NONThermal Radiation Processes in X-ray Jets

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ABSTRACT

Analytic approximations for synchrotron, synchrotron self-Compton (SSC), and external Compton (EC) processes are used to constrain model parameters for knot and hot-spot emission in extended jets of radio galaxies. Equipartition formulas are derived that relate the Doppler factor δ and the comoving magnetic field B assuming a nonthermal synchrotron origin of the radio emission and synchrotron, SSC, and EC origins of the X-ray emission. Expressions are also derived for δ and B that minimize the total jet powers of the emitting region in synchrotron, SSC, and EC models for the X-ray emission. The results are applied to knot WK7.8 of PKS 0637−752. Predictions to test two-component synchrotron and EC models are made for Chandra and the Gamma-Ray Large Area Space Telescope.

Subject headings: galaxies: active — galaxies: jets — gamma rays: theory — radiation mechanisms: nonthermal — X-rays: galaxies

1. INTRODUCTION

The ability of the Chandra X-Ray Observatory to resolve knots and hot spots in radio jets has opened a new chapter in jet research (for a recent review, see Stawarz 2004). The radio emission in the extended jets on multi–kiloparsec- to megaparsec-size scales is almost certainly nonthermal synchrotron radiation, but the origin of the X-ray emission is controversial. In many knots and hot spots, the spectral energy distribution (SED) at X-ray energies is a smooth extension of the radio and optical fluxes, so that a synchrotron origin of the X-ray emission is implied. In other cases, the X-ray flux exceeds the level implied by smoothly extending the radio/optical SED. But even in these cases, a one-component synchrotron interpretation may be possible (Dermer & Atoyan 2002), and a two-component synchrotron model can be preferred on energetic and spectral grounds (Atoyan & Dermer 2004).

Besides the synchrotron mechanism, two other nonthermal processes are often considered to account for the X-ray fluxes observed from the knots and hot spots of radio jets, namely, the synchrotron self-Compton (SSC) and the external Compton (EC) processes (Harris & Krawczynski 2002). The target photons for the EC model can be cosmic microwave background radiation (CMBR) photons (Tavecchio et al. 2000) or nuclear jet radiation (Brunetti et al. 2001). The EC model involving CMBR target photons is the currently favored interpretation for quasar X-ray knots and hot spots in which the X-ray spectrum is not a smooth extension of the radio/optical spectrum (Celotti et al. 2001; Sambruna et al. 2004). In this model, the X-ray emission from knots such as WK7.8 of PKS 0637−752 is argued to be due to CMB photons that are Compton- upscattered by nonthermal electrons from kiloparsec-scale–emitting regions in bulk relativistic motion at distances of up to several hundred kiloparsecs from the central engine.

In a recent paper (Atoyan & Dermer 2004), we have addressed the difficulties of the X-ray EC model in explaining the opposite behaviors of the X-ray and radio spatial profiles. This model requires large energies, particularly in debeamed cases where the observer is outside the Doppler beaming cone. Here we concentrate on radiation from the extended X-ray jets, provide equations suitable for observers to interpret multiwavelength X-ray data of knot and hot-spot emission with synchrotron, EC, and SSC models, and evaluate jet powers. Application to knot WK7.8 of PKS 0637−752 is used to illustrate the results.

2. APPROXIMATE EXPRESSIONS FOR RADIATION PROCESSES

We consider a spherical blob with radius r, and comoving volume \(V_c = 4\pi r^3/3\) that moves with bulk Lorentz factor \(\Gamma = (1 - \beta^2)^{-1/2}\). Emission from the blob is observed at angle \(\theta_{\text{obs}} = \arccos \mu\) with respect to the jet direction. The Doppler factor \(\delta = [\Gamma(1 - \beta\mu)]^{-1}\). A randomly oriented magnetic field with intensity \(B\) is assumed to fill the volume of the blob. Nonthermal relativistic electrons are assumed to be uniformly distributed throughout the blob with an isotropic pitch-angle distribution and a Lorentz-factor distribution \(N_\gamma(\gamma)\), where \(N_\gamma(\gamma) \, d\gamma\) is the number of electrons with comoving Lorentz factors \(\gamma\) between \(\gamma\) and \(\gamma + d\gamma\).

For power-law electrons in the range \(\gamma_1 \leq \gamma \leq \gamma_2\),

\[
N_\gamma(\gamma) = K \Gamma^{-\gamma} H(\gamma; \gamma_1, \gamma_2),
\]

where the Heaviside function \(H(\gamma; \gamma_1, \gamma_2) = 1\) if \(\gamma_1 \leq \gamma \leq \gamma_2\), and \(H(\gamma; \gamma_1, \gamma_2) = 0\) otherwise. Normalizing to the total comoving electron energy \(W_e = m_e c^2 \int_1^{\infty} \gamma^2 N_\gamma(\gamma) \, d\gamma\) implies \(K \equiv (p - 2)W_e/(m_e c^2 \gamma_1^{-p})\) when \(p > 2\) and \(\gamma_2 \gg \gamma_1\).

The \(f_c \equiv n_c \bar{f}\), synchrotron radiation spectrum is approximated by the expression

\[
f_c \equiv \frac{\delta^4}{8\pi d_L^2} c e B \epsilon_B^2 N_\gamma(\gamma_1), \quad \gamma_1 = \sqrt{\frac{\epsilon_\gamma}{\epsilon_B}},
\]

where \(\epsilon = h\nu/m_e c^2\), \(\epsilon_\gamma = (1 + z)\epsilon\), \(u_B = B^2/8\pi\) is the magnetic field energy density, \(d_L\) is the luminosity distance of the source at redshift \(z\), and \(\epsilon_B = B^2/\epsilon_c\), where the critical magnetic field \(B_c = m_e^2 c^4/\epsilon_c h = 4.414 \times 10^{13} \text{ G}\).
The expression

\[ f^\text{EC} = \frac{\delta^6}{6\pi d_L^2} c\sigma_T u^* \gamma^N \gamma^N (\gamma^N) = \frac{1}{\delta} \sqrt{\frac{\epsilon}{2\epsilon}} \]  

(3)

is used to approximate the \( \nu F_\nu \) spectrum in the EC process (Dermer 1995; Dermer et al. 1997). Here we assume that in the stationary frame, the radiation field is isotropic and monochromatic with dimensionless photon energy \( \epsilon \), and energy density \( u^* \) of the target photon field. Moreover, all scattering is assumed to take place in the Thomson regime, which holds for X-ray emission from Compton-scattered CMBR (Georganopoulos et al. 2001 treat scattering in the Klein-Nishina regime). For the CMBR, we let \( \epsilon_* = 2.70k_B T_{\text{CMB}}(1+z)m_e c^2 = 1.24 \times 10^{-6}(1+z)^{-\frac{1}{2}} \) and \( u^* = 4 \times 10^{-13}(1+z)^4 \) ergs cm\(^{-3}\).

For the SSC spectrum, the internal photon target density is the synchrotron radiation spectrum \( n_{\gamma ^*}(\epsilon) \sim n_{\gamma ^*}(\epsilon/c^2) \), where \( n_{\gamma ^*}(\epsilon) \) is the synchrotron spectral emissivity. Using a \( \delta \)-function approximation for the Compton-scattered spectrum in the Thomson regime gives

\[ f^\text{SSC} = \frac{\delta^4}{9\pi d_L^2} c\sigma_T u^* \gamma^* \Sigma \]  

(4)

(Dermer et al. 1997), where the Compton-synchrotron logarithm \( \Sigma \) is \( C = \ln (a_{\text{max}}/a_{\text{min}}) \), \( a_{\text{max}} = \min (\epsilon/\gamma, \epsilon/\gamma, \epsilon/e^{-1}) \) and \( a_{\text{min}} = \max (\epsilon/\gamma, \epsilon/e, \epsilon/e) \) (Gould 1979), and \( \epsilon^* = \epsilon/\delta \).

Equation (2), (3), and (4) are used to approximate the synchrotron, EC, and SSC \( \nu F_\nu \) fluxes, respectively, and are accurate to better than 50% when \( 2 \leq \gamma \leq 3.5 \) in the power-law portion of the spectrum, compared to more precise treatments (Blumenthal & Gould 1970; Gould 1979).

3. CONSTRAINTS ON \( \delta \) AND \( B \)

The total particle energy density \( u_{\text{par}} \) is related to \( u^* \) through the relation \( u_{\text{par}} = W_{u^*}/V^* = k_{\text{eq}} u^* \), where \( W_{u^*} = W(1 + k_{r^*}) \) is the total comoving particle energy, \( k_{\text{eq}} \equiv (1 + k_{r^*})k_{\text{eq}} \) is a parameter that measures the deviation of total particle to magnetic field energy density, and \( k_{r^*} \) is the ratio of total proton energy to electron energy. The term \( k_{eq} = W_{eq}/V_{eq} u^* \) gives the ratio of electron (including positron) and magnetic field energy densities. Equations (1) and (2) imply

\[ f^e = \frac{(\delta B)^{5+p/2}}{6\pi d_L^2} c\sigma_T u^* \gamma^* \Sigma \frac{\epsilon^{5+p/2}(p-2)}{m_e c^2 \gamma^6} \]  

(5)

where \( u_{\text{par}} = B^2/8\pi = 7.75 \times 10^{25} \) ergs cm\(^{-3}\) is the critical magnetic field energy density. The electron injection index \( p \) is related to the observed photon energy index through the usual relation \( \alpha = (p-1)/2 \), where \( F^\nu \propto \nu^{-\alpha} \).

Solving for \( \delta B \) gives \( \delta B = \delta B^*/\sigma \),

\[ \delta B = R^{1-p} \]  

(6)

which is a familiar expression from synchrotron theory. The equipartition magnetic field is given when \( k_{r^*} = 1 \), \( p = 2 \), or \( \alpha = \frac{3}{2} \), with \( \gamma^* = (p-2)/(p-3/2)^{2(s+5+p)} \).

The photon energies \( \epsilon \) and \( \nu F_\nu \) fluxes (ergs cm\(^{-2}\) s\(^{-1}\)) of knot WK7.8 are \( 3.88 \times 10^{-12} \), \( 2.6 \times 10^{-12} \) at 4.8 GHz, \( 6.96 \times 10^{-12} \), \( 2.95 \times 10^{-12} \) at 8.6 GHz, \( 3.48 \times 10^{-6} \), \( 8.6 \times 10^{-10} \) at 4.3 \times 10^14 Hz, and \( 3.1 \times 10^{-3} \), \( 2.5 \times 10^{-14} \) at 3.8 \times 10^10 Hz, using the HST optical values given by Schwartz et al. (2000) and the flux values from Figure 8 of Chartas et al. (2000). The redshift \( z = 0.651 \) for PKS 0637–752, so that \( d_L = 1.19 \times 10^{28} \) cm for a flat LCDM cosmology with a Hubble constant of 72 km s\(^{-1}\) Mpc\(^{-1}\) and \( \Omega_M = 0.73 \), as implied by the WMAP data (Spergel et al. 2003). Using these values with a blob size \( r_b = r_b \) kiloparsecs and \( p = 2.6 \) (\( \alpha = 0.8 \)) implies \( \delta B_{\text{eq}} = 577/(k_{eq} 0.29 0.19/0.16) \) from equation (6) for the radio synchrotron model, where \( B_{\text{eq}} \) is the comoving magnetic field in units of microgauss. For the X-ray/EC model, we obtain \( \delta = 7(1 + 0.54 0.01 0.01 0.01) \) using equation (7). For the X-ray SSC model, we obtain \( \delta = 2.3 \times 10^{4}(0.54 0.01 0.01 0.01) \) from equation (8).

Figure 1 shows the relation between \( \delta \) and \( B \) for the radio synchrotron, X-ray EC, and X-ray SSC models with \( \gamma = 30 \) and \( k_{eq} = 1 \) for the case of a pair \( (k_{r^*} = 0) \) and \( e-p \) \( (k_{r^*} = m_e/\gamma_1 m_e \approx 61) \) jet. Increasing \( B \) implies an increased number of electrons to maintain equipartition between the magnetic field and particle energy. Consequently, \( \delta \) must decline to produce the same radio or X-ray fluxes. Because the SSC flux is proportional to the product of nonthermal electron and magnetic field energy, \( \delta \) declines even faster with \( B \) for the X-ray SSC than for the radio synchrotron model.

The intercections of the X-ray EC and X-ray SSC lines with the radio synchrotron line give solutions satisfying each pair of models. These solutions also result in \( \text{about} \) the minimum total energies required in these models. The EC model implies values of \( B \) of tens of microgauss and requires emission regions in relativistic motion. The SSC model requires large magnetic fields exceeding milligauss levels with debeamed \( (\delta \ll 1) \) emission.

The \( \delta-B \) diagram presented here is based on the equipartition assumption \( u_{\text{par}} = k_{eq} u^* \) for each process separately. By contrast, Tavecchio et al. (2000) assume equipartition for the synchrotron radio emission but determine the dependence of \( \delta \) and \( B \) that reproduces the radio and X-ray data when equipartition is not assumed. The basic dependences in the two approaches can be derived and compared in the specific case \( p = 3 \), corresponding to a flat \( \nu F_\nu \) spectrum. The bolometric synchrotron luminosity \( L \sim u_{\text{par}} \delta^6 \sim B^2 \delta^4 \), so \( u_{\text{par}} \sim u_{\text{par}} \delta^6 \sim B^2 \delta^4 \), so \( B^2 \delta^2 \) \sim const, as given by equation (7). If equipartition is not assumed when jointly satisfying the
very efficiently. The second electron component, if injected cospatially in a region with the same magnetic field, must, however, have a low-energy cutoff so as not to overproduce optical radiation (Atoyan & Dermer 2004).

For a nonthermal radio synchrotron and an EC X-ray model, jointly solving equations (2) and (3) gives

$$\epsilon_b = \frac{\delta^3}{2\varepsilon_0^2} \left( \frac{\gamma}{\varepsilon_0} \right) \left( \frac{\epsilon_{\text{EC}}}{2\varepsilon_0} \right)^{(3-p)/(p+1)},$$

so that $W_b \propto \delta^3$. Using equations (1) and (3) to solve for $K$ gives

$$W_r = \frac{m_c c^2}{3\varepsilon_0^2} \left( \frac{\varepsilon_{\text{EC}}}{\varepsilon_0} \right)^{3p/(p+1)},$$

so that $W_{\text{rad}} \propto \delta^{(3-p)\gamma}$. The required particle kinetic energy decreases rapidly with $\delta$ to produce the observed X-ray flux in the EC model, and the magnetic field energy increases rapidly to jointly fit the radio synchrotron and EC X-rays. The Doppler factor $\delta_{\text{EC}}$ that minimizes jet power is given by

$$\delta_{\text{EC}}^{3p/(p+1)} = \frac{9}{8} \left( \frac{\gamma}{\varepsilon_0} \right)^{3p/(p+1)} \left( \frac{\varepsilon_{\text{EC}}}{\varepsilon_0} \right)^{3p/(p+1)}$$

We now consider the SSC X-ray model. Jointly solving equations (2) and (4) gives $K = 2\pi c^2 \Sigma_{\text{EC}} (\epsilon_f/\epsilon_v)^{3-p}/(\sigma_T \Sigma_{\text{EC}} f_v)$ and

$$\epsilon_b = \delta^{-3p/(p+1)} \left( \frac{\epsilon_{\text{EC}}}{\epsilon_v} \right)^{3p/(p+1)},$$

from which one obtains

$$\delta_{\text{SSC}}^{3p/(p+1)} = \frac{8}{3}(p+1) \left( \frac{\gamma}{\varepsilon_0} \right)^{3p/(p+1)} \left( \frac{\varepsilon_{\text{EC}}}{\varepsilon_0} \right)^{3p/(p+1)}$$

for the Doppler factor $\delta_{\text{SSC}}$ that gives the minimum jet power for the SSC model.

5. DISCUSSION

We have derived the minimum jet power $L_{\text{jet}}$ for synchrotron, EC, and SSC models of the knots and hot-spot X-ray emission. The two-component synchrotron model does not connect the radio and X-ray fluxes, so that $L_{\text{jet}}$ depends only on the product $\delta B$. Thus, moderate values of $\delta$ are possible. For the parameters of knot WK7.8 with $\gamma_i = 30$ and $k_{\text{SSC}} = m_p/\gamma_i$, $\delta = 560(1 + k_{\text{SSC}})^{0.26}/(\gamma_i^{0.14} k_{\text{SSC}}^{0.5})$, implying a mini-
maximum jet power of $7 \times 10^{46}$ ergs s$^{-1}$. This is also equal to $L_{j,\text{min}}$ for the synchrotron/EC model, which, however, only holds for specific values of $\delta = 27$ and $B = 36$ $\mu$G (see Fig. 2). This is because most of the energy is contained in electrons with $\gamma \sim \gamma_i$, which is restricted to low values in the EC model. Much larger values of $\gamma_i$ are allowed in the two-component synchrotron model, so that even smaller jet powers are possible in this model.

The large value of $\delta = 27$ for the minimum jet power in the EC model implies small and improbable observing angles $\theta \leq \delta^{-1} \approx 2^\circ$ with a deprojected length of $\approx 2$ Mpc of the jet in PKS 0637$-$752. For larger observing angles corresponding to $\delta \leq 10$, a jet power exceeding $10^{48}$ ergs s$^{-1}$ is implied (Fig. 2). The jet power could be reduced by assuming a jet composed of $e^+$-$e^-$ plasma. The decay of gamma rays in the two-component synchrotron model (Atoyan & Dermer 2003, 2004) will produce pairs, but at much higher energies than needed. If the pair plasma were produced in a compact inner jet, then the energy requirements would be hard to explain because of large adiabatic losses in the course of the expansion of the blob from subparsec to kiloparsec scales (see Celotti & Fabian 1993 for other arguments against a pair jet).

The SSC model for knot WK7.8 is ruled out. This model formally satisfies the radio and X-ray fluxes with $\delta_{\text{SSC}} = 0.014$ and corresponding magnetic field $B = 0.07$ G when $\Sigma_c = 10$, but it requires comoving particle and field energies $\gg 10^{41}$ ergs.

The synchrotron/EC model for knot WK7.8 allows a non-variable X-ray spectrum that cannot be softer than the radio spectrum and predicts a $\gamma$-ray flux at the level of $0.3 \times 10^{-9}$ photons ($>100$ MeV) cm$^{-2}$ s$^{-1}$. This is detectable at strong significance with the Gamma-Ray Large Area Space Telescope (GLAST) in the scanning mode over 1 yr of observation but may be difficult to distinguish from the variable inner jet radiation. The two-component synchrotron model allows variability at X-ray energies, although at a low level because of the source size, with nonvarying $\gamma$-ray flux below the GLAST sensitivity (see Fig. 2 in Atoyan & Dermer 2004).

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fig. 2.—Total comoving energy $W_{\gamma}$ in units of $10^{50}$ ergs (solid line) and jet power $L_{\gamma}$ in units of $10^{49}$ ergs s$^{-1}$ (long-dashed line) as a function of $\delta$, divided into particle (dotted lines) and magnetic field (dashed lines) components for a radio synchrotron and X-ray EC model of knot WK7.8 of PKS 0637$-$752. The comoving magnetic field is shown by the heavy dotted line. The minimum electron Lorentz factor $\gamma_i = 30$, $\Sigma_c = 10$, and $r_s = 1$ kpc, and we consider a jet made of $e^-$-$\mu^-$ plasma.