained by a simple CI model and the parameters we quote correspond to the CI model. We did not model knot C due to significant differences in X-ray–optical properties (Perlman & Wilson 2005).

For all the fits shown in Fig. 1, \(\gamma_c < \gamma_b\). However, one can fit the spectrum with \(\gamma_c > \gamma_b\) with proper choices of the parameters \(\alpha, \gamma_c\) and \(\gamma_c\). This degeneracy arises due to the unavailability of the ultraviolet (UV) spectral index since the present model predicts the corresponding particle spectral index as \(-c(\alpha + 1)\) or \(-c(p + 1)\) (equations 9 and 10) depending upon the above two conditions. Future observations at these photon energies may help in validating the present model and also will remove this degeneracy. Also, to obtain a precise values for \(p\) and \(\alpha\), spectral indices at radio–optical and X-ray energies should be known accurately. In general \(t_{\text{obs}}\) and \(t_{\text{esc}}\) can be energy dependent and in such a situation the solution (equation 3) may differ from its form and the index beyond \(\gamma_b\) may not be the one discussed above.

Using the present model we estimated the fluxes at GeV–TeV energies due to inverse Compton scattering and these are given in Table 1. For the inverse Compton process the target photon can be either synchrotron photon (SSC) or cosmic microwave background radiation (IC/CMBR) or both. From the observed superluminal velocities of 2\(^c\) to 6\(^c\) and the viewing angle of \(10^\circ\)–\(20^\circ\) (Biretta, Sparks & Macchetto 1999) we found that the synchrotron photon energy density dominates over the Doppler-boosted CMBR. Hence the fluxes quoted in Table 1 are due to the SSC process and are below the sensitivity of the present gamma-ray telescopes MAGIC (Majumdar et al. 2005), HESS and the upcoming experiment GLAST.\(^2\)

Hence discrimination of the models based on GeV–TeV observations as discussed in Georganopoulos et al. (2006) for 3C 273 cannot be done for the M87 jets.

A possible scenario of the present model is where the AR is a region around an internal shock following an external shock. The electrons injected into the AR can be those that are already accelerated by an external shock and are advected downstream to be accelerated further by the internal shock (Pope & Melrose 1994; Tammi & Dempsey 2007). An internal shock description for the knots in AGN jets has already been discussed in the literature (Rees 1978; Sahayanathan & Misra 2005). Alternatively, re-acceleration of a power-law electron distribution by turbulence at boundary shear layers can also be another possible scenario (De Young 1986; Stawarz & Ostrowski 2003). Inclusion of these scenarios in their exact form into the present model will make it more complex and is beyond the scope of the present work.

Perlman & Wilson (2005) proposed a modified CI model where the volume within which particle acceleration occurs is energy dependent. This is expressed in terms of a filling factor \(f_{\text{acc}}\) which is the ratio between the observed flux and the flux predicted by the simple CI model. They found \(f_{\text{acc}}\) declining with increasing distance from the nucleus suggesting particle acceleration taking place in a larger fraction of the jet volume in the inner jet than the outer jet. The energy dependence of \(f_{\text{acc}}\) also indicates that particle acceleration regions occupy a smaller fraction of the jet volume at higher energies. Even though the model is phenomenological, it indicates that the process of high-energy emission from the knots is as complicated as their physical region. However, the mechanism responsible for the filling factor is not explained.

Stawarz et al. (2006) explained the knot HST-1 of the M87 jet as a region when the reconfinement shock reaches the jet axis. They considered, at the initial stage of the M87 jet, the particles expanding freely, decreasing the pressure rapidly relative to the ambient gas pressure. This will develop (in the case of M87) a reconfinement shock which reaches the jet axis at a location which coincides with that of the knot HST-1. They postulate this location as the beginning of HST-1, while its outer parts are identified as the stationary reflected shock formed when the reconfinement shock reaches the jet axis. Also they evaluated the ambient radiation field along the jet axis and estimated the TeV gamma-ray emission from HST-1 initiated by an outburst experienced at the core. Since the reconfinement

\(^2\) http://www-glast.slac.stanford.edu/.
shock requires an initial free expansion, the knots downstream from HST-1 cannot be explained by this model.

Fleishman (2006) explained the flattening of non-thermal spectra in the UV and X-ray bands observed from the knots of the M87 and 3C 273 jets through diffusive synchrotron radiation (DSR) in random small-scale magnetic fields, whereas the synchrotron spectrum from regular large-scale magnetic fields dominates the spectra at the low-energy band. The DSR spectrum at high energy is $\propto \nu^{-\alpha}$ where $\alpha$ is the observed photon frequency and $\nu$ is the spectral index of the random magnetic field assumed to be a power law. Honda & Honda (2007) proposed a filamentary jet model to explain the observed X-ray spectral index. In their model, the jet comprises magnetic filaments of transverse size $\lambda$ and particles trapped in these filaments are accelerated by diffusive shock acceleration. The acceleration of the electrons bound to a large filament is controlled by the radiative losses before escape from the filament, whereas the electrons trapped in smaller filaments escape via energization. A critical scale $\lambda_\text{c}$ discriminates between the large- and small-scale filaments. They considered a situation where the magnetic field is larger for filaments with larger size and found the electron energy peaks when trapped in the filament of size $\lambda_\text{c}$. The X-ray spectrum is explained by the synchrotron radiation of the electrons accelerated in the filaments of size $\lambda > \lambda_\text{c}$. However, synchrotron radiation from large-scale magnetic field itself can reproduce the observed X-ray spectrum (present model) involving a smaller number of parameters and/or assumptions (Section 2).

Recently Liu & Shen (2007) proposed a two-zone model to explain the observed spectra of the knots of the M87 jet. In their model electrons are accelerated to relativistic energies in the acceleration region (AR) and lose most of their energies in the cooling region (CR) through the synchrotron process. They considered that the AR and CR are spatially separated and introduced a break in the particle spectrum injected in the CR through the advection of particles from the AR to the CR. This along with the cooling break in the CR produces a double broken power law with indices $-p$, $-(p+1)$ and $-(p+2)$ which is then used to fit the observed spectra. However, the present model assumes that the AR and CR are copatiotial, supporting a more physical scenario where electrons accelerated by the shock cool in its vicinity.

### 4 CONCLUSION

The observed radio–optical–X-ray spectra from the knots in the jets of the Fanaroff–Riley type I (FR I) radio galaxy M87 are explained within the framework of a two-zone model. We considered a power-law electron distribution which is further accelerated in an acceleration region and injected into a cooling region where they lose their energy through synchrotron radiation. In its simplest form, the model does not consider any specific acceleration process but assumes an energy independent acceleration time-scale. Future observations of the M87 knots at UV-to-X-ray photon energies will confirm the present model and constrain the parameters involved.

We explored the possibility of the present model to reproduce the X-ray flux of other FR I galaxies (detected by Chandra) which are observed to have lower radio luminosity and relatively smaller jets when compared with FR II galaxies. The X-ray emission from a FR I jet is quite well accepted to be of synchrotron origin whereas for FR II and quasars it may be due to IC/CMBR. However, the latter is still under debate [see Harris & Krawczynski (2006) for a review of the X-ray emission from extragalactic jets]. The X-ray emission from the knots and/or the jets of the FR I galaxies, namely 3C 66B (Hardcastle, Birkinshaw & Worrall 2001), 3C 346 (Worrall & Birkinshaw 2005), Cen A (Hardcastle, Kraft & Worrall 2006) and 3C 296 (Hardcastle et al. 2005), listed in the online catalogue of extragalactic X-ray jets XJET, which are not explained by synchrotron emission from simple one-zone models, can be reproduced by the present model.

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3 http://hea-www.harvard.edu/XJET/.

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