INTERPRETATION OF THE RADIO/X-RAY KNOTS OF AGN JETS WITHIN THE INTERNAL SHOCK MODEL FRAMEWORK

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Abstract

The dynamics of relativistically moving blobs ejected out of a central AGN are considered. It is assumed that the collision between two blobs is completely inelastic, such that the bulk kinetic energy lost in the collision is used to energize electrons to relativistic energies via acceleration in internal shocks that are formed by the collision. These high-energy electrons, which are produced on a timescale corresponding to the collision timescale, cool by radiative losses due to synchrotron and inverse Compton processes. The model is applied to the radio/X-ray knots of several AGNs. For three of these sources we have analyzed long (>40 ks) Chandra observations and report on constraints on the X-ray spectral indices. In the framework of this model the AGNs are inferred to sporadically eject relativistic blobs on timescales ranging from $10^{11}$ to $10^{12}$ s for different sources. It is shown that the collision timescales can be longer than the age of the knot, and hence nonthermal electrons are continuously being injected into the system. This continuous injection, in contrast to an instantaneous one-time injection, gives rise to a characteristic spectral break rather than a high-energy cutoff in the spectrum.

Subject headings: galaxies: active — galaxies: jets — X-rays: galaxies

1. INTRODUCTION

Study of the knots in kiloparsec-scale jets of active galactic nuclei (AGNs) has been given a new dimension after the advent of Chandra, which, due to its excellent spatial resolution, is able to resolve bright X-ray knots of such jets (Chartas et al. 2000; Sambruna et al. 2001, 2002; Tavecchio et al. 2000). In most of the cases, the X-ray knots coincide with their radio/optical counterparts (Sambruna et al. 2001, 2002; Pesce et al. 2001; Marshall et al. 2001; Wilson & Yang 2002). The discovery of such knots in different energy bands provides useful information about the basic emission mechanism and the underlying acceleration processes involved there. The radio and optical emission from these knots are generally accepted to be of synchrotron origin, whereas the X-ray emission can be due to either synchrotron (Worall et al. 1989; Tavecchio et al. 2000; Pesce et al. 2001; Sahayanathan et al. 2003) or inverse Compton processes (Sambruna et al. 2001, 2002; Pesce et al. 2001; Sahayanathan et al. 2003) or inverse Compton processes (Sambruna et al. 2001, 2002; Pesce et al. 2001; Tavecchio et al. 2000; Schwartz et al. 2000; Chartas et al. 2000; Sahayanathan et al. 2003). If the radio-to-optical index ($\alpha_{ro}$) is larger than the optical-to-X-ray index ($\alpha_{ox}$), a single emission mechanism cannot explain the observed fluxes (see, however, Dermer & Atoyan [2002], who show that if Klein-Nishina losses are important, spectral hardening can occur), and the X-ray emission may be due to inverse Comptonization. On the other hand, if $\alpha_{ro}$ is smaller than $\alpha_{ox}$, synchrotron origin of the X-ray is acceptable (Tavecchio et al. 2000; Sambruna et al. 2002; Pesce et al. 2001). This synchrotron origin of X-rays for knots with $\alpha_{ro} < \alpha_{ox}$ was strengthened for the knots of 3C 271 by Pesce et al. (2001), who show that the alternate inverse Compton model would require exceptionally large Doppler factors. When the X-ray emission can be attributed to the inverse Compton (IC) process, the possible choices of target photons are radio/optical synchrotron photons (synchrotron self-Compton [SSC]; Schwartz et al. 2000) or the cosmic microwave background (IC/CMB; Tavecchio et al. 2000; Sambruna et al. 2001, 2002; Pesce et al. 2001; Sahayanathan et al. 2003). Tavecchio et al. (2000) have shown that the SSC interpretation would require large jet powers and magnetic fields much lower than the equipartition values, whereas IC/CMB requires relatively low jet power and near-equipartition magnetic fields.

These possible radiative process identifications have to be associated with (and confirmed by) dynamical models regarding the origin and subsequent evolution of the radiating nonthermal particles. In many models, these nonthermal particles are assumed to be generated by a short-duration acceleration process, and the particle distribution is determined by radiative losses (Sambruna et al. 2001, 2002; Tavecchio et al. 2000; Jaffe & Perola 1973; Kardashev 1962; Pacholczyk 1970). The high-energy particles cool more efficiently and hence get depleted in time, giving rise to a time-dependent high-energy cutoff in the nonthermal particle distribution. If the X-ray emission is attributed to synchrotron emission by these particles, then these models predict an exponentially decreasing X-ray spectrum (Sambruna et al. 2001, 2002; Tavecchio et al. 2000; Pesce et al. 2001). On the other hand, it may also be possible that the acceleration process exists for longer than the age of the knot, and hence there is a continuous injection of nonthermal particles. In this case, a time-dependent break in the nonthermal particle distribution occurs at $\gamma = \gamma_c$, where $\gamma_c$ is determined by the condition that the cooling timescale for electrons with $\gamma = \gamma_c$ is equal to the age of the knot (Heavens & Meisenheimer 1987; Meisenheimer et al. 1989). This model predicts the X-ray spectral index $\alpha_x$ to be $\approx \alpha_t + \frac{1}{4}$, where $\alpha_t$ is the radio spectral index. Thus the predicted spectrum depends, in particular, on the duration of the nonthermal particle production and, in general, on the production mechanism.

While there is no consensus on the origin of these nonthermal particles, one of the standard models is the internal shock scenario (Rees 1978; Spada et al. 2001), in which the particles are energized by Fermi acceleration in shocks produced during the interaction of relativistically moving blobs ejected from the central engines with different speeds. This model has also been used to explain the prompt emission of gamma-ray bursts (Rees...
A detailed description of the shock formation and subsequent electron acceleration is complicated and would require numerically difficult magnetohydrodynamic simulations. Moreover, the limited number of observables, which can be obtained from the featureless spectra in two or three different energy bands, may not be able to constrain the various assumptions and/or the initial conditions of such a detailed study. Nevertheless, a qualitative idea as to whether the internal shock model is consistent with the present observations (and if so, qualitative estimates of the model parameters) would be desirable. Such an estimate would provide insight into the temporal behavior of the central engine.

In this work, we implement an internal shock model with simplifying assumptions and compute the time evolution of the nonthermal particles produced. We compare the results obtained with the broadband fluxes from knots of several AGN jets and their observed positions. The motivation here is to find a consistent set of model parameters that can explain the observations and thereby make qualitative estimates of their values. Apart from the fluxes at different energy bands, the spectral indices in each band can also provide important diagnostic information about the nature of these sources. Hence, we have analyzed long (>40 ks) Chandra observations of three AGNs and report the constraints that were obtained on the X-ray spectral indices of the individual knots.

In § 2, a brief description of the data analysis technique and the results obtained are presented. In § 3, the internal shock model and the assumptions used in this work are described, while in § 4 the results of the analysis are presented and discussed. Throughout this work, $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$ are adopted.

2. DATA ANALYSIS

Long-exposure Chandra observations of the sources PKS 1136−135, PKS 1150+497, and 3C 371 were performed with the Advanced CCD Imaging Spectrometer (ACIS-S) with the source at the aim point of the S3 chip. The Observation ID (ObsID) and the exposure time of the observation are given in Table 1. Earlier shorter duration observations of these sources revealed two bright knots for each source, whose positions from the nucleus and/or the other knot.

### TABLE 1

| Source Name          | ObsID | Exposure (ks) | Knots | $F_{0.3-1.0}$ (ergs cm$^{-2}$ s$^{-1}$) | $\alpha_x$ |
|----------------------|-------|---------------|-------|--------------------------------------|------------|
| PKS 1136−135 ....... | 3973  | 77.37         | A     | 0.63                                 | 1.24$^{+0.51}_{-0.66}$ |
| PKS 1150+497 ....... | 3974  | 68.50         | A     | 3.15                                 | 0.66$^{+0.28}_{-0.15}$ |
| 3C 371 ............... | 2959  | 40.86         | A     | 3.32                                 | 1.43$^{+0.83}_{-0.78}$ |

Note.—Col. (1): Source name. Col. (2): Chandra Observation ID. Col. (3): Exposure time. Col. (4): Knots prominent in X-ray. Col. (5): Flux in 0.3–3.0 keV energy band. Col. (6): X-ray energy spectral index.

The reprocessed data from the Chandra X-Ray Center were analyzed using the latest calibration files to produce the image and spectra. The X-ray counts from each individual knot were extracted using a circular region centered at the knot. The background was estimated from the counts obtained from same-size regions located at the same distance from the nucleus but at different azimuth angles. The radius of the circular region was chosen to be 0.74 for the sources PKS 1136−135 and PKS 1150+497, while for 3C 371 a smaller radius of 0.66 was used. These sizes were chosen to minimize any possible contamination from the nucleus and/or the other knot.

Spectral fits were undertaken on the data using the XSPEC package in C statistic mode, which is the appropriate statistic when the total counts are low. The flux and the energy spectral indices obtained are listed in Table 1.

3. THE INTERNAL SHOCK MODEL

In the internal shock model framework, temporal variations of the ejection process produce density fluctuations (moving with different velocities), which collide at some distance from the source to produce an observable knot. This distance depends on the timescale over which the variation takes place. In general the system will exhibit variations over a wide range of timescales, and knot-like features are produced at different distance scales. In this work, we consider large-scale jets (with deprojected distances...
≈100 kpc), which are expected to arise from variability occurring on a corresponding large timescale. Variations on smaller timescales would produce knot structures on smaller distance scales, for example, parsec-scale or even smaller jets, which would be unresolved for these sources. These smaller timescale variations will be smoothed out at large distances, and hence one expects the jet structure of these sources to be determined by variations over a single characteristic timescale. To further simplify the model, we approximate the density and velocity fluctuations as two discrete blobs with equal masses, $M_1 = M_2 = M$, having Lorentz factors $\Gamma_1$ and $\Gamma_2$ that are ejected one after the other, from the central engine with a time delay of $\Delta t_{12}$. The collision of the blobs is considered to be completely inelastic; i.e., the blobs coalesce and move as a single cloud, which is identified with the observed knot. From conservation of momentum, the Lorentz factor of the knot is

$$\Gamma = \sqrt{\frac{\Gamma_1^2 \beta_1 + \Gamma_2^2 \beta_2}{2}} + 1, \quad (1)$$

where $\beta_1, 2 = v_1, 2/c$ are the velocities of the blobs normalized to the speed of light. Since the collision is inelastic, a fraction of the bulk kinetic energy is dissipated. Denoting all quantities in the rest frame of the knot by subscript $K$, this energy $\Delta E_K$ can be estimated as

$$\Delta E_K = [\Gamma_{1K} + (\Gamma_{2K} - 2)]Mc^2. \quad (2)$$

The Lorentz factors of the blobs in the knot’s rest frame $\Gamma_{1K,2K} = (1 - \beta_{1K,2K}^2)^{-1/2}$ are computed using

$$\beta_{1K,2K} = \frac{\beta_{1,2} - \beta}{1 - \beta_{1,2} \beta}, \quad (3)$$

where $\beta = (1 - 1/\Gamma_1^2)^{1/2}$. The timescale on which this energy will be dissipated can be approximated to be the crossing-over time of the two blobs,

$$T_{ON,K} \approx \frac{2\Delta x_K}{c(\beta_{2K} - \beta_{1K})}, \quad (4)$$

where $\Delta x_K$ is the average size of the two blobs in the rest frame of the knot. It is assumed that this dissipated bulk kinetic energy, $\Delta E_K$, gets converted efficiently to the energy of the nonthermal particles produced during the collision. The number of nonthermal particles injected per unit time into the knot is taken to be

$$Q_K(\gamma)d\gamma = A\gamma^{-p}d\gamma \text{ for } \gamma > \gamma_{\text{min}}, \quad (5)$$

where $\gamma$ is the Lorentz factor of the electrons, $p$ is the particle index, and $A$ is the normalization constant given by

$$A = \frac{\Delta E_K}{T_{ON,K}} \frac{(p - 2)}{m^2c^2 \gamma_{\text{min}}^{p - 2}}. \quad (6)$$

Here the injection is assumed to be uniformly occurring for a time $T_{ON,K}$. The cloud is permeated with a tangled magnetic field, $B_K$.

The kinetic equation describing the evolution of the total number of nonthermal particles in the system, $N(\gamma, t_K)$, is

$$\frac{\partial N_K(\gamma, t_K)}{\partial t_K} + \frac{\partial}{\partial \gamma} [P(\gamma, t_K)N_K(\gamma, t_K)] = Q_K(\gamma). \quad (7)$$

$P(\gamma, t)$ is the cooling rate given by

$$P(\gamma, t_K) = -[\dot{\gamma}_{S}(t_K) + \dot{\gamma}_{IC}(t_K)], \quad (8)$$

where $\dot{\gamma}_{S}(t_K)$ and $\dot{\gamma}_{IC}(t_K)$ are the cooling rates due to synchrotron and inverse Compton of the cosmic microwave background radiation (CMBR), respectively (Sahayanathan et al. 2003).

The nonthermal particle distribution $N_K(\gamma, t_K)$ produces the synchrotron and inverse Compton spectra that are computed at an observation time $t_K = t_{K,O}$. The inverse Compton spectrum is computed after taking into account the anisotropy of the CMBR spectrum in the rest frame of the plasma (Dermer 1995). Finally, the flux is transformed from the source frame to the observer’s frame at Earth, taking care of the Doppler boosting (Begelman et al. 1984) and cosmological effects.

Equation (7) can be solved analytically (Kirk et al. 1998) or numerically computed using the technique given in Chang & Cooper (1970). Rather than studying the complete analytical expression, it is perhaps more illuminating to study the asymptotic limits. It is convenient to define a critical Lorentz factor $\gamma_c$ for which the cooling timescale for synchrotron and IC losses is equal to the observation time $t_{K,O}$. Then for $\gamma < \gamma_c$, there is effectively no cooling, and the particle spectrum is $N(\gamma, t) \propto (\gamma - \gamma_c)^{-p}$, i.e., the injection rate times the observed time. For $\gamma > \gamma_c$, the cooling time is shorter than the observed time and hence the particle spectrum is in quasi-equilibrium $N(\gamma, t) \propto (\gamma - \gamma_c)^{-p - 2}$. These two regimes in the particle spectra give rise to a composite synchrotron spectrum with a spectral break.

Adiabatic cooling has been neglected in equation (7). The adiabatic cooling timescale, $t_{\text{adb}}$, is $\approx R(t)/v_{\text{exp}}$, where $R(t)$ is the size of the knot, and $v_{\text{exp}}$ is the speed at which the knot is expanding. Since $R(t_{K,O}) = R_i + v_{\text{exp}}t_{K,O}$, where $R_i$ is the initial size of the knot, it follows that $t_{\text{adb}}$ is always greater than $t_{\text{obs}}$ for the case when the initial size of the knot $R_i \approx R(t_{K,O})$ and hence adiabatic cooling can be neglected. In the other extreme, if $R_i < R(t_{K,O})$, $t_{\text{adb}}$ is at most $t_{\text{obs}}$. For $\gamma \gg \gamma_c$, the cooling timescale is much smaller than $t_{\text{obs}}$, and hence adiabatic cooling may still be neglected. For $\gamma < \gamma_c$, since $t_{K,O} \approx t_{\text{adb}}$ and not much larger, the effect of adiabatic cooling can only change the number density by a factor of a few. Thus for an order of magnitude calculation as required for this work, adiabatic cooling can always be neglected.

The predicted spectrum and size of a knot depends on nine parameters, which are the mass of the blobs $M$, their average size $\Delta x_K$, the Lorentz factors $\Gamma_1$ and $\Gamma_2$, the particle injection index $p$, the minimum Lorentz factor $\gamma_{\text{min}}$, the initial magnetic field $B_0$, the inclination angle of the jet $\theta$, and the observation time $t_{K,O}$.

From these parameters and the location of the knot in the sky plane, one can infer the time delay $\Delta t_{12}$ between the ejection of the two blobs. The projected distance of the knot from the source $S$ can be written as

$$S = c(\beta_{1K} + \beta_{2K}) \sin \theta, \quad (9)$$

where $t_O = t_{K,O}$ is the time of the observation after the formation of the knot in the source frame. The time elapsed, $t_c$, after the ejection of the first blob and the start of the collision, is given by

$$t_c = \frac{v_2 t_{12} - \Delta x_1}{v_2 - v_1}, \quad (10)$$

where $\Delta x_1$ is the size of the first blob, $\approx \Gamma_{1K} \Delta x_K/\Gamma$. Thus $\Delta t_{12}$ can be estimated using the above equation, where $t_c$ is given.
by equation (9), and it essentially depends on four parameters, \( \theta, \Gamma_1, \Gamma_2, \) and \( t_{\text{K-O}}. \)

A total time, \( t_{\text{tot}} \), can be defined to be the time that has elapsed between the ejection of the first blob and the observation, \( t_{\text{tot}} = t_c + t_o. \) For two knots, A and B, the time difference between the ejection of their first blobs, \( t_{\text{AB}} \), is then

\[
t_{\text{AB}} = t_{\text{tot}}^A - t_{\text{tot}}^B - t_{\text{LT}},
\]

where \( t_{\text{LT}} \) is the light travel time difference between the two knots, which is approximated by

\[
t_{\text{LT}} = \frac{S^A - S^B}{c \tan \theta}.
\]

The power of the jet can be defined in two different ways. The instantaneous power, which is the power when the system is active, can be defined to be the average energy of the blobs divided by the timescale on which the blobs are ejected. This power can be estimated for each knot to be

\[
P_{\text{ins}} \approx \frac{M c^2 (\Gamma_1 + \Gamma_2)/2}{\Delta t_{12}}.
\]

On the other hand, the time-averaged power of the jet can be defined as the typical energy ejected during active periods divided by the timescale on which such activity occurs. For two knots, A and B, this can be approximated by

\[
P_{\text{ave}} \approx \frac{[M^A c^2 (\Gamma_1^A + \Gamma_2^A) + M^B c^2 (\Gamma_1^B + \Gamma_2^B)]/2}{\Delta t_{\text{AB}}}. 
\]

Two a posteriori checks have to be imposed to ensure self-consistency. The total number of nonthermal particles that is injected, \( N_{\text{nth}} \), should be less than the number of particles in the knot, \( N_K \approx 2 M/m_p \), and the magnetic field, \( B_K(t_K) \) should be less than the equipartition value \( B_{\text{eq}}. \)

4. RESULTS AND DISCUSSION

The model has been applied to those knots of kiloparsec-scale jets that have been detected by Chandra and for which radio and optical data are available. This criterion was satisfied by the two brightest knots of the AGN: PKS 1136–135, PKS 1150+497, PKS 1354+195, 3C 273, and 3C 371. In this work, the knot closer to the nucleus is referred to as knot A, and the farther one as knot B. For these sources this nomenclature is the same as in the literature except for 3C 371, for which the farther one has been referred to as knot A. For three of these sources, the X-ray spectral indices were constrained using long-exposure observations as described in §2. The observed properties of the sources and the knots are given in Tables 1 and 2.

Figure 1 shows the observed radio, optical, and X-ray fluxes of these knots along with the computed spectra corresponding to model parameters that are given in Table 3. Since the number of parameters is large compared to the observables, a unique set of parameter values cannot be obtained. Two consistency checks have been imposed on the parameter values: that the number of nonthermal electrons that will be injected into the system, \( N_{\text{nth}} \), is smaller than the total number of protons, \( N_K \); and that the magnetic field, \( B \), is less than the equipartition value, \( B_{\text{eq}}. \) Both of these conditions are satisfied by the parameter sets, as shown in Table 3, where the ratios \( B/B_{\text{eq}} \) and \( N_{\text{nth}}/N_K \) are given.

For each source, the time delay \( \Delta t_{12} \) between the ejection of the two blobs that form the knots are nearly equal to the time difference between the ejection of the first blobs of knot A and knot B, \( t_{\text{AB}}. \) This gives an overall single timescale of activity for each source, which ranges from \( 10^{11} \) to \( 10^{12} \) s and can reproduce the knot properties, as had been assumed in the development of the simple internal shock model. This result is important since if it had not been true, a more complex temporal behavior would have to be proposed, wherein the jet structure is due to variability of the source in two different timescales, the first being the time difference between the ejection of two blobs that form a knot, and the second being the time difference between the activities that produced the two knots.

The cross-over time \( T_{\text{ON},K} \) is determined here by equation (4). Since \( \beta_K - \beta_{KX} \approx (\Gamma_1 - \Gamma_2)/\Gamma \approx 0.3, T_{\text{ON},K} \approx 10^2 (\Delta x_K/5 \times 10^{11} \text{ cm}) \text{ s.} \) During this time, i.e., the time when there is injection of particles into the system, the knot would travel a distance \( \approx c T_{\text{ON}} \approx c T_{\text{ON},K} \approx 50 (\Gamma/5) (\Delta x_K/5 \times 10^{11} \text{ cm}) \text{ kpc.} \) This is a significant fraction of the total observable distance traveled by the knot, from formation \( \approx c t_c \approx 100 \text{ kpc} \) (see Table 3) to the termination of the jet in the radio lobe, \( \approx 200 \text{ kpc.} \) Hence, as shown in Table 4, it is possible to fit the spectra of all the knots with an observation time \( t_{\text{O,K}} \), which is less than the crossing-over time \( T_{\text{ON},K} \), implying that there is continuous injection of particles into the system. In this scenario, the synchrotron and IC spectra have a break corresponding to a Lorentz factor \( \gamma_c \), where the cooling timescale equals the observation time (Sahayanathan et al. 2003). This is in contrast to one-time injection models (i.e., when \( t_{\text{O,K}} > T_{\text{ON},K} \)) in which an exponential cutoff in the spectra occurs. However, this does not exclude the possibility that for some knots, \( t_{\text{O,K}} > T_{\text{ON},K} \) and such cutoff in spectra would be detected.

The knots of 3C 371 and knot A of PKS 1136–135 are unique in this sample, since their X-ray fluxes lie below the extrapolation of the radio/optical spectra to X-ray wavelengths. This allows for the interpretation that the X-ray flux is due to synchrotron emission (Sambruna et al. 2002; Pesce et al. 2001; Sahayanathan
et al. 2003). For knot A of PKS 1136–135 and knot B of 3C 371, this implies that the spectral break for the synchrotron emission occurs at the X-ray regime (Fig. 1), which in turn indicates that these sources are relatively younger ones. Indeed, the ratio of the observation time to the injection time, $t_{O,K}/t_{ON,K}$, for these sources is smallest (Table 4). On the other hand, for knot A of 3C 371, the spectral break can occur at the optical band even if the X-ray flux is interpreted as being due to synchrotron emission (Fig. 1) and hence this source need not be relatively young. However, this is only possible if $t_{O,K} < t_{ON,K}$ and there is continuous injection of particles. Otherwise, a sharp cutoff in the spectrum at the optical band would have occurred, and the X-ray emission would not be due to synchrotron emission.

Figure 1 shows that the radio, optical, and X-ray spectral indices for different knots may vary and highlights the need for more spectral measurements in all bands. A definite prediction of this model is that for most knots, the X-ray spectral index should be equal to the radio spectral index, indicating that the X-ray flux is due to IC/CMBR. Such spectral constraints would be particularly important since, although it has been demonstrated here that the internal shock model can explain the broadband spectra of these sources, there could be other models that may be physically and observationally more favorable. Recently Jester et al. (2005) have analyzed Very Large Array (VLA) and Hubble Space Telescope (HST) images of 3C 273 and have found that the optical and radio spectral indices are different, indicating the presence of an additional emission mechanism for the source. Earlier, Atoyan & Dermer (2004) argued that the X-ray flux is due to a second population of nonthermal electrons rather than being the IC/CMBR spectra of the same distribution that produces the radio and optical emission. They point out in the IC/CMBR model that, since the X-ray emission is due to electrons that are only a factor of 10 more energetic than those that produce the radio, a source in which the X-ray flux falls rapidly from the center should also exhibit a similar decrease in radio emission that is not observed (e.g., 3C 273 and PKS 1354+195). Moreover, the jet power required in the IC/CMBR model can be very large, $\sim 10^{48}$ ergs s$^{-1}$, which may be larger than the power inferred from the giant radio lobes ($\lesssim 10^{47}$ ergs s$^{-1}$). While the former argument may not be strictly applicable to the internal shock model (since each knot is

### Table 3

| Source      | Knot | $\theta$ (deg) | $\Gamma_1$ | $\Gamma_2$ | $\Gamma^*$ | $t_{KO}$ (10$^{11}$ s) | $t_{t}$ (10$^{12}$ s) | $t_{te}$ (10$^{12}$ s) | $\log M$ (g) | $\gamma_{\min}$ | $p$ (10$^2$ G) | $B$ (10$^5$ G) |
|-------------|------|----------------|------------|------------|------------|------------------------|-----------------------|----------------------|----------------|----------------|----------------|----------------|
| PKS 1136−135 | A    | 11.5           | 4.6        | 5.4        | 5.0        | 0.25                    | 11.8                  | 11.6                  | 38.0            | 2              | 2.4            | 1.1            |
|             | B    | 10.2           | 4.1        | 5.9        | 5.0        | 8.5                     | 13.1                  | 17.3                  | 36.4            | 20             | 2.9            | 4.5            |
| PKS 1354+195 | A    | 8.21           | 1.7        | 2.3        | 2.0        | 9.0                     | 8.1                   | 8.1                   | 38.1            | 37             | 3.0            | 1.7            |
| 3C 273      | A    | 8.23           | 2.2        | 4.0        | 3.1        | 2.1                     | 27.0                  | 24.0                  | 36.8            | 50             | 2.7            | 0.4            |
| 3C 371      | A    | 15.18          | 1.6        | 2.4        | 2.0        | 5.9                     | 0.18                  | 1.4                   | 35.5            | 20             | 2.5            | 1.0            |
|             | B    | 2.0            | 2.4        | 2.2        | 2.3        | 0.39                    | 0.75                  | 36.8                  | 10              | 2.4            | 0.6            |

Note.—Seven of the model parameters and derived quantities. The eighth parameter is $x_K = 5.0 \times 10^{13}$ cm for all sources. Columns marked with an asterisk are derived quantities and not parameters. Col. (1): Source name. Col. (2): Knot. Col. (3): View angle. Col. (4): Lorentz factor of the first blob. Col. (5): Lorentz factor of the second blob. Col. (6): Lorentz factor of the knot. Col. (7): Observation time. Col. (8): Collision time. Col. (9): Total time. Col. (10): Mass of the blobs. Col. (11): Minimum Lorentz factor of the particle injected into the knot. Col. (12): Injected particle spectral index. Col. (13): Magnetic field.

### Table 4

| Source      | Knot | $\Delta t_{ON}$ (10$^{11}$ s) | $t_{t}$ (10$^{12}$ s) | $B/B_{eq}$ | $N_{nth}/N_e$ | $\log P_{on}$ (ergs s$^{-1}$) | $\log P_{sw}$ (ergs s$^{-1}$) | $T_{ON,K}$ (10$^{13}$ s) | $t_{KO}/T_{ON,K}$ | $D$ (kpc) |
|-------------|------|--------------------------------|-----------------------|------------|--------------|-----------------------------|-------------------------------|------------------------|-------------------|-----------|
| PKS 1136−135 | A    | 1.1                            | 3.1                   | 0.55       | 0.88         | 48.60                       | 48.17                         | 20.4                   | 0.01               | 112.8     |
|             | B    | 2.5                            | ...                   | 0.74       | 0.74         | 46.65                       | ...                           | 9.1                    | 0.93               | 163.4     |
| PKS 1150+497 | A    | 0.9                            | 5.0                   | 0.12       | 0.13         | 47.98                       | 47.31                         | 17.0                   | 0.94               | 50.5      |
|             | B    | 3.9                            | ...                   | 0.65       | 0.43         | 46.63                       | ...                           | 10.7                   | 0.53               | 96.1      |
| PKS 1354+195 | A    | 7.5                            | 18.0                  | 0.04       | 0.38         | 47.49                       | 47.15                         | 9.6                    | 0.94               | 78.7      |
|             | B    | 17.0                           | ...                   | 0.64       | 0.78         | 46.10                       | ...                           | 9.6                    | 0.90               | 135.5     |
| 3C 273      | A    | 20.0                           | 34.0                  | 0.03       | 0.80         | 46.00                       | 46.63                         | 5.4                    | 0.39               | 240.7     |
|             | B    | 31.6                           | ...                   | 0.02       | 0.16         | 46.60                       | ...                           | 9.6                    | 0.84               | 248.5     |
| 3C 371      | A    | 1.4                            | 1.5                   | 0.39       | 0.88         | 45.59                       | 46.98                         | 7.2                    | 0.83               | 11.2      |
|             | B    | 1.0                            | ...                   | 0.28       | 0.29         | 47.14                       | ...                           | 16.3                   | 0.14               | 7.7       |

Note.—Col. (1): Source name. Col. (2): Knot. Col. (3): Time delay between the ejection of the blobs. Col. (4): Time delay between the ejection of the first and the third blob. Col. (5): Ratio of the magnetic field to equipartition magnetic field. Col. (6): Ratio of nonthermal electrons to the total number of electrons. Col. (7): The instantaneous power. Col. (8): Time-averaged power. Col. (9): Timescale over which nonthermal particles are injected. Col. (10): Ratio of the observation time to particle injection timescale. Col. (11): Deprojected distance.

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a separate entity, and the distance from the source is not a measure of the age of the source), the power requirement for some sources may indeed be very large; e.g., knot A of PKS 1136–135 requires $P_{\text{ave}} \approx 2 \times 10^{48}$ ergs s$^{-1}$ (Table 3). However, the energy requirement may be decreased if the magnetic field is subequipartition, e.g., 3C 273 (Table 3). Thus it is desirable to obtain direct observational signatures, such as spectral indices, to discriminate between models.

A realistic description of the knots is more complicated than the simple model considered here. For example, the forward and reverse shocks that should form when the blobs collide may provide different injection rates and at different locations within the knot. However, the physics of these shock formations and the subsequent acceleration of particles are complicated and unclear, especially if they are mediated by magnetic fields. In the future, results from sophisticated numerical simulations could be compared with higher resolution data (which can resolve the internal structure of the knots) to prove (or disprove) the internal shock model.

In summary, a simple internal shock model is consistent with the broadband spectra of knots in AGN kiloparsec-scale jets. The age of the knots ($t_{O,K}$) may be smaller than the timescale of injection of nonthermal particles ($T_{\text{ON},K}$), which implies there may be spectral breaks in the synchrotron and IC spectra instead of exponential high-energy cutoffs. The jets are powered by AGNs, which sporadically eject out material on a $10^{11}$–$10^{12}$ s timescale.

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REFERENCES

Atoyan, A., & Dermer, C. 2004, ApJ, 613, 151
Begelman, M. C., Blandford, R. D., & Rees, M. J. 1984, Rev. Mod. Phys., 56, 255
Chang, J. S., & Cooper, G. 1970, J. Comput. Phys., 6, 1
Chartas, G., et al. 2000, ApJ, 542, 655
Dermer, C. 1995, ApJ, 446, L63
Dermer, C., & Atoyan, A. 2002, ApJ, 568, L81
Heavens, A., & Meisenheimer, K. 1987, MNRAS, 225, 335
Jaffe, W. J., & Perola, G. C. 1973, A&A, 26, 423
Jester, S., Rosser, H.-J., Meisenheimer, K., & Perley, R. 2005, A&A, 431, 477
Kardashev, N. S. 1962, Soviet Astron., 6, 317
Kirk, J. G., Reiger, F. M., & Mastichiadis, A. 1998, A&A, 333, 452
Lazzati, D., Ghisellini, G., & Celotti, A. 1999, MNRAS, 309, L13
Marshall, H. L., et al. 2001, ApJ, 549, L167
Meisenheimer, K., et al. 1989, A&A, 219, 63
Pacholczyk, A. G. 1970, Radio Astrophysics (San Fransisco: W. H. Freeman)
Panaitescu, A., Spada, M., & Meszaros, P. 1999, ApJ, 522, L105
Pesce, J. E., et al. 2001, ApJ, 556, L79
Rees, M. J. 1978, MNRAS, 184, 61P
Rees, M. J., & Meszaros, P. 1994, ApJ, 430, L93
Sahayanathan, S., Misra, R., Kembhavi, A. K., & Kaul, C. L. 2003, ApJ, 588, L77
Sambruna, R. M., et al. 2001, ApJ, 549, L161
———. 2002, ApJ, 571, 206
Schwartz, D. A., et al. 2000, ApJ, 540, L69
Spada, M., Ghisellini, G., Lazzati, D., & Celotti, A. 2001, MNRAS, 325, 1559
Tavecchio, F., Maraschi, L., Sambruna, R. M., & Urry, C. M. 2000, ApJ, 544, L23
Wilson, A. S., & Yang, Y. 2002, ApJ, 568, 133
Worall, D. M., Birkinshaw, M., & Hardcastle, M. J. 2001, MNRAS, 326, L7