THE 300 kpc LONG X-RAY JET IN PKS 1127–145, \( z = 1.18 \) QUASAR: CONSTRAINING X-RAY EMISSION MODELS

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ABSTRACT

We present a \(~100\) ks Chandra X-ray observation and new VLA radio data of the large-scale, 300 kpc long X-ray jet in PKS 1127–145, a radio-loud quasar at redshift \( z = 1.18 \). With this deep X-ray observation we now clearly discern the complex X-ray jet morphology and see substructure within the knots. The X-ray and radio jet intensity profiles are seen to be strikingly different, with the radio emission peaking strongly at the two outer knots while the X-ray emission is strongest in the inner jet region. The jet X-ray surface brightness gradually decreases by an order of magnitude going out from the core. The new X-ray data contain sufficient counts for spectral analysis of the key jet features. The X-ray energy index of the inner jet is relatively flat with \( \alpha_X = 0.66 \pm 0.15 \) and steep in the outer jet with \( \alpha_X = 1.0 \pm 0.2 \). We discuss the constraints implied by the new data on the X-ray emission models and conclude that “one-zone” models fail and that at least a two-component model is needed to explain the jet’s broadband emission. We propose that the X-ray emission originates in the jet proper while the bulk of the radio emission comes from a surrounding jet sheath. We also consider intermittent jet activity as a possible cause of the observed jet morphology.

Subject headings: galaxies: jets — quasars: individual (PKS 1127–145) — X-rays: galaxies

Online material: color figures

1. INTRODUCTION

Jets span distances of hundreds of kilometers to megaparsecs and constitute the largest manifestation of the active galactic nucleus (AGN) phenomenon. However, fundamental questions about the nature of jets remain unanswered, while emission processes associated with the production of X-rays and \( \gamma \)-rays are critical to understanding quasars. The discovery of many X-ray jet knots over the past six years with the Chandra X-Ray Observatory (Chandra; Weisskopf et al. 2002) indicates that jets, in particular large-scale jets (>100 kpc), are common (e.g., Schwartz et al. 2000; Marshall et al. 2001, 2005; Worrall et al. 2001; Sambruna et al. 2002, 2004; Siemiginowska et al. 2003a, 2003b).

The synchrotron origin of the radio-to-optical jet emission has now been well established. However, the origin of the jet X-ray emission is puzzling (see Harris & Krawczynski 2006 for a review), since a straight extrapolation of the synchrotron (radio to optical) continuum into the X-rays severely underpredicts the luminosity of powerful Chandra large-scale jets. Thus, the same single power-law population of electrons cannot produce the radio, optical, and X-ray emission in the framework of a homogeneous one emission zone approximation (see, for example, Sambruna et al. 2004). The synchrotron self-Compton (SSC) process cannot easily explain the data because it does not produce enough X-rays at the equipartition fields and therefore requires large departures from the minimum-power condition (Chartas et al. 2000; Harris & Krawczynski 2002; Kataoka & Stawarz 2005). It was proposed that the X-rays from large-scale quasar jets might be associated with inverse Compton (IC) scattering of the cosmic microwave background (CMB) photons, implying large jet bulk Lorentz factors (\( \Gamma \)) at hundreds of kiloparsecs from the active nuclei (Tavecchio et al. 2000; Celotti et al. 2001; Schwartz 2002). However, recent Chandra observations indicate several problems with this simple model: (1) the observed offsets between X-ray and radio peak brightnesses in some jet knots, with the X-ray peak being closer to the core; (2) the large variety of X-ray spectral indices observed in several jets; and (3) the spectral dependence of the knot shapes and profiles, as well as possible knot substructure (see Harris & Krawczynski 2006 for a wide discussion).

The most widely discussed types of models fall into two main classes: (1) synchrotron scenarios invoking separate populations of radiating electrons and/or nonstandard broadband electron spectra (Dermer & Atoyan 2004; Stawarz et al. 2004) and (2) more complex versions of the IC/CMB models involving knot inhomogeneity or jet deceleration (Tavecchio et al. 2003; Georganopoulos & Kazanas 2004). The most recent Spitzer Space Telescope and Chandra observations of the famous 3C 273 jet reported by Uchiyama et al. (2006) and Jester et al. (2006) seem to favor the former (i.e., synchrotron) scenario, revealing peculiar spectral shapes of the synchrotron (polarized) knot continua in the IR-to-UV photon frequency range and characteristic broadband spectral changes along the outflow. Both of these are consistent with the two-electron population/nonstandard particle spectra synchrotron model but could not be explained in the framework of the inverse Compton scenario. Yet the question remains whether the 3C 273 jet is representative of other large-scale quasar jets detected by Chandra or is a unique source.

A possible discriminant between synchrotron and IC/CMB emission models in all the sources is related to significant differences in lifetimes of the radiating particles, which would manifest themselves in the observed jet morphologies at different wavelengths. In particular, X-rays emitting synchrotron electrons (with Lorentz factors \( \gamma \geq 10^2 \)) have much shorter lifetimes than the lower energy radio emitting electrons, and hence one might expect the X-ray...
emission from knots to be more compact than the corresponding radio emission. Instead, the electron cooling times related to the IC/CMB emission are long, since the X-rays are produced by a low-energy population of electrons ($\gamma < 300$), thus implying continuous, intraknot X-ray emission outside the bright knots. Such an idealized picture may be, however, significantly complicated by intermittent/modulated jet activity and efficient particle acceleration acting within the entire jet volume (Stawarz et al. 2004).

In such a case, the multiwavelength morphology of the outflow is controlled by the jet activity and acceleration timescales rather than by the radiative cooling timescales of the particles.

The differences in the lifetimes of the radiating electrons could also shape the spectral profiles along the jets, i.e., runs of both broadband (e.g., radio to optical) power-law slopes and narrowband (e.g., radio or X-ray) spectral indices. However, in order to extract such information from the data, deep multiwavelength observations are needed. We note that Sambunara et al. (2004) found very flat ($\alpha_X \sim 0.5$) to almost inverted ($\alpha_X \sim 0.1$) spectra in a few X-ray jets (although with large uncertainties—the majority have errors from 0.3 to 0.9), which they associated with the IC/CMB from the electron population near the low-energy cutoff of the electron distribution. Alternatively, in the framework of the synchrotron scenario, flat X-ray continua may indicate spectral pileup occurring at the high-energy part of the electron energy distribution, which is in fact expected if the continuous particle acceleration acts efficiently enough (see Stawarz & Ostrowski 2002).

One of the longest X-ray jets known\(^8\) was discovered by Chandra in the second year of the mission (Siemiginowska et al. 2002, hereafter Paper I). With a length of almost 300 kpc projected onto the sky, this jet, associated with the redshift $z = 1.18$ radio-loud quasar PKS 1127−145, poses several questions for X-ray emission models. The one-sided jet shows an X-ray surface brightness that declines with the distance from the core, while the radio brightness increases. The jet slightly curves, with position angle (P.A., with respect to the core) changing from $\sim 64^\circ$ at the core to $\sim 43^\circ$ at the jet’s end. The discovery observation identified three main knots along the jet, with the farthest knot, C, being the weakest. The prominent knots, A and B, are connected by continuous X-ray emission that stops beyond knot B at $\sim 22''$ from the core. The Very Large Array (VLA)\(^9\) maps show very low brightness emission along the jet (Fig. 5 in Paper I), and the X-ray—radio intensity ratio decreases along the jet. The Hubble Space Telescope (HST) WFPC2 observation gives upper limits to the knots’ optical brightness, but they are too high for constraining the emission models. Thus, only radio and X-ray observations can be used to study emission processes in this jet.

The new Chandra data significantly improve on the discovery observation. With the deep exposure and high signal-to-noise ratio (S/N) it is obvious that the jet morphology is complex, and some substructure is clearly visible in the large knots. We now do not detect the offsets of $0.8'' − 2''$ between the X-ray and radio peak brightnesses reported in Paper I, but we conclude that they are now mostly attributable to the jet substructure. We also obtain well-constrained spectral information for the main jet features. We discuss the results in the context of currently considered emission models and pose questions. This is clearly a remarkable jet providing us with many constraints on the current emission models. Below we discuss in detail “one-component” emission models and show that they fail to explain the PKS 1127−145 jet data.

We suggest that a two-component model (the proper jet and a sheath) can describe the data. We also consider the possibility of modulated jet activity, which could be responsible for the observed jet morphology.

The X-ray data are presented in § 2, radio data in § 3, jet morphology and spectral properties in §§ 4 and 5, and optical data in § 6, and a discussion of the results and implications for jet models is in § 7. Throughout this paper we use the cosmological parameters based on the Wilkinson Microwave Anisotropy Probe (WMAP) measurements (Spergel et al. 2003): $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$. At $z = 1.18$, $1''$ corresponds to $\sim 8.3$ kpc. For a power-law radiation spectrum we adopt the convention: flux density, $S_v \propto \nu^{-\alpha}$.

2. CHANDRA OBSERVATIONS

The new observation of PKS 1127−145 with Chandra was obtained on 2005 April 25−27 (ObsID 5708) with $\sim 106$ ks exposure. This was the second Chandra observation of this quasar following the discovery of the X-ray jet in the AOI pointing (30 ks, ObsID 866). The source was placed $30''$ from the default aim-point position on the ACIS-S back-side illuminated CCD, chip S3 (Proposers’ Observatory Guidel [POG]). To reduce the effects of pileup we collected the data in 1/8 subarray readout mode of one CCD only, which resulted in a 0.441 s frame readout time. The quasar’s count rate of 0.62 counts s$^{-1}$ gives 8%−10% pileup in the core for this choice of the readout mode (see POG). After standard filtering, the effective exposure time for this observation was 103,203 s.

The standard offset pointing was used in this observation to avoid the node boundary. However, due to the drift of the optical axis since the Chandra launch in 1999 the aim-point location has moved closer to the node boundary (POG), and the quasar core was crossing the node during the observation. This affected the core data, and about 30% of the core photons were marked as bad due to their location on the node boundary. Because of the choice of the roll angle the jet was placed away from the node, and the jet data more than $3''$ away from the quasar centroid are not affected by the node boundary.

The X-ray data analysis was performed with the CIAO, version 3.3 software\(^10\) using calibration files from the CALDB 3 database. We ran acis_process_events to remove pixel randomization and to obtain the highest resolution image data. The X-ray position of the quasar (R.A. $= 11^h30^m07.05^s$, decl. $= -14^\circ49'27.3''$, J2000.0) agrees with the radio position (Johnston et al. 1995) to better than 0.25$''$ (which is smaller than Chandra’s 90% pointing accuracy of 0.6$''$; Weisskopf et al. 2003). All spectral modeling was done in Sherpa (Freeman et al. 2001).

3. VLA OBSERVATIONS

The VLA observations of 2001 February from program AH730 (1.4 and 8.5 GHz) are described in Paper I but are also included in Table 1 for completeness. The 1.4 GHz data were rammaged here with a smaller (uniform weighted) beam, revealing the presence of the X-ray—detected feature O. This is the only radio detection of this knot at the sensitivity of the higher frequency VLA maps (below).

We also reduced 5 GHz observations obtained as part of this program (2001 June) that were not available at the time of submission of Paper I. These data were taken in a less extended (B) configuration to synthesize matched resolution images at different frequencies (Fig. 6). All data were calibrated in AIPS (Briddle &

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\(^8\) See http://hea-www.harvard.edu/XJET/.

\(^9\) The VLA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

\(^10\) Available at http://cxc.harvard.edu/proposer/POG/index.html.

\(^11\) Available at http://cxc.harvard.edu/ciao/.
Greisen 1994), and imaging was done in DIFMAP (Shepherd et al. 1994). Four antennas were subarrayed to another project as our observations commenced, so effectively, only 23 antennas participated in this experiment.

New longer integration 8.5 GHz data were obtained in 2005 May mainly to improve the sensitivity in order to better define the radio jet morphology than in the previous 2001 image published in Paper I. Three antennas were being retrofitted for the EVLA (Expanded VLA) at the time, leaving 24 in the new experiment. The first hours of observations were flagged as this was when the target was rising (15°–25° elevation) and high cloud cover was reported. This left 6.25 hr of on-source time in the 8 hr observing run. After standard calibration and imaging, we removed the core (3.23 Jy) with the uvsub task in AIPS to isolate the inner jet emission. We merged the new 8.5 GHz data set with the previous one from 2001 but found no significant improvement in the images produced; only data from the latter epoch are used here. In the final core-subtracted image clean components were convolved with a circular Gaussian of FWHM = 0.7′, so radio structures appearing noncircular in Figures 7 and 8 are intrinsically elongated.

Off-source rms levels for the radio images are listed in Table 1 along with the resulting dynamic range relative to the image peaks. In all cases, the rms is higher than the expected theoretical limit (factors from ~3 to ~10 times larger). This is presumably due to a combination of the bright radio core and the low declination of the target making the field difficult to map. In the vicinity of the core, imaging artifacts (in the north-south direction) are somewhat obvious and the rms levels are even higher than the off-source values. This is reflected in the upper limits for several of the undetected inner radio knots reported in Table 2.

4. JET MORPHOLOGY

4.1. X-Ray Morphology

We consider the X-ray morphology of the large-scale jet starting ~3′ away from the quasar centroid. The analysis of the quasar core and the small-scale structure in the vicinity of the quasar will be presented elsewhere.

The smoothed ACIS-S image in Figure 1 shows a complex structure of continuous X-ray emission along the jet up to ~22″ distance from the core. There are several brightenings present within diffuse X-ray emission between the brightest knots. The jet width is resolved, and a structure at ~8″ distance from the core that shows a kink is "real." We discuss this kink in §§5 and 6.

We constructed an X-ray jet profile along the jet and a control profile with the regions shown in Figure 2. The background for each jet’s cell was taken from an annulus with radial widths of the jet cell, excluding the readout streaks, the control region, and a bright point source. The resulting profile is presented in Figure 3.

The X-ray emission declines gradually along the jet with the knots A, B, and C present. Figure 4 is a zoomed version of Figure 3 to present the emission beyond knot B. The X-ray jet emission seems to stop at the "edge" of knot B before it slightly increases to form knot C. Comparison between the jet and control profiles in Figure 4 indicates that the emission of knot C ends at ~30″, although the emission within the final 4″ (between 26″ and 30″) is only marginally detected.

The morphology of each knot is quite different. The profile of knot A shows a relatively sharp rise and a plateau before a gradual decline, while the knot B profile is more peaked with a strong rise and decline (see Fig. 4). Knot C is the faintest knot with the X-ray emission spread over a larger area. As we show below, X-ray emission covers the area of the strongest radio emission, which is also diffuse here. One gets an impression that knot C looks more like a lobe than a knot. However, even with Chandra resolution we still can only resolve structures on ~1″ scales, and even "compact" knots A and B are of the size of the entire M87 jet, for example (see Fig. 6 in Harris & Krawczynski [2006] for comparison of the jet projected lengths). Thus, what we see reflects the overall integrated intensity within each region, while there might be many smaller scale regions that cannot be resolved.

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**Table 1**

| Program  | Obs. Date | Config. | Freq. (GHz) | Integ. Time (hr) | Beam Size (arcsec) | P.A. (deg) | rms (mJy beam⁻¹) | Dynamic Range |
|---------|----------|---------|-------------|------------------|-------------------|-----------|-----------------|--------------|
| AHT730  | 2001 Feb 6 | BnA     | 1.4        | 2.1              | 2.71 × 1.62       | 84.4      | 0.30            | 18000        |
|         | 2001 Feb 6 | BnA     | 8.5        | 3.4              | 0.63 × 0.37       | 77        | 0.053           | 65000        |
|         | 2001 Jun 18 | CnB    | 4.9        | 2.6              | 2.77 × 1.66       | 84        | 0.12            | 33000        |
| AC779   | 2005 May 10 | B       | 8.5        | 6.25             | 0.7 × 0.7         | ...       | 0.04            | 81000        |

**Table 2**

| Feature | \(D^a\) (arcsec) | Total Counts \(b\) | Net Counts \(b\) | \(\alpha_X\) | \(S(0.5–2 \text{ keV})^c\) (mJy) | \(S(2–10 \text{ keV})^c\) (mJy) | \(S(1.4 \text{ GHz})^d\) (mJy) | \(S(5 \text{ GHz})^d\) (mJy) | \(S(8.5 \text{ GHz})^d\) (mJy) | \(\alpha_X^e\) |
|---------|----------------|--------------------|-----------------|-------------|-------------------------------|-------------------------------|-----------------------------|-----------------------------|-----------------------------|-------------|
| I........| 3.8            | 475 ± 22           | 323.6 ± 25.1    | 0.07 ± 0.11 | 7.9 ± 0.6                      | 16.8 ± 1.3                    | ...                         | ...                         | 2.2 ± 1.0                    | ...          |
| O........| 7.3            | 118 ± 11           | 89.9 ± 12.1     | 0.09 ± 0.09 | 2.2 ± 0.3                      | 4.6 ± 0.6                     | 2.5 ± 0.3                   | <0.45                       | <0.2                       | >1.35        |
| A........| 11.2           | 156 ± 12           | 132.7 ± 13.4    | 0.66 ± 0.15 | 3.2 ± 0.3                      | 6.8 ± 0.7                     | 6.4 ± 0.9                   | 1.2 ± 0.2                   | <0.27                      | 1.3 ± 0.17   |
| B........| 18.6           | 87 ± 9             | 77.35 ± 9.8     | 1.1 ± 0.2   | 1.98 ± 0.25                    | 2.6 ± 0.3                     | 43.2 ± 4.3                  | 14.4 ± 1.4                 | 8.2 ± 0.8                   | 0.91 ± 0.07  |
| C........| 28.5           | 40 ± 6             | 20.9 ± 7.7      | 1.2 ± 0.2   | 0.57 ± 0.21                    | 0.54 ± 0.20                   | 53.2 ± 5.3                  | 16.7 ± 1.7                 | 11.8 ± 1.2                  | 0.85 ± 0.08  |

\(^a\) Distance from the core to the center of the box region.

\(^b\) Total or net counts with energy within 0.3–8 keV.

\(^c\) Flux in units of 10⁻¹⁵ ergs cm⁻² s⁻¹; flux errors are based on the counts errors only.

\(^d\) Flux density estimated for the regions defined by the X-ray features (see Fig. 2). The rms in the maps and the beam size are given in Table 1. The sizes of the regions assumed for extracting the spectra are 3.4″ × 1.96″ for I, 3.1″ × 2.36″ for O, 5.12″ × 2.64″ for A, 4.41″ × 2.13″ for B, and 7.03″ × 5.63″ for C.

\(^e\) Radio spectral index measured between 1.4 and 8.5 GHz.
Fig. 1.—ACIS-S exposure-corrected image ($E = 0.3–7$ keV), which has been smoothed with a Gaussian kernel ($1 \sigma = 0.615''$). The quasar core has been excluded from the image within a circular region with 3'' radius. The knots are marked with labels along the jet. The “kink” region in the jet is marked by an arrow. The direction of the CCD readout is indicated by an arrow on the right. The color scale is marked on a color bar with units of $8.13 \text{ photons cm}^{-2} \text{s}^{-1} \text{arcsec}^{-2}$. The sky coordinates are in J2000.0. North is up and east is to the left.

Fig. 2.—Left: Regions assumed for the extraction of the jet profile and the control profile are shown in the raw ACIS-S image ($E = 0.3–7$ keV). The readout streak regions and the point source to the northwest marked in the image have been excluded from the analysis. Right: ACIS-S raw image data overlaid with the spectral regions (I, O, A, B, and C, counting away from the quasar along the jet) assumed for the extraction of the jet X-ray spectra. North is up and east is left. The readout streak is labeled and is visible on both the east and west sides of the quasar core. The pixel size is set to half of the original ACIS pixel, and it is equal to 0.246''. The 10'' scale is marked with an arrow.
From looking at both the jet profile and the smoothed X-ray image it is clear that the morphology of the jet is complex. In addition to the three knots we identify brightenings (knots O and I) between the core and knot A, as well as a drop in the surface brightness at \( \gamma = 0.24 \pm 0.00 \) from the core. We also detect the emission between the knots.

4.2. Radio Morphology

The VLA radio maps at 1.4 and 5 GHz are presented in Figure 6. The VLA 8.5 GHz map is presented in Figures 7 and 8; in this map the core has been subtracted to highlight the very faint jet structure. It is obvious that the radio emission of the innermost jet is very faint, with knot A at the detection threshold. The emission becomes strong at the outermost regions with knots B and C being quite strong. There is continuous emission between the last two knots, so their peak brightnesses are connected.

The 8.5 GHz radio profile of the jet shown in Figure 5 shows the jet brightness increasing toward the final knot. The brightness of the last two knots is almost identical. The innermost regions of the jet, identified as region I, are also detected at this frequency, while there is only an upper limit to the radio emission at the location of the O feature.

Table 2 presents the radio flux density measurements for each map. Given the three radio frequencies we can determine the radio spectral index for the brightest knots and get \( \alpha_r \) equal to 0.8 and 0.9 for knots B and C, respectively.

4.3. Radio and X-Ray Connection

Figure 5 compares X-ray and radio intensities along the jet. The profile intensities were extracted assuming the same box region for the radio 8.5 GHz and X-ray (0.3–7 keV) data (using DS9 projection) and taking 2.5\( \alpha \)width for the region box. The two profiles look quite different. The X-ray intensity decreases with the knots on top of a continuous emission, while the radio intensity stays at a very low level to about 16\( \alpha \), where it sharply

![Figure 3](image-url)  
Fig. 3.—Top: X-ray surface brightness profile of the jet extracted from the regions shown in Fig. 2. The upper triangles mark the location of the middle point of the box, and the profile is connected with a solid black line. The control profile is marked with the lower triangles and connected by the dashed gray line. Photon energy is within 0.3–7 keV. Units are counts pixel\(^{-2}\) (the standard ACIS pixel size is 0.492\( \alpha \)). Bottom: Hardness ratio along the jet \( (H - S)/(H + S) \), where \( S \) is the counts between 0.5 and 2 keV and \( H \) is the counts between 2 and 7 keV. The error bars were calculated using BEHR, a Bayesian method described in Park et al. (2006). [See the electronic edition of the Journal for a color version of this figure.]

![Figure 4](image-url)  
Fig. 4.—Zoom into the three outermost knots of the jet X-ray surface brightness profile, extracted from the regions shown in Fig. 2. The upper triangles mark the location of the middle point of the box, and the profile is connected with a solid line. The control profile is marked with the lower triangles connected by the dashed line. [See the electronic edition of the Journal for a color version of this figure.]

![Figure 5](image-url)  
Fig. 5.—Radio (8.5 GHz, dashed line) and X-ray (0.3–7 keV, solid line) brightness along the jet in arbitrary units. The X-ray scale has been multiplied by 3 \( \times \)10\( ^{5} \) for a visual comparison of the radio and X-ray profiles. The intensity was calculated within DS9 using a projection region of 2.5\( \alpha \) width along the jet. [See the electronic edition of the Journal for a color version of this figure.]
Fig. 6.—VLA 1.4 and 4.9 GHz images of PKS 1127–145. The lowest contour levels plotted are 0.75 mJy beam$^{-1}$ (1.4 GHz) and 0.39 mJy beam$^{-1}$ (4.9 GHz) and increase by factors of $\sqrt{2}$ up to peaks of 5.46 and 4.14 Jy beam$^{-1}$, respectively. The (uniform weighted) beam sizes are nearly identical: $2.71'' \times 1.62''$ at P.A. = 84.4$^\circ$ and $2.77'' \times 1.66''$ at P.A. = 84.0$^\circ$, respectively.

Fig. 7.—X-ray image, smoothed with a Gaussian kernel ($\sigma = 0.615''$), overlaid with the 8.5 GHz radio contour map. The radio core has been subtracted. The colors indicate the X-ray brightness between black and yellow of $10^{-10}$ and $10^{-5}$ photons cm$^{-2}$ s$^{-1}$ pixel$^{-2}$, respectively. The radio contours are plotted between 0.2 and 2.0 mJy beam$^{-1}$, at 0.2, 0.3, 0.5, 0.7, 1.0, 1.2, 1.3, 1.5, 1.7, and 2.0 mJy beam$^{-1}$. The radio beam is circular (0.7$''$). The scale is indicated with the arrows. North is up and east is left.
rises to form knot B, than decays to a diffuse level and rises again to form knot C. The three knots I, A, and B are the strongest X-ray features, while knots B and C dominate the radio emission. The X-ray emission of knot A is very prominent in comparison to the radio emission. It does not have an obvious peak but rather a broad flat profile. Knot A is very faint in radio, and its radio spectrum is very steep ($\alpha_r > 1.35$) in comparison to knots B and C, whose spectra are more typical, $\alpha_r = 0.8–0.9$ (see Table 2).

The emission from knot B is very prominent in both radio and X-rays, and the knot profiles can be studied in more detail. In Paper I we reported the offsets between the radio and X-ray peak brightnesses of 1.4$''$ for this knot (using the radio data with uncertainties of 1$''$ at 1.4 GHz and X-rays with uncertainties of 0.3$''$). Now, with the improved S/N Chandra image and 8.5 GHz radio data we can directly model the profiles of the knot and obtain more accurate locations of the peaks (see Fig. 5). We measure that the radio (8.5 GHz) and X-ray peak brightnesses are coincident to within 0.2$''$. The X-ray emission precedes the radio emission for this knot in the sense that the X-rays start rising before the radio and decay earlier than the radio. Thus, the X-ray profile of this knot seems to be shifted in comparison to the radio profile.

The radio emission of knot C is strong, and its profile shows a step before the final rise to the maximum at 28$''$. Then the emission drops and the knot ends at 31$''$. The X-ray emission is very faint with constant intensity.

5. SPECTRAL PROPERTIES OF THE X-RAY KNOTS

Figure 3 show the hardness ratio along the jet. We define the hardness ratio as $(H - S)/(H + S)$, where $H$ is the hard source counts with 2–7 keV energies and $S$ is the soft source counts with 0.5–2 keV energies. The hardness ratio errors are calculated using the Bayesian algorithm of Park et al. (2006). The jet’s X-ray spectrum has a constant hardness ratio up to about 8$''$, with a sudden drop in the jet intensity in the vicinity of the “kink.” The hardness ratio suggests a spectral change at this point that continues farther along within knot A. It seems that the jet spectrum hardens along knot A and then becomes softer again before hardening within knot B. The S/N is too low to study the hardness ratio variations beyond knot B.

To characterize the jet spectral properties we extracted the X-ray spectra of small parts of the jet, assuming the box regions shown in Figure 2. The total number of counts and the best-fit power-law model parameters are presented in Table 2. The power-law slope indicates a hard (flat) spectrum, $\alpha_X \sim 0.6–0.7$, for the inner regions I, O, and knot A and a soft (steep) spectrum, $\alpha_X \sim 1–1.2$, for the outer knots B and C.

To check whether the difference in the X-ray emission between the inner and outer jet is significant we extracted the spectra from the two large regions: the inner jet region contains knots I, O, and A, and the outer jet contains knots B and C. We then fit these two
spectra (using the calibration files appropriate for the new extraction regions) with an absorbed power-law model. We obtain the power-law slopes for each region, $\alpha_{X,\text{inner}} = 0.64 \pm 0.07$ and $\alpha_{X,\text{outer}} = 1.29 \pm 0.22$. Thus, the spectral difference between the two regions is at the $\sim 2.8$ $\sigma$ level. The hardness ratios based on the source counts for the inner and outer jets are $-0.48^{+0.04}_{-0.04}$ and $-0.74^{+0.10}_{-0.08}$, respectively.

5.1. X-Ray Diffuse Emission

We analyzed the X-ray emission between the knot A and B regions, e.g., in the annulus with inner and outer radii of 14" and 16.5". There are a total of 24 counts with energy between 0.3 and 8 keV and 18.3 ± 5.4 net counts (assuming a background annulus with the same radii, but excluding the jet region). The detected number of counts is too small for detailed spectral analysis. However, the spectrum is soft based on the hardness ratio of $-0.73^{+0.12}_{-0.15}$.

6. OPTICAL JET?

An optical image of PKS 1127−145 that was taken with HST (Paper I) shows a number of galaxies with a large galaxy across the X-ray jet. A damped Lyα (DLA) system at redshift 0.312 has been described by Bergeron & Boisse (1991) and Bechtold et al. (2001; see also Bechtold et al. 2002 for detailed optical spectra). Because the DLA galaxy has to be located close to the line of sight to the quasar, it may affect the emission from the quasar jet. Our comparison between the X-ray and radio jet morphology indicates that the change in the jet shape is present in both bands (see Figs. 1 and 6); thus, we can exclude the absorption of jet emission by the foreground galaxy as a cause of the observed jet morphology. A slight change in the direction of the jet might therefore be intrinsic to the jet or a result of gravitational lensing of the jet by the foreground galaxy.

There is no detection of the optical jet and the limits for the optical jet emission were given in Paper I for knots B and C. The limits for knot A and remaining inner knots cannot be obtained due to the galaxies in the field. These limits are too high to provide additional constraints on the jet properties. Deeper optical/IR imaging is necessary to improve the limits.

7. DISCUSSION

The radio and X-ray images of the PKS 1127−145 jet and the analysis of the jet’s broadband spectral properties reveal significant differences between the inner (<14"), knots I, O, and A, hereafter the “inner jet”) and the outer portions of the jet (16"–30", knots B and C, hereafter the “outer jet”). This is not unusual among the large-scale quasar jets: for example, it is seen in the 3C 273 jet (Uchiyama et al. 2006 and references therein). However, one should note the large extension of the PKS 1127−145 jet: both its inner and outer parts have projected sizes of ~100 kpc each, while the entire 3C 273 jet structure is only ~60 kpc long.

The PKS 1127−145 inner jet is very weak in the radio band, especially at high frequencies (8.5 GHz), while it is bright in X-rays. However, the X-ray and radio luminosities of the outer jet are roughly comparable (see Figs. 5, 7, and 9). A general trend of a smooth decrease in the X-ray flux and a slow increase in the radio flux can be noted along the jet, with the exception of the innermost knot I (for which the measured radio fluxes may suffer from contamination of the extremely bright core). This, discussed previously by Hardcastle (2006), is again reminiscent of the 3C 273 jet. In particular, the ratio of 1 keV to 1.4 GHz luminosities decreases by about 2 orders of magnitude starting from $(L_{0.1})_{1\text{keV}} / (L_{0.1})_{1.4\text{GHz}} \approx 50$ at the position of knot O, to ~0.5 at the position of knot C. At high radio frequencies this decrease seems to be even stronger, since the upper limits for the 8.5 GHz flux for knots O and A translates to the luminosity ratio $(L_{0.1})_{1\text{keV}} / (L_{0.1})_{8.5\text{GHz}} > 100$.

The X-ray spectral index is constant within the inner knot, $\alpha_X \approx 0.65−0.7$, and it is slightly smaller than the radio spectral indices between 1.4, 5, and 8.5 GHz, namely, $\alpha_5^{1.4}, \alpha_5^{8.5} > 1.3$. It is also smaller than the radio–to–X-ray power-law slopes (see Fig. 10), although the errors in estimating the appropriate radio fluxes are large. We note that at the position of knot A the 8.5 GHz flux is especially low and the high-frequency part of the radio continuum is very steep. Thus, the electrons emitting X-ray photons in the inner jet, regardless of the particular emission process (synchrotron or inverse Compton), are characterized by a much flatter energy spectrum than the radio-emitting ones. The situation is, however, much different for the outer jet. Here the relatively large X-ray spectral indices, $\alpha_X \approx 1−1.2$, seem to be larger than the radio–to–X-ray power-law slopes or radio spectral indices, which are all ≤1 (see Fig. 10).

Lack of reliable optical data makes it difficult to investigate the broadband energy distribution of the inner jet emission. On the other hand, as shown recently by Uchiyama et al. (2006) and Jester et al. (2006) for the case of the 3C 273 jet, a comparison between the broadband radio-to-optical and the optical–to–X-ray power-law slopes can be misleading in deducing the origin of the jet X-ray emission unless detailed optical photometry, and not solely upper limits, is available. Such detailed optical information is unfortunately not available for the PKS 1127−145 jet, so below we focus strictly on the confrontation of the radio and X-ray data, in particular their global characteristics, instead of modeling isolated knot regions. First we discuss whether the observed morphological and spectral properties of the radio/X-ray PKS 1127−145 jet can be explained in the framework of the “one emitting zone” IC/CMB and synchrotron models. The particular issues to be explained are (1) a decrease of the X-ray flux, (2) an increase of the radio flux, (3) a steepening of the X-ray continuum,
7.1. The “One-Zone” Inverse Compton Hypothesis

The simplest version of the one-zone IC/CMB model to consider would involve relativistic outflow with negligible bulk deceleration and energy dissipation, expanding adiabatically when propagating through the intergalactic medium. This, in fact, was argued by Tavecchio et al. (2004) to be the case for the Chandra jets in PKS 1510–089 and 1641+399, so below we check whether it also applies to the PKS 1127–145 source. Under the above assumptions, the appropriate inverse Compton luminosity of the jet plasma with the comoving volume \(V^*\) observed at a given frequency \(\nu_{\text{IC}} \sim \delta^2 \nu_{\text{CMB}} \gamma^2\) can be written as

\[
(n_{\nu_{\text{IC}}}) = \delta^2 \Gamma^{-2} \sigma T V^* U_{\text{CMB}}^z \left[ \gamma^3 n^* (\gamma) \right]_{\gamma = \sqrt{\nu_{\text{IC}} / \nu_{\text{CMB}} \delta^2}}
\]

where \(\Gamma\) and \(\delta\) are the jet Lorentz and Doppler factors, \(U_{\text{CMB}}^z\) is the jet comoving energy density of the CMB radiation, and \(n^* (\gamma)\) is the electron energy distribution such that the electron energy density is \(U_e^z = \int \gamma m_e c^2 n^* (\gamma) d\gamma\) (see, e.g., Stawarz et al. 2003). Here the unprimed quantities correspond to the stationary rest frame at the redshift of the source. The adiabatic losses due to the jet’s expansion between the location \(r_0\) and \(r\) from the nucleus leads to \(N^* (\gamma, r) = (r/r_0)^{-A/2} N^* (\gamma_0, r_0)\) and \(\gamma = (r/r_0)^{3/2} \gamma_0\), where \(N^* (\gamma, r) \equiv n^* (\gamma) V^*\), and \(A = 2\) or 1 for two- or three-dimensional expansion, respectively (see, e.g., Stawarz et al. 2004). Thus, the observed monochromatic—e.g., X-ray—inverse Compton luminosity is evolving along the adiabatically expanding (in two dimensions, the case considered hereafter for illustrative purposes) and nondecelerating jet as \(L_{\nu_{\text{IC}}} (r) \propto r^{-2(p-1)/3}\), where we assumed a power-law form for the electron energy distribution \(n^* (\gamma) \propto \gamma^{-p}\).

Meanwhile, changes of the observed synchrotron luminosity at some given observed frequency \(f_{\nu_{\text{syn}}} \sim 3eB^2 r^2 /4\pi m_c c^2\), where \(B\) is the jet magnetic field intensity, can be found from the appropriate expression,

\[
(n_{\nu_{\text{syn}}}) = \delta^4 e^2 c \sigma T U_B^z \left[ \gamma^3 n^* (\gamma) \right]_{\gamma = \sqrt{4\pi m_e c^3 / 3eB^2}}
\]

where \(U_B^z = B^2 /8\pi\) is the jet comoving magnetic field intensity. Thus, the observed monochromatic synchrotron—e.g., radio—luminosity scales as \(L_{\nu_{\text{syn}}} (r) \propto r^{-2(p+1)/2}\), since magnetic field density does change within adiabatically expanding outflow, \(B = B(r)\). As a result, the ratio of the observed inverse Compton to synchrotron luminosities at chosen observed frequencies (e.g., 1 keV and 1.4 GHz) reads as \(L_{\nu_{\text{IC}}} (r) / L_{\nu_{\text{syn}}} (r) \propto r^{-(p+1/2)}\), assuming that the shape of the electron energy distribution is roughly the same all along the jet (which is a good approximation for the value \(p \sim 3 \pm 0.5\) suggested by the observed range of the X-ray and low-frequency radio indices in the PKS 1127–145 jet). Note that the \(L_{\nu_{\text{IC}}} / L_{\nu_{\text{syn}}}\) ratio is then completely described by the magnetic field evolution and the electron spectral index so long as \(\delta\) does not change down the jet.

It follows immediately from the above that in the case of adiabatic expansion of a jet with conserved magnetic energy flux, both inverse Compton and synchrotron luminosities decrease along the outflow. For example, if the jet magnetic field consists predominantly of a poloidal or toroidal component, the field is expected to scale with a distance as \(B(r) \propto r^{-p} \) or \(r^{-p+1}\), respectively. The former ("poloidal") scaling cannot, however, hold along the entire jet length, i.e., from the jet base (a few to several Schwartzschild radii from the nucleus) up to the jet termination point (about 300 kpc from the active center). Indeed, taking the maximum magnetic field intensity \(B(100 \text{ kpc}) \sim 10^4 G\) at the jet base (as appropriate for 10 Schwartzschild radii from the central black hole with mass \(\approx 10^9 M_\odot\)), a poloidal field would imply unrealistically low intensities on hundred-kiloparsec scales, \(B(100 \text{ kpc}) \sim 10^{-12} G\) (see recent discussion in Sikora et al. [2005] regarding the magnetic field in quasar jets). Therefore, we consider only the \(B(r) \propto r^{-3}\) case (see in this context Tavecchio et al. 2004), in which the X-ray (inverse Compton) luminosity scales with distance as \(L_{\nu_{\text{IC}}} (r) \propto r^{-4/3}\) while the radio (synchrotron) one as \(L_{\nu_{\text{syn}}} (r) \propto r^{-10/3}\) for the assumed \(p = 3\). This scaling of luminosities indicates that in the framework of the one-zone IC/CMB model no adiabatic expansion of the PKS 1127–145 jet is possible, since otherwise the expected attenuation of the X-ray and radio fluxes would be inconsistent with the data. Indeed, taking the positions of knots O and C relative to the core as \(r_0 = 7.3''\) and \(r_C = 28.5''\), respectively (see Table 2), one should expect \(L_{\nu_{\text{IC}}} (r_C) / L_{\nu_{\text{IC}}} (r_0) \sim 0.2\) and \(L_{\nu_{\text{syn}}} (r_C) / L_{\nu_{\text{syn}}} (r_0) \sim 0.01\). Meanwhile, the observations indicate that although the 1 keV luminosity decreases by about an order of magnitude between knots O and C, the 1.4 GHz luminosity increases by as much as a factor of \(\sim 10\) instead of decreasing by a factor of 100.

Given the above conclusion we now consider an efficient confinement of the outflow, i.e., no jet expansion, which would give the slowest attenuation of the synchrotron (radio) luminosity. We also allow for the jet deceleration, \(\delta = \delta (r)\), and nonadiabatic changes of the jet magnetic field due to the related dissipation of the jet kinetic energy. Expressions (1) and (2) then give \(L_{\nu_{\text{IC}}} (r) \propto \delta (p+3)\) and \(L_{\nu_{\text{syn}}} (r) \propto \delta (p+5)/2 B^{(p+1)/2}\). In this case, an increase of...
the radio luminosity could be obtained if the jet magnetic field is amplified. For instance, for a choice of \( \delta(r_\text{C})/\delta(r_\text{O}) \approx 0.7 \) and \( B(r_\text{C})/B(r_\text{O}) \approx 7 \) the X-ray luminosity decreases as \( L_X(r_\text{C})/L_X(r_\text{O}) \approx 0.1 \), while the radio luminosity increases as \( L_R(r_\text{C})/L_R(r_\text{O}) \approx 10 \), resulting in (required by the data) a factor of \( \sim 0.01 \) change in the X-ray–to–radio luminosity ratio. However, such changes would imply a significant amplification of the jet magnetic field energy density, since \( U_B^\prime(r_\text{O}) \approx B^2 \) so that \( [B(r_\text{C})/B(r_\text{O})]^2 \approx 50 \). If, therefore, the energy equipartition between the jet magnetic field and the radiating electrons is valid for knot O, \( U_B^\prime(r_\text{O}) \approx U_B^\prime(r_\text{C}) \), then for knot C the equipartition would have to be broken, \( U_B^\prime(r_\text{C}) \gg U_B^\prime(r_\text{O}) \). In order to keep the energy equipartition, one would have to assume that the normalization of the electron energy distribution also increases along the jet just like \( U_B^\prime \), giving \( L_X(r) \propto \delta^{p+3}/B^2 \) and \( L_R(r) \propto \delta^{(p+5)/2}B^{p+5}/2 \), i.e., that the amount of the jet energy dissipated to the radiating particles is always equal to that transferred to the jet magnetic field. This would imply then slightly more efficient deceleration and slightly less efficient magnetic field amplification, namely, \( \delta(r_\text{C})/\delta(r_\text{O}) \approx 0.4 \) and \( B(r_\text{C})/B(r_\text{O}) \approx 4 \), to reproduce the observed luminosity profiles.

Sambruna et al. (2006) fit the one-zone IC/CMB model to two X-ray jets, in the quasars 1136–135 and 1150+497, with similar jet luminosity trends to that observed in PKS 1127–145, and obtained exactly the same change in IC/CMB model parameters as calculated above, i.e., lowering \( \delta \) with increase in the \( B \) field and in the normalization of the electron distribution along the jet (see their Fig. 12). As shown above, this is in fact a natural consequence of the equipartition requirement in the IC/CMB model if the decreasing (along the outflow) X-ray luminosity anticorrelates with the radio one. Tavecchio et al. (2006) proposed that such changes in the jet parameters and the resulting radio and X-ray profiles are due to the entrainment of the intergalactic medium by the large-scale jet, but as shown by Hardcastle (2006) the entrained masses required are implausibly high in some cases.

Yet the observed changes of the X-ray and radio spectral indices along the PKS 1127–145 jet pose problems to the inverse Compton scenario. Indeed, in the framework of the IC/CMB model electrons emitting the observed 1 keV photons have Lorentz factors \( \gamma_X \approx 10^3/\delta \), while the electrons emitting the observed 1.4 GHz synchrotron radiation have Lorentz factors \( \gamma_R \approx 10^4/(B^{-5/2})^{1/2} \), where \( B^{-5} \equiv B/10^{-5} \ G \). Thus, for any Doppler factor \( \delta \approx \sim 1 \) and a magnetic field close to the equipartition value \( B^{-5} \leq 1 \) (see Paper I; Kataoka & Stawarz 2005) one has \( \gamma_X \approx \gamma_R \). This means that radiative cooling, if it is a dominant factor shaping the spectral indices’ profiles along the PKS 1127–145 jet, would be more pronounced in radio frequencies than in the X-rays. In other words, the radio continuum should have to steepen more significantly with distance than the X-ray continuum. In fact the observed behavior is just the opposite: the radio spectral indices decrease along the jet, while the X-ray spectral index eventually increases. What is even more surprising is that in the outer portion of the jet the X-ray spectral index is larger than the radio one, which—in the framework of the IC/CMB model—would imply that the energy distribution of the radiating electrons unexpectedly steepens toward the lower energies.

Thus, we conclude that the simplest one-zone IC/CMB model is not consistent with the observed morphological and spectral properties of the PKS 1127–145 radio/X-ray jet unless arbitrary additional assumptions are invoked. In any case, its adiabatic version can be completely rejected.

7.2. The “One-Zone” Synchrotron Hypothesis

Because of the extremely large jet lengths and extremely short radiative cooling timescales of electrons with energies required for the synchrotron X-ray emission [Lorentz factors \( \gamma_X \approx 10^5/\sqrt{B-5}^{1/2} \)], one obvious requirement of the synchrotron hypothesis is continuous acceleration of the high-energy electrons along the jet. The simplest version of the one-zone synchrotron model would therefore be a scenario in which some unspecified acceleration mechanism is acting continuously and similarly within the entire uniform jet volume, producing and maintaining a uniform electron energy distribution with the steep power-law plus flat-spectrum component at high energies. Such an energy spectrum could be characterized in a zero-order approximation by two power laws with indices \( p_1 \) and \( p_2 < p_1 \) at low and high electron energies, respectively. As in the case of the inverse Compton hypothesis, let us check whether such a simple model can account for the observed properties of the PKS 1127–145 jet.

Just like in \( \S \) 7.1, one can conclude that no adiabatic expansion of the jet is possible, since the radio luminosity would decrease along the jet much faster than the X-ray. An efficient confinement of the jet and nonnegligible dissipation of the bulk kinetic energy give a scaling of the high- and low-energy synchrotron luminosities \( L_X(r) \propto \delta^{p+5}/B^{p+1/2} \) and \( L_R(r) \propto \delta^{p+5}/B^{p+1/2} \), and thus \( L_X/L_R \propto \delta^{p-5} \). Let us take the illustrative spectral indices of the electron energy distribution close to \( p_1 = 3 \) (representing the low-frequency radio continuum) and \( p_2 \approx 2 \) (representing freshly accelerated, i.e., uncooled X-ray-emitting electrons). We note that, for example, relatively well understood stochastic acceleration of particles due to resonant scattering on turbulent MHD waves characterized by the energy spectrum \( W(k) \propto k^{-q} \) is expected to result in formation of the steady state particle energy distribution \( n_s(\gamma) \propto \gamma^{-q}, \) where \( q = p - 1 \) (for particle energies below the maximum energy defined by the radiative loss timescale; see the discussion in Kataoka et al. 2006). Thus, for the typical turbulence energy index \( 1 \leq q \leq 2 \) one should indeed expect particle spectra with \( 0 \leq p \leq 1, i.e., much flatter than those claimed by the shock scenarios (\( p \sim 2 \)).

It follows immediately that the agreement between the predicted and the observed luminosity profiles along the PKS 1127–145 jet is possible only if the high-energy spectral component of the radiating electrons is very flat, and if in addition the magnetic field is strongly amplified along the jet. Namely, the decrease of the X-ray luminosity by a factor of 0.1 and the increase of the radio luminosity by a factor of 10 would be possible for \( p_2 = 0 \) only if \( \delta(r_\text{C})/\delta(r_\text{O}) \approx 0.1 \) and \( B(r_\text{C})/B(r_\text{O}) \approx 100 \), while \( p_2 > 0 \) would require even more drastic magnetic field amplification. These changes of the jet parameters are worrisome, simply because it is difficult to isolate the appropriate mechanisms causing such a strong jet deceleration and extremely effective conversion of the jet kinetic energy to the magnetic one (see again comments by Hardcastle [2006] on the entrainment process on large scales). Although it can be argued that some magnetic field amplification and some bulk deceleration are taking place along the extragalactic large-scale jets anyway, as suggested by the observed (in many cases) increase in the radio surface brightness and decrease in the jet-counterjet brightness asymmetry away from a core, the particular model parameters obtained above are rather too extreme and should be considered implausible.

On the other hand, the assumption about the uniform electron energy distribution within the entire jet is neither a natural nor a realistic one for the synchrotron/continuous acceleration scenario. In fact, if the high-energy flat-spectrum (pileup) component in the electron distribution is produced, it results most probably from turbulent acceleration processes. Thus, the normalization, the effective spectral index, and the cutoff energy of such a pileup component should depend on the local plasma conditions at a given distance along the jet (magnetic field intensity, turbulence
parameters, jet velocity structure, etc.). These factors can significantly influence model predictions when compared to the simplest scenario discussed above (which can hardly explain the observed radio/X-ray flux profiles along the PKS 1127–145 jet). Discussing all these effects would require much deeper insight into the microscopic processes in relativistic magnetized plasma, which are still hardly known. We can, however, briefly consider one simple possibility and discuss the consequences of the assumption that the normalization of the high-energy flat-spectrum electron component producing synchrotron X-rays depends on the kinematic parameters of the jet. Since the jet shear boundary layer is the site of choice for generation of the high-energy electrons (Stawarz & Ostrowski 2002), one could speculate that the efficiency of the particle acceleration process [and thus the normalization of the electron distribution $K_2$, where $n_e(\gamma) = K_2 \gamma^{-p_e}$ at high energies] is somehow proportional to the velocity shear across the relativistic outflow, $d\Gamma/dR \sim \Gamma/R_j$ (where $R$ is the radial jet dimension and $R_j$ is the jet radius). But the characteristic distance from the core. That is to say, for the confined cylindrical jet ($R_j = \text{const}$) and a constant jet viewing angle, we introduce a simple scaling $K_2 \propto 8^m$ with the power-law coefficient being $m > 0$ for generality. In such a case, with $p_2 = 0$ and $p_1 = 3$ considered previously, the synchrotron X-ray and radio luminosities should go as $L_X \propto \delta^{(2m+5)/2} B_1^{1/2}$ and $L_R \propto \delta^8 B^2$. Therefore, taking $m = 5$ as an arbitrary illustrative value, one can find that moderate changes $\delta(R_c)/\delta(R) \sim 0.6$ and $B(R_c)/B(R) \sim 8$ reproduce well the luminosity profiles observed along the PKS 1127–145 jet. These are then not implausible anymore.

However, the observed changes of the X-ray and radio spectral indices are again problematic for the simple synchrotron model discussed here. While it is true that one should expect some aging of the X-ray continuum, it is not clear why the observed increase of the X-ray spectral index is so gradual and in addition accompanied with a flattening of the radio spectrum. If one assumes that the freshly accelerated high-energy part of the electron energy distribution is indeed very flat ($p_2 < 2$), then the spectral index of the constantly injected radiatively cooled (by the standard synchrotron-type energy losses) high-energy particles should be equal to $\alpha = 0.5$. This is quite close to the X-ray spectral index observed within the inner jet. Meanwhile, in the outer jet the X-ray spectral index steepens, suggesting either a significant change in the initial power-law slope of the electron pileup component (down to $p_2 \geq 2$) or significant differences in the cooling mechanism in the inner and outer jet. Whatever the case, it is hard to understand why in the inner jet, where the postulated pileup emission would be relative flat (and hence the required acceleration process is especially efficient), the observed synchrotron continuum at high radio frequencies is very steep.

To summarize, we conclude that the simplest one emitting zone version of the synchrotron model with uniform (although non-standard, i.e., concave) electron energy spectrum also cannot easily explain the observed morphological and spectral properties of the PKS 1127–145 radio/X-ray jet.

7.3. A Two-Component Model: The Jet and a Sheath

A natural solution to the problems encountered by the homogeneous one-zone models is to assume that the observed radio and X-ray radiative components are produced in separate regions, possibly by separate and different acceleration processes. Here we suggest that indeed the detected X-ray photons originate within the proper jet flow, while the radio photons come from a sheath—a slow-moving radial extension of the jet boundary (mixing) layer. Such a possibility is in fact not novel, since it is a variation of the stratified jet scenario (for discussions on different aspects of this issue see De Young 1986; Komissarov 1990; Laing 1996; Ostrowski 2000), noted before in the particular case of the Chandra quasar jets by Hardcastle (2006). We emphasize that this “proper jet—sheath” model is not exactly the same as the “spine—shear layer.” The “sheath” here is associated with some extension of the jet boundary (similar to 3C 273 jet/coconoo system; see Bahcall et al. 1995), while the “proper jet” means a fast spine together with the shear layer.

In the framework of the two-component jet model, all the information regarding the broadband jet emission is restricted to the X-ray band. In other words, there are not many additional constraints that could help to distinguish between the synchrotron and inverse Compton origin of the observed X-ray keV photons—both these possibilities have to be kept in mind. However, in an analogy to the X-ray jet in 3C 273, where almost the same gradual decrease of the X-ray flux and steepening of the X-ray continuum along the jet is observed, one could argue that also in the case of PKS 1127–145 the X-ray radiation is most probably due to the synchrotron emission of the high-energy electrons accelerated continuously within the jet volume (see a discussion in Uchiyama et al. 2006; Jester et al. 2006 and references therein).

Note also that, assuming a radio–to–X-ray continuum characterized by a single power law with a slope $\alpha_{X,R} \leq 0.6$ (corresponding to the particle spectral index $p \leq 2.2$), the expected radio emission of the proper jet would be always below the observed radio emission from the PKS 1127–145 jet regions, since all the radio–to–X-ray spectral indices shown in Figure 10 are $>0.6$. The same is true for the optical emission, as the optical upper limits available for the knots B and C (Paper I) imply optical–to–X-ray power-laws slopes $<1.0$. That is not to say that the jet broadband emission is in reality a single power-law form. Indeed, it may be characterized by a more complicated spectral shape for which, however, we do not have any strong evidence.

By definition, a two-component model doubles the number of free parameters, making model predictions more flexible when confronted with the data. Let us therefore briefly discuss whether the observational X-ray/radio constraints 1–4 listed at the beginning of §7 could be explained in a natural way in the framework of such a scenario.

7.3.1. The Proper Jet

The observed smooth decrease of the X-ray flux, when unconnected with the increase of the radio one, is in fact expected as a result of the decrease in the inverse Compton or synchrotron luminosities along the (even extremely slowly) decelerating and/or expanding jet. These luminosities (see eqs. [1] and [2] above) can be expressed as

$$L_{IC} = \int (L_{IC})_{\nu} d\nu \sim \delta^6 \Gamma^{-2} \frac{\sigma_T}{m_c c} \nu^{e} U'_{\text{IC}} \left\langle \frac{\gamma^2}{\gamma} \right\rangle_U e', \quad (3)$$

respectively, where $U_{\text{IC}}' = 1.2 \times 10^{-11} \Gamma^2$ ergs cm$^{-3}$ at the redshift of PKS 1127–145, where the factor $\left\langle \gamma^2/\gamma \right\rangle$ of $\int \gamma^{2-p} d\gamma/\int \gamma^{1-p} d\gamma$ characterizes the electron energy spectrum $n'(\gamma) \propto \gamma^{-p}$ with $p \sim 3$ considered hereafter, and where $V' \sim \pi R^2 l'$ is the comoving emitting volume of some cylindrical portion of the jet with the longitudinal and radial (with respect to the jet axis) dimensions $l'$ and $R$, respectively. For example, assuming the energy equipartition $U'_{\text{IC}}(r) \sim U'_{\text{IC}}(r)$ along the jet, an attenuation of the jet magnetic field $B(r) \propto r^{-k}$ (where $k > 0$), and a constant
Thus, radiative cooling of the jet electrons in PKS 1127–145 X-ray–emitting electrons occurs at the distance along the jet, photons.\[40x725]luminosity profile\[40x736]jet’s (small) opening angle\[40x506]the jet Doppler factor between knots I and C. This would imply\[40x714]spectral shape of the emitting electrons (i.e., factor \( \gamma^2 \langle \gamma \rangle \)) is roughly constant along the jet. Thus, the observed decrease of the X-ray luminosity, by a factor of 14 between knots I and C (see Fig. 9), requires \( k \approx 0.8 \) for the negligible changes in the jet Doppler factors. This, in turn, implies a decrease of the jet magnetic field by a factor of \( \approx 0.2 \) along the jet, which is the most extreme change needed, i.e., a lower limit, since some nonnegligible (although rather small) decrease of the jet Doppler factor should be expected. Indeed, if the jet Doppler factor decreases by only a factor of 2 between knots I and C, then no decrease of the jet magnetic field intensity is needed to explain the observed decrease of the X-ray (i.e., synchrotron) luminosity along the PKS 1127–145 jet. This is a much more comfortable situation than the significant amplification required by one-zone models discussed above.

In the case of the inverse Compton X-ray luminosity assuming the radiating electrons–magnetic field energy equipartition \( U'_n(r) \sim U'_e(r) \sim r^{-2k} \), one similarly gets \( L_{\text{IC}}(r) \sim r^{-2k} \delta^4(r) \), leading to the required \( k \approx 1.65 \) for the negligible changes in the jet Doppler factor between knots I and C. This would imply a significantly larger decrease of the jet magnetic field intensity than before (by a factor of 0.03), but again, any small decrease of \( \delta(r) \) along the jet can adjust required parameters.

We now check whether the observed gradual increase in the jet X-ray spectral index (i.e., when decoupled from flattening of the radio continuum) can be incorporated into the synchrotron and the inverse Compton scenarios, by means of adjusting the appropriate radiative losses and dynamical timescales. We note that at the redshift of PKS 1127–145, the comoving energy density of the jet magnetic field dominates over the energy density of the CMB radiation as measured in the jet rest frame, \( U'_B > U'_{\text{CMB}} \), if only \( B > 20 \Gamma \mu G \). This condition is difficult to fulfill, since in the case of quasar large-scale jets we expect \( \Gamma > 1 \) and \( B > 10 \mu G \). Therefore, radiative cooling of the jet electrons in PKS 1127–145 is expected to be mainly due to inverse Comptonization of the CMB photons.

The transition between slow- and fast-cooling regimes for the X-ray–emitting electrons occurs at the distance along the jet, \( r_{\text{ct}} \), where the dynamical timescale \( t'_d = r/c \) equals the radiative loss timescale \( t'_d = 3m_e c^2 / 4\sigma_T c^7 \chi U'_n(\text{CMB}) \). Here \( U'_n(\text{CMB}) = (4/3)U'_{\text{CMB}}(1+z)^{1/2} \), and the \( z = 0 \) value of the CMB energy density is \( U'_{\text{CMB}} \approx 4 \times 10^{-13} \text{ergs cm}^{-3} \). With \( \chi = (\nu / \nu'_{\text{CMB}} \delta^4)^{1/2} \), the observed X-ray photon energy \( h\nu_X \approx 1 \text{ keV} \), and the energy of the CMB photons \( h\nu_{\text{CMB}} = 0.001 \text{ eV} \) at the redshift \( z = 0 \), one can find

\[
 r_{\text{ct}} \approx \frac{9m_e c^2 \delta^{1/2}}{16 \sigma_T U'_{\text{CMB}}(1+z)^{1/2} \Gamma X} \approx 256 \Gamma^{-1} \text{ Mpc} \quad (5) 
\]

This, when compared to the projected distance of knot B at which the break in the X-ray spectrum is observed, \( r_B \approx 18'' \approx 150 \text{ kpc} \), is extremely large. In fact, it can be found that the de-projected distance of knot B equals the expected break radius only for unrealistic jet parameters. Namely, \( r_B / \sin \theta \approx r_{\text{ct}} \) (where \( \theta \) is the jet viewing angle) requires large bulk Lorentz factors of the jet and very large jet inclinations, \( 45^\circ < \theta < 90^\circ \) for \( 13 < \Gamma < 20 \), leading to the energetic problems. This means that the IC/CMB model cannot explain the observed steepening of the X-ray continuum along the PKS 1127–145 jet in terms of the spectral aging of the low-energy electrons. Instead, an \textit{intrinsic} change of the electron spectral shape (i.e., not due to the radiative cooling but particle acceleration processes) has to be invoked to explain observations, which is also the case for the synchrotron scenario (for which the analogously evaluated \( r_{\text{ct}} \) is much smaller than \( r_B \)).

### 7.3.2. \textit{A Sheath}

Now we turn our attention to the jet sheath that, by assumption, dominates the observed radio emission of the PKS 1127–145 jet. Here we investigate whether the sheath hypothesis can explain in a simple way the observed increase of the radio flux along the jet accompanied by a flattening of the radio continuum. Note first that very similar spectral (radio) behavior is in general observed in all lobes of Fanaroff and Riley type II (FR II) radio galaxies. In particular, a steepening and an attenuation of the radio emission away from the jet termination point in the direction of the nuclei observed in FR II sources is widely interpreted as a result of the spectral aging of the radio-emitting plasma (see Kaiser 2000 and references therein). In the case of the PKS 1127–145, however, we propose that the observed radio emission originates from some radial extension of the outflow rather than from the radio lobe (i.e., plasma backflowing from the jet termination hot spot). Thus, the question we should answer is why the inner jet (knots I–A) produces a very weak and steep-spectrum radio sheath, while the outer jet (knots B and C) produces a relatively bright and flat-spectrum one. (On the other hand, a strict distinction between a jet sheath and a lobe may be quite artificial, especially in the outer portions of the jet.)

We propose that the reason for the observed PKS 1127–145 jet behavior is the difference in the dominant cooling process of the radio-emitting sheath's electrons: a radiative cooling within the inner sheath (surrounding the inner jet) and an adiabatic cooling within the outer one (corresponding to the outer jet). As is well known, the frequency-independent adiabatic losses cannot significantly affect the spectral shape of the synchrotron emission, while the frequency-dependent radiative losses result in a spectral steepening above a given frequency. Such a steepening may be significant (resulting even in spectral cutoffs at low radio frequencies), depending on the detailed evolution of the radiating particles, which in turn depends on the structure of the magnetic field in the emission region. This could possibly explain a flat radio spectrum outer sheath and steep-spectrum outer sheath. In order to investigate this idea in more detail, we assume a nonrelativistic bulk velocity of the sheath plasma and inefficient particle acceleration processes acting thereby. This is rather for illustrative purposes only and an order-of-magnitude estimate, since in the observer’s rest frame the sheath material may be still moving relativistically, if only the inertia of the proper jet is big enough to ensure a relativistic advance velocity of the jet’s head. In fact, this may be the case of PKS 1127–145, which could also help us to understand the apparent lack of the countersheath on the other side of the nucleus (just like in 3C 273 as discussed in Stawarz 2004).

The radiative (synchrotron and IC/CMB at \( z = 1.18 \)) cooling timescale for the electrons emitting synchrotron photons at frequency \( \nu \) can be expressed as

\[
t_{\text{rad}} \sim \min \left( 10B_{-5}^{-3/2}, 5B_{-5}^{-1/2} \nu_{10}^{-1/2} \right) \text{ Myr}, \quad (6)
\]

where “\( \min \)” indicates a minimum of two values, \( \nu_{10} \equiv \nu / 10^{10} \text{ Hz} \) and, as before, \( B_{-5} \equiv B / 10^{-5} \text{ G} \). Meanwhile, the timescale for the adiabatic losses can be approximated as

\[
t_{\text{ad}} \sim \frac{R}{dR/dt} \approx 0.03R_{10} \beta_{ad}^{-1} \text{ Myr}, \quad (7)
\]
where \( R_{10} \equiv R/10 \) kpc, and we assumed that the sheath expansion velocity is roughly constant at a given distance from the nucleus, \( c/\beta_{ad} = dR/dt \sim \text{const.} \) Our model then requires \( t_{\text{rad}} < t_{\text{ad}} \) for the inner sheath and \( t_{\text{rad}} > t_{\text{ad}} \) for the outer one. As argued below, this may be in fact expected.

Assuming that the radio sheath in PKS 1127−145 is in a direct contact with the gaseous environment of the intergalactic medium (IGM) characterized by the particle number density \( n_p \) and temperature \( T \), the velocity of the sideways expansion for the sheath can be found as \( \beta_{ad} \sim (p_{\text{th}}/n_p m_p c^2)^{1/2} \), where \( p_{\text{th}} \) is the internal pressure of the radio-emitting (ultrarelativistic) plasma. With the minimum-power condition fulfilled within the sheath, one has \( p_{\text{ad}} \sim U_B \), and therefore \( \beta_{ad} \sim 10^{-3} B_{-5} n_{-3}^{-1/2} \), where \( n_{-3} \equiv n_p/10^{-3} \) cm\(^{-3}\). Now, for the inner sheath we assume pressure balance \( p_{\text{ad}} \sim p_0 \), where \( p_0 = n_k kT \) is the thermal pressure of IGM. This implies that the expansion of the inner sheath is happening at the sound speed, \( \beta_{ad} \sim (kT/m_p c^2)^{1/2} \), i.e., \( \beta_{ad} \sim 10^{-3} \) for the expected \( T \approx 10^7 \) K, and that the magnetic field intensity within the sheath, \( B_{-5} \sim (n_k kT/8\pi) \), is simply \( B_{-5} \sim 0.6 \text{nG} \). For the expected \( n_{-3} \lesssim 1 \) on 10–100 kpc distances from the center of the typical galaxy group environment (see, e.g., Mathews & Brighenti 2003), coinciding by assumption with the core of PKS 1127−145 radio source, our simple model interestingly gives a very realistic value, \( B_{-5} \approx 1 \), and thus the radiative lifetime \( t_{\text{rad}} \lesssim 10 \) Myr for the electrons emitting \( \gtrsim 1 \) GHz synchrotron photons. This timescale, as required, is then shorter than the expansion timescale \( t_{\text{ad}} \sim 30R_{10} \) Myr. Moreover, the obtained radiative cooling is roughly comparable to the jet lifetime at the position of knot A, which can be crudely evaluated as \( t_{\text{ad}} \approx 10 \) Myr for the jet advance velocity \( v_{\text{ad}} \approx 0.1 \) c and the assumed jet viewing angle \( 15^\circ \). Thus, a very weak (and steep-spectrum) radio emission at the position of knot A may be explained by the sheath hypothesis.

Meanwhile, farther away from the core, at the position of the outer jet, a decreased pressure of the ambient medium is likely to result in a more rapid expansion of the sheath. Namely, anticipating a relatively steep profile of the IGM density \( n_g \propto r^{-\zeta} \) with \( \zeta \gtrsim 2 \), one can expect that the thermal medium surrounding the outer sheath is as rarefied as \( n_{-3} \lesssim 0.1 \). In this case, taking \( B_{-5} \approx 1 \) as before, one obtains the adiabatic cooling timescale \( t_{\text{rad}} < 10R_{10} \) Myr, likely shorter than (or at least comparable with) the radiative timescale for the electrons emitting \( \lesssim 10 \) GHz synchrotron photons, again as required by the model. Thus, dominant adiabatic cooling can indeed result in the flat-spectrum radio emission at the position of knots B and C. It is interesting that the expansion velocity of the outer sheath in the framework of the proposed scenario is expected to be larger than the sound speed in IGM, \( \beta_{ad} > 10^{-3} \). This could possibly result in formation of a weak shock in the thermal medium that is closest to the radio structure. Further investigation of this issue, involving analysis of the X-ray environment of PKS 1127−145 radio source, is in preparation.

### 7.4. Modulated Jet Activity

The bolometric luminosity of the PKS 1127−145 nucleus, based on the observed optical-UV isotropic continuum, is about \( L_{\text{iso}} \sim 8 \times 10^{46} \text{ ergs s}^{-1} \) (Blažejowksi et al. 2004). The black hole mass determined by Fan & Cao (2004) is about \( M_{\text{BH}} \approx 7 \times 10^8 M_\odot \), which gives an Eddington luminosity of \( L_{\text{Edd}} \sim 9 \times 10^{46} \text{ ergs s}^{-1} \). Thus, PKS 1127−145 seems to accrete close to the Eddington limit, since \( L_{\text{iso}}/L_{\text{Edd}} \sim 1 \). During the jet activity epoch the quasar would then provide a total energy of

\[
E_{\text{tot}} \sim 2.5 \times 10^{58} \left( \frac{\eta}{0.01} \right) \left( \frac{t_{\text{life}}}{\text{Myr}} \right) \text{ ergs,}
\]

where \( \eta \equiv L_{\text{jet}}/L_{\text{iso}} \) is the efficiency factor of converting the accretion power into the kinetic power carried with the jet. Because the \( >200 \) kpc projected length of the PKS 1127−145 jet implies \( t_{\text{life}} > 3 \) Myr (with the speed of light providing an upper limit for the jet advanced velocity, and with the illustrative jet viewing angle of \( 15^\circ \)), the total energy transported by the jet is \( E_{\text{tot}} > 10^{56} \) ergs, assuming continuous jet activity (i.e., constant kinetic power of the outflow during the entire activity epoch).

In this context we raise an issue on the nature of the knots in PKS 1127−145: can they be considered as the extended shock waves formed within a more or less continuous jet outflow? In our opinion they cannot, since the projected linear sizes of these knots are uncomfortably large (>10 kpc). Instead, we believe that it is much more natural to consider knots I, O, A, B, and C as representing the separate portions of the jet produced by the active PKS 1127−145 core in separate epochs of its higher activity (see a discussion in Stawarz et al. 2004; Paper I). Since all of the PKS 1127−145 knots are a few tens of kiloparsecs long, the postulated duration of a continuous activity epoch would be roughly \( \sim 10^9 \) yr. It is therefore not surprising that this kind of intermittence is the most pronounced in PKS 1127−145, possessing the longest X-ray jet known.

It is interesting that the radio core of PKS 1127−145 itself has been classified as a gigahertz-peaked spectrum (GPS) source (Stanghellini et al. 1998), which are established to be young, i.e., \( \lesssim 10^8 \) yr old, versions of powerful radio galaxies (see O’Dea 1998). However, as argued by Blažejowski et al. (2004), based on the multiwavelength spectrum and the luminosity dominated by \( \gamma \)-rays, the unresolved core (at least the component producing its high-energy emission) seems to be related rather to the blazar phenomenon (in this context see also Tornikoski et al. 2001). The presence of a >200 kpc long radio/X-ray jet additionally questions the GPS nature of the PKS 1127−145 quasar. On the other hand, in the framework of the “modulated jet activity” scenario—evidenced by double-double radio galaxies (Schoenmakers et al. 1999) and postulated by Reynolds & Begelman (1997) to explain statistics of GPS sources—there may be no contradiction in the above. Namely, the blazar core of PKS 1127−145 at the moment of the observation could be considered as being again in the very active state, i.e., producing another portion of the jet matter with the enhanced kinetic luminosity. At this moment, the new born portion of the jet resembles the “classical” GPS object, but at some later time it will be observed as an extended jet “knot” (similar to the knots I, O, A, B, and C discussed in this paper).

We note that signatures of intermittent AGN jet activity have also been suggested by many recent Chandra observations of X-ray clusters (Fabian et al. 2003; McNamara et al. 2005). Typical timescales for this activity can be determined from the cluster X-ray and radio morphology, and they are within \( 10^8−10^9 \) yr depending on the source (see, e.g., Nulsen et al. 2005a, 2005b; Forman et al. 2005, 2006). A total energy of \( 10^{58}−10^{60} \) ergs contained within large radio cavities in the most powerful clusters provides an estimate of the total energy carried out by the jet and radio plasma, consistent with our estimates for the quasar PKS 1127−145.

### 8. SUMMARY AND CONCLUSIONS

The new X-ray and radio data of the PKS 1127−145 jet do not provide an unambiguous conclusion on the dominant jet X-ray emission process. It is clear that simple synchrotron or inverse Compton models do not apply and that more complex models need to be developed. However, one needs to remember that the above discussion is based on averaging X-ray and radio morphologies that do not closely match and ignoring any individual substructures that might be present in the jet. As noted at
the beginning of the discussion the PKS 1127–145 jet is about 10 times longer than the 3C 273 jet, while characteristic timescales for energy losses in both jets are similar. In addition, nearby sources (e.g., M87 or Cen A) show that jets have smaller scale structures that cannot be resolved in the higher redshift sources.

The X-ray and radio morphology and spectral properties of the PKS 1127–145 jet are similar to those of the 3C 273 jet, indicating that the 3C 273 jet is not unusual but a representative case for other quasar jets. The homogeneous one-zone (either IC/CMB or synchrotron) models are not consistent with the PKS 1127–145 X-ray and radio data, and their adiabatic versions can be rejected in general. A possible solution is a model in which the radio emission is produced within a jet sheath, while the X-rays come from the proper jet. This implies possibly a much different spectral and spatial evolution of the X-ray and radio spectra. In addition to this, we speculate that the jet intermittence also plays a role in shaping the observed jet morphology in PKS 1127–145.

One needs to remember that the two highest redshift X-ray jets known to date (GB 1508+5714, Siemiginowska et al. 2003a; GB 1745+624, Cheung et al. 2006) are faint, and the resolution scale in X-rays is of the order of ~10 kpc. Thus, the conclusions about the dominant emission processes are based on averaging over unknown jet structures. Statistical analysis of large samples of high-redshift jets may be the only method available to study jet properties and their impact on the environment in the early universe.

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