A MODIFIED SYNCHROTRON MODEL FOR KNOTS IN THE M87 JET
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ABSTRACT

To explain the broadband spectral shape of knots in the M87 jet from radio through optical to X-rays, we propose a modified synchrotron model that considers the integrated effect of particle injection from different acceleration sources in the thin acceleration region. This results in two break frequencies at two sides of which the spectral index of knots in the M87 jet changes. We discuss the possible implications of these results for the physical properties in the M87 jet. The observed flux of the knots in the M87 jet from radio to X-rays can be satisfactorily explained by the model, and the predicted spectra from ultraviolet to X-rays could be further tested by future observations. The model implies that knots D, E, F, A, B, and C1 are unlikely to be candidates for the TeV emission recently detected in M87.

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

1. INTRODUCTION

The giant radio galaxy M87, situated nearly at the center of the Virgo Cluster at a distance of 16 Mpc (e.g., Macri et al. 1999), has been studied extensively from the radio (e.g., Owen et al. 1989 and references therein; Biretta et al. 1995; Sparks et al. 1996), optical (e.g., Perlman et al. 2001a, hereafter P01; Biretta et al. 1991), UV (Waters & Zepf 2005, hereafter WZ05), and X-rays (e.g., Marshall et al. 2002, hereafter M02; Wilson & Yang 2002). The predicted TeV gamma rays (Bai & Lee 2001) and the possible position where the TeV emission from the M87 jet (Georganopoulos et al. 2005; Cheung et al. 2007) have also been confirmed at a high confidence level by High Energy Stereoscopic System (H.E.S.S.) observations (Aharonian et al. 2003, 2006). In particular, Perlman & Wilson (2005, hereafter PW05) analyzed diagnostics and the physical interpretation of the X-ray emissions from the M87 jet in detail. Many other observations have also been done, such as photometric surveys of the jet and polarimetry maps of the jet (Perlman et al. 1999).

In the M87 jet, the optical–X-ray spectral index ($\alpha_{\text{ox}}$) increases from 1.2–1.4 at 2$''$–7$''$ from the nucleus (knots D and E) to 1.7–1.9 at 15$''$–18$''$ from the nucleus (knots B and C1). The Chandra data confirm steep X-ray spectra of the knots in the M87 jet ($\alpha_{\text{x}} > \alpha_{\text{ox}}$) and are thus consistent with a synchrotron origin for the X-ray jet emission (M02; Wilson & Yang 2002; PW05). So far, there have been three standard theoretical synchrotron models. The KP model (Kardashev 1962, hereafter K62; Pacholczyk 1970) assumes that the source of the emission is a single burst of energetic electrons with an isotropic pitch-angle distribution and thus no scatter. Because of the likely scattering of relativistic particles by hydromagnetic waves (e.g., Wentzel 1977), the KP model is physically unreasonable and therefore will not be mentioned further in this Letter. The JP model (Jaffe & Perola 1973) assumes the same initial conditions as those of the KP model but allows scattering in the pitch-angle distribution so that it can maintain an isotropic distribution all the time. The resulting spectrum is an essentially exponential rollover above the synchrotron loss break frequency. The continuous injection (CI) models (K62; Heavens & Meisenheimer 1987, hereafter HM87) assume that a power-law distribution of relativistic particles is being continuously added to the emitting region, but the CI model of HM87 further takes the advective transport of the accelerated electrons downstream into account. The CI model of K62 has a similar spectral shape to the one of HM87.

But these synchrotron models also have some problems. As shown in WZ05, considering the X-ray flux, the CI model is only applicable for the inner knots (knots D and E) and explains the UV turnover (Fig. 1), but for other outer knots (such as knots F and A) this model systematically overpredicts the observed UV turnover. PW05 also found that such a model cannot explain the spectral index at X-rays. Without considering the X-ray data, the predicted X-ray flux by the CI model is higher than the observed one, but the exponential high-energy rollover of the JP model underpredicts the X-ray flux by many orders of magnitude, and the slope at X-rays is much larger than that observed. The two standard models cannot fit the X-ray flux and the spectral index at X-rays under the single index of the electron energy spectrum at injection and a single-emission process. We summarize the criteria for fitting the spectral energy distributions (SEDs) of the knots in the M87 jet discussed in WZ05 and PW05. First, the first break frequency should be under the UV turnover (Fig. 1), especially for knots D, A, and B; second, a steeper X-ray spectral index than the optical is needed, so there may be a second break frequency between UV data and X-ray data; finally, the best-fitting model should explain the flux and index of the X-ray data as well as that of the radio, optical, and UV data.

In § 2, we describe in detail our modified synchrotron model for knots in the M87 jet. In § 3, we present and discuss the fitting results of this model to the wide-band spectra of knots D, E, F, A, B, and C1. A summary is given in § 4.
where $\beta = bB_z^2$; $b$ is a constant, and $B_z$ represents the component of the magnetic field perpendicular to the velocity of the particle. The synchrotron energy losses are $dE/dt = -\beta E^2$. The injection of a constant spectrum $qE^{-\nu}$ in the CI model of K62 actually implies that the acceleration region is the same as the main emission region in the knots. However, this assumption may not be true in general, especially for the shocks’ acceleration mechanism, which may be the dominant mechanism of the particle acceleration in jets. Based on the observational evidence of shocks in the M87 jet (Perlman et al. 1999; PW05; Harris & Krawczynski 2006), a more physical scenario would be that the acceleration region and the main emission region are not strictly cospatial in the M87 jet, and the accelerated injection electrons may be advected downstream (this process is similar to the CI model of HM87). The electrons’ advection throughout the jet and diffusion throughout the jet’s cross section with the decrease of the synchrotron lifetimes from low energies to high energies may result in spatially stratified emission regions along the jet (M02) and the consistent narrowing of the jet from radio to optical to X-rays (PW05). For the acceleration region, a more complex but physical scenario may be that there are many acceleration sources in a compact acceleration region that is unresolved by the telescope beam and each source has a power-law distribution of the injection population of relativistic electrons. We assume that all the sources accelerate electrons under similar conditions (e.g., similar magnetic fields, etc.) with the same mechanism, which results in the same spectral index $p$, similar electron number density, and the same maximum energy and fluid velocity for the injection populations of relativistic electrons. We then derive the flux expression of the modified synchrotron model:

$$I_\nu \propto \begin{cases} \nu^{-(p-1)/2}, & \nu \ll \nu_{b1}, \\ \nu^{-p/2}, & \nu_{b1} > \nu \gg \nu_{b1}, \\ \nu^{-(p+1)/2}, & \nu > \nu_{b2}, \end{cases}$$

$$v_{b1} = c_s r^2, \quad v_{b2} = c_s \beta^2 E_0^2, \quad c_s = 3.4 \times 10^3 B^{-3},$$

where $t$ (in years) is the synchrotron lifetime and $v_{b1}$ and $v_{b2}$ (in hertz) are the first and second break frequencies, respectively.

3. Fitting Results and Discussion

Now, we apply the above modified synchrotron model to the observed knot emission in the M87 jet. These include knots...
D, E, F, A, B, and C1 (as shown in Fig. 1 of Harris & Krawczynski 2006).

The data we used are listed in Table 1. These include the published radio to UV data (P01), UV data at 1.8 × 10^{15} Hz (WZ05), and X-ray data (PW05). There is another reported X-ray measurement (M02) made 12 days before the PW05 observation. M02 did not use the same regions to integrate the fluxes for various components as did P01, PW05, however, did use the same regions as P01, so we use PW05 data points in our model fitting. There was no X-ray measurement for knot C1. So we estimated its flux density using the measurements for knot C and fitting. There was no X-ray measurement for knot C1, so we estimated the same flux ratio of knot C1 to knot C at both the optical (1.0 × 10^{15} Hz) and the X-ray band.

TABLE 1

| Knot | VLA (mJy) | HST (mJy) |
|------|-----------|-----------|
| D    | 161.54 ± 1.92 | 48.05 ± 0.81 |
| E    | 144.90 ± 1.86 | 1218.00 ± 12.00 |
| F    | 808.40 ± 8.30 | 544.70 ± 5.60 |
| A    | 1994 Feb 04 | P01 |
| B    | 1998 Apr 04 | P01 |
| C1   | 1998 Feb 26 | P01 |
| C    | 1998 Feb 26 | P01 |

The error bars for the PW05 X-ray data were estimated by assuming the same relative precision in both the PW05 and the M02 data (see text).

TABLE 2

| Knot | \( p \) | \( p_{01} \) (10^{14} Hz) | \( p_{02} \) (10^{15} Hz) |
|------|---------|----------------|----------------|
| D    | 6.21    | 97.5           | 2.39           |
| E    | 6.97    | ...            | 2.40           |
| F    | 7.30    | 10.1           | 2.56           |
| A    | 6.35    | 6.94           | 2.54           |
| B    | 4.50    | 1.69           | 2.35           |
| C1   | 3.00    | 1.34           | 2.58           |

Notes.—Col. (1): Knot designation. Col. (2): First break frequency. Col. (3): Second break frequency. Col. (4): Spectral index of electrons. Col. (5): Reduced \( \chi^2 \).

We find that the value of the particle spectral index \( p \) is about 2.36 on average, which agrees well with the latest expectations from both diffusive shock acceleration theory (2.0–2.5; Kirk & Dendy 2001) and acceleration by relativistic shocks (2.23
in the ultrarelativistic limit; Kirk 2001). Particle acceleration at shocks (e.g., Blandford & Ostriker 1978) through the first-order Fermi process is generally believed to occur in jets.

PW05 proposed a possible phenomenological model to modify the CI model. They suggest that the filling factor of the volume within which particles are accelerated declines with increasing energy at X-ray energy along the jet (not in the direction perpendicular to the jet), but they cannot explain the running mechanism of the filling factor. To explain the curved X-ray spectra of BL Lac objects, Perlman et al. (2005) consider an episodic particle acceleration model that assumes only a time-variable particle acceleration. This results in a logarithmic curvature rather than a sudden break and could be related to the broadband spectral shape too. Fleishman (2006) suggests a very different model, which explicitly takes into account the effect of the small-scale random magnetic field, probably present in the M87 jet. But the energy densities contained in small-scale and large-scale magnetic fields may be incomparable; we think that the electrons in the large-scale magnetic field could also give rise to emission of the knots in our model, especially at high frequencies. The idea of a secondary population of the relativistic electrons that have a different spectral index from the first population is discussed by Jester et al. (2005), which is partially similar to our model. But we consider a lot of populations of relativistic electrons that have the same spectral index in the acceleration region and discuss the detailed process that may be responsible for the knots in the M87 jet.

4. CONCLUSION

We propose a modified CI model that considers a decay of spectral index of injection electrons possibly due to the sum of the injection spectrum from different acceleration sources with synchrotron losses in the thin acceleration region, so there are two break frequencies at two sides of which the spectral index changes for the spectra of knots in the M87 jet. We consider that the emission of the knot may be still emitted by the relativistic electrons in the large-scale magnetic field at high frequencies as well as the low frequencies, but not by the small-scale random magnetic field (e.g., Fleishman 2006). Our model gives a satisfactory fit to the SEDs of knots in the M87 jet. Based on our analysis, knots D, E, F, A, B, and C1 are unlikely to be responsible for the TeV emission detected in M87. The fitting results from our model imply that the particles in M87 are accelerated by shocks, and as a whole the second break frequencies of knots decrease down the jet. We also predict the spectra of knots from UV to X-rays, which could be tested by future observations in the band.

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