A survey of extended radio jets in AGN with Chandra and HST: First Results

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ABSTRACT

We present the first results from an X-ray and optical survey of a sample of AGN radio jets with Chandra and HST. We focus here on the first six sources observed at X-rays, in four of which a bright X-ray jet was detected for the first time. In three out of four cases optical emission from the jet is also detected in our HST images. We compare the X-ray morphology with the radio as derived from improved processing of archival VLA data and we construct spectral energy distributions (SED) for the most conspicuous emission knots. In most cases the SEDs, together with the similarity of the X-ray and radio morphologies, favor an inverse Compton origin of the X-rays. The most likely origin of the seed photons is the Cosmic Microwave Background, implying the jets are still relativistic on kiloparsec scales. However, in the first knot of the PKS 1136-135 jet, X-rays are likely produced via the synchrotron process. In all four cases bulk Lorentz factors of a few are required. The radio maps of the two jets not detected by either Chandra or HST suggest that they are less beamed at large scales than the other four detected sources. Our results demonstrate that, at the sensitivity and resolution of Chandra, X-ray emission from extragalactic jets is common, yielding essential information on their physical properties.

Subject Headings: Galaxies: active — galaxies: jets — (galaxies:) quasars: individual — X-rays: galaxies
1. Introduction

Jets are a common feature of radio-loud Active Galactic Nuclei (AGN), providing a means for powering the luminous giant radio lobes which first marked extreme activity in these systems. A detailed understanding of jet physical conditions (e.g., emission mechanisms, balance between particle and magnetic field energies, acceleration processes) requires knowing their morphologies and spectral energy distributions at various energies, hence the importance of multiwavelength imaging. However, while hundreds of kpc-scale radio jets are known (Bridle & Perley 1984), until now only a handful were detected in the optical with HST\footnote{Based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5–26555.} and ground-based telescopes (Sparks et al. 1994; Scarpa et al. 1999). Even fewer jets were known at X-ray wavelengths from Einstein and ROSAT, at limited resolution and sensitivity (Feigelson et al. 1981; Harris & Stern 1987; Biretta et al. 1991). These studies established the non-thermal nature of the multiwavelength emission of jets, attributing the smooth radio-to-optical continuum to synchrotron emission, while the X-rays were interpreted either as the high-energy tail of the synchrotron emission, or as due to inverse Compton scattering of the synchrotron photon themselves off the high energy electrons in the jet, the synchrotron-self Compton process (see Harris 2001 for a recent review).

The advent of the Chandra X-ray Observatory is opening a new chapter in the study of jets. The main features that make Chandra ideal to study X-ray emission from kpc-scale jets in AGN are its high angular resolution (0.5″ FWHM at 1 keV) and sensitivity in the 0.2–10 keV energy band. Indeed, several jets were already detected at X-rays with Chandra, a few of which were previously known from the optical (Chartas et al. 2001; Harcastle
et al. 2001; Pesce et al. 2001; Wilson et al. 2001; Worrall et al. 2001). The first surprise came from the Chandra “first light” image of the distant blazar PKS 0637–752, where a bright X-ray jet was discovered with a morphology close to the radio but with only a weak optical counterpart (Chartas et al. 2000; Schwartz et al. 2000). Canonical synchrotron or SSC models fail to reproduce adequately the radio-to-X-ray spectral distribution of the jet. The latter is instead well explained by a model invoking inverse Compton scattering of the cosmic microwave background photons (IC/CMB) off the jet electrons (Tavecchio et al. 2000; Celotti et al. 2001). The attractiveness of this model is that it accounts successfully for the shape of the X-ray spectrum of PKS 0637–752, and yields minimum estimates for the jet kinetic power. The IC/CMB model was applied successfully to explain the X-ray emission of other jets (Chartas et al. 2001; Sambruna et al. 2001).

The detection of the PKS 0637–752 jet and its unexpected properties raised several questions. In particular: is PKS 0637–752 an exceptional object or are X-ray and optical emission a common feature of extended radio jets in AGN? What is the role of the IC mechanism as opposed to the synchrotron mechanism in accounting for the large scale X-ray emission of jets?

To address these questions, we obtained Chandra (cycle 2) and HST (cycle 9) time to perform a survey of 17 carefully selected radio jets, to find their X-ray and optical counterparts and start addressing their physical properties. Given the sensitivity of both Chandra and HST, and the selection criteria of our jet sample (see below), this survey represents an unbiased probe of the occurrence of X-ray and optical emission from extragalactic jets in AGN. We also have a program to image these jets uniformly at radio wavelengths using the VLA, VLBA, and MERLIN (Cheung et al. 2002).

In this paper, we present the results of the first six objects observed with Chandra. We focus on the X-ray counterparts of the extended radio features, leaving the discussion of the
nuclear properties to a future paper (Gambill et al. 2002). We find a high detection rate of
the jets at X-rays, with four out of six objects showing a bright X-ray jet with complex and
different morphologies. Three out of these four X-ray jets also have optical counterparts in
our HST images. While the HST results will be fully presented in a future paper (Scarpa et
al. 2002), here we use optical fluxes extracted from the HST images. The remaining jets of
the survey will be presented in a future publication.

The plan of this paper is as follows. In § 2 we review the sample selection criteria, the
observations and the data analysis, in § 3 we present the results for the six Chandra targets,
including a comparison with the radio data, and in §§ 4 and 5 we discuss the implications.
Throughout this work, $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$ are adopted. Spectral indices
are defined as $F_\nu \propto \nu^{-\alpha}$.

2. Observations

2.1. Sample Selection

The targets of the program were selected from the radio, without any \textit{a priori}
knowledge of their optical and X-ray emission properties. In this sense our survey is
unbiased toward detections at shorter wavelengths.

Specifically, the survey sample was extracted from the list of known radio jets of Bridle
& Perley (1984) and Liu & Xie (1992), according to the following criteria: 1) The radio
jet is $\gtrsim 3''$, i.e., long enough to be easily resolved with Chandra and HST; 2) The radio
jet has radio surface brightness $S_{1.4 \text{ GHz}} \gtrsim 5\text{ mJy/arcsec}^2$ at $> 3''$ from the nucleus, i.e.,
bright enough to be detected in reasonable Chandra and HST exposures for average values
of the radio-to-X-ray and radio-to-optical spectral indices, $\alpha_{rx} \sim 0.8$ and $\alpha_{ro} \sim 0.8$; and
3) High-resolution (1'' or better) published radio maps show that at least one bright ( $\gtrsim 5$
mJy) radio knot is present at > 3″ from the nucleus. These criteria gave a sample of 17 radio jets, spanning a range of redshifts, core and extended radio powers, and classification (quasar, BL Lac, radio galaxy). However, most sources show one-sided jets, indicating substantial beaming.

The awarded exposures were 10 ks per target with Chandra ACIS-S (occasionally, targets were observed for slightly more or less than 10 ks to accommodate gaps in the Chandra schedule) and one orbit per target with HST. The X-ray flux limit for a 2σ detection in a typical 10 ks ACIS-S observation is $F_{0.4-8\,\text{keV}} \sim 2 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. It is important to note that the short Chandra and HST exposures were designed to find the X-ray/optical counterpart of the radio jet, but are not sufficient for a detailed study of their morphologies and spectra.

Here we report the results for the first six observed sources: 0723+679, 1055+018, 1136−135, 1150+497, 1354+195, and 2251+134. Their basic properties, reported in Table 1, are representative of the whole sample. A bright X-ray jet was detected in 0723+679, 1136−135, 1150+497, and 1354+195. Except for 0723+679, an optical counterpart to the X-ray jet is present as well in the HST images.

### 2.2. Data Reduction and Analysis

The Chandra observations were performed with ACIS-S, with the source at the aimpoint of the S3 chip. As most sources have bright X-ray cores, to reduce pileup of the nucleus (which can affect the study of the jet inner regions) we used a 1/8 subarray mode with only the S3 chip turned on, giving an effective frametime of 0.4 s. Nevertheless, the core X-ray flux of 1354+195, 1055+018, 1136−135, and 1150+497 was still piled-up, as suggested by the observed count rates of the cores (Gambill et al. 2002). The fraction
of core pileup is $\gtrsim 5\%$, according to the measured counts/frame ($\gtrsim 0.27 \text{ c/frame}$) and Figure 6.25 of the Chandra Proposers Observatory Guide (Rev. 3.0, December 2000). In addition, for each source a range of roll angles was specified in order to locate the jet away from the charge transfer trail from the nucleus and avoid flux contamination. The Chandra data were reduced following standard screening criteria and using the latest calibration files provided by the Chandra X-ray Center. Pixel randomization was removed, and only events for ASCA grades 0, 2–4, and 6 and the energy range 0.4–8 keV, where the background is negligible and the ACIS-S calibration best known, were retained. We also checked that no flaring background events occurred during the observations. After screening, the effective exposure times range between 9–11 ks (Table 2).

Several knots were detected at X-rays in the Chandra images (Table 2). X-ray counts from each knot were extracted in a circular region of radius 1″, with the background estimated in a circular region of radius 8″ at a nearby position free of serendipitous X-ray sources. The source extraction radius of 1″ encircles $\gtrsim 90\%$ of the flux at 1 keV, based on the ACIS-S encircled energy fraction (Fig. 6.3 in the Chandra Proposer Observatory Guide).

Let $S$ be the total (before background subtraction) counts in the source area $A_S$, and $b$ the background counts in the area $A_B$. The background counts rescaled to the source region are $B = b \times A_S/A_B$. The net counts of the source are thus $N = S - B$. The uncertainties on the net X-ray counts, $\sigma_N$, were calculated according to the formula $\sigma_N = \sqrt{(\sigma_S)^2 + (\sigma_B)^2}$, where $\sigma_S$ and $\sigma_B$ are the uncertainties on the source and background, respectively. The latter were calculated following Gehrels (1986), as appropriate in a regime of low counts: $\sigma_S = 1 + \sqrt{S + 0.75}$ and $\sigma_B = (1 + \sqrt{b + 0.75}) \times (A_S/A_B)$.

For all the radio features not detected in the Chandra images, we estimated the 3σ upper limits to the X-ray flux. These were extracted in a 1″-radius region centered on the
radio position of the knot, with the background estimated as discussed above. In the cases of the non-detected jets of 2251+134 and 1055+018, rather than quoting upper limits for each individual radio feature, we give a total upper limit integrated over the whole jet emission.

In the cases of 1150+497 and 1354+195, available radio images show the presence of jet knots at \( \sim 2'' \) from the core. At this distance, the Chandra PSF of the X-ray core is non-negligible, given the bright core emission of the two sources (Fig. 3 and 4). Inspection of the X-ray maps of 1150+497 and 1354+195, however, shows enhancements of the flux above the PSF wings at the position of the inner radio knots, suggesting possible X-ray emission of the knots. These were denominated “knots A” in Table 2 for both sources. To derive their net X-ray flux, we adopted the following procedure. We extracted the counts from a circular aperture of radius 1'', centered on the radio position of the knot. To subtract the contribution of the PSF, the background was evaluated in a circular region with the same radius and at the same distance from the nucleus, but at various azimuth angles. We find that the net (background-subtracted) counts vary by as much as 30% depending on the background region, suggesting local disuniformities of the core PSF most likely due to the fact that significant pileup affects the PSF in both sources. Given the large excursion of values, the counts reported in Table 2 for knots A of 1150+497 and 1354+195 are simple average values, while the uncertainties are their standard deviations. Thus, they represent rather conservative uncertainties for the X-ray fluxes of these knots.

We also analyzed archival radio images at 5 GHz from the Very Large Array\(^2\) database (Thompson et al. 1980). Data for 1055+018, 1136–135, and 1354+195 were retrieved from the VLA archive at NRAO and calibrated in AIPS using standard procedures. The data

\(^2\)The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
were taken from programs AM213 (17 Aug 1987), AE59 (30 Oct 1988), and AB331B (20 Apr 1985), respectively. To the best of our knowledge, these data are unpublished. The images of 0723+679 and 1150+497 were published originally by Owen & Puschell (1984) and have been reimaged by us using calibrated (u,v) data kindly provided by F. Owen. The image of 2251+134 was reimaged from data originally published in Price et al. (1993).

We chose to restore the radio images of the X-ray detected knots using circular beams with FWHM=0.86″ in order to match the resolution of the final smoothed Chandra images. The two images of the non-detected jets were restored with circular beams with FWHM=1.5″ for 1055+018 and 1.5″ for 2251+134. More details will be given in Cheung et al. (2002).

*HST* observations were performed with STIS in CLEAR mode, with an effective wavelength of 5852 Å. The calibration used for flux extraction is based on the keyword \texttt{PHOTFLAM}=8.97 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{2} \text{ Å}^{-1} \text{ count}^{-1}, corresponding to 1.08 \times 10^{-7} \text{ Jy/count s}^{-1}. The *HST* observations will be the subject of a separate paper (Scarpa et al. 2002).

Upper limits to the optical flux for extended radio features (counterlobes) in each object were calculated using measurements of the background surface brightness in the corresponding *HST* images. The surface brightness measurements were converted to fluxes assuming a square aperture with an area of 1 arcsec$^2$. For undetected optical counterparts to radio jet knots, we estimate conservatively a 3σ upper limit of 0.06 μJy. This limit is based on the fact that the weakest detected jet knots in our *HST* images were 0.02 μJy (one in 1150+497 and two in 1040+123; Scarpa et al. 2002). Since the background signals in all our *HST* images were comparable, we took 0.02 μJy as a conservative estimate for the detection limit of any undetected knots for all the sources. The expected/observed optical positions

\footnote{The flux scale of this experiment was based on contemporaneous measurements of 0727–115 (4 Jy) obtained from the University of Michigan on-line database (the average of three measurements within one week of the archival VLA observation).}
of most jet features in these objects place them reasonably well away from contamination by light from their host galaxies, except in the cases of 0723+679 and 2251+134. For selected features in these two objects (the counterlobe and jet, respectively), we measured the Poissonian noise directly in galaxy subtracted images within a circular aperture with radius 1′′ coincident with the expected positions of the features. We expect the jet knots in 0723+679 to be compact enough that they would have manifested themselves above the smooth galaxy profile, therefore, the 3σ upper limit of 0.06 µJy was applied to them.

3. Results

Figures 1–5 show the *Chandra* ACIS-S images of the six sources (color scale). The detected X-ray jets are plotted in Fig. 1–4 while Fig. 5 shows the sources where the jets were not detected (1055+018 and 2251+134). The X-ray images were produced by smoothing the raw *Chandra* data with a Gaussian of width=0.3″ in the energy range 0.4–8 keV, with final resolution of 0.86″ FWHM. Overlaid on the X-ray images are the radio contours from the archival VLA data, smoothed to the same (for the detected X-ray jets) resolution as *Chandra*. In the four sources in Figure 1–4 (0723+679, 1136–135, 1150+497, and 1354+195), an X-ray counterpart to the radio jet is clearly detected, with knotty and widely different morphologies. Their properties are given in Table 2: distance from the core, Position Angle (PA), and net X-ray counts. We stress that the nomenclature adopted in Table 2 is X-ray driven and does not reflect the previous nomenclature of the radio knots. The apparent (projected) jet lengths vary from 6.7″ (33 kpc) in 1136–135 to 27″ (145 kpc) in 1354+195. The jets are not resolved in a direction perpendicular to their axes.

A summary of the X-ray and radio properties is given below for each detected jet.

**0723+679**: A bright X-ray knot (B) is detected at 6.3″ from the nucleus, with a weaker
one (A, 1.6σ detection) at 4.3″. Both coincide with radio knots in the VLA radio map (Owen & Puschell 1984). The jet appears to bend after the first knot. Faint X-ray emission is also visible from the hot spot of the extended radio counter-lobe, with the peak of the X-ray emission being displaced from the peak of the radio emission by ~ 1″. On the whole, the jet X-ray and radio brightnesses track each other very well. There is no indication in the HST image of an optical counterpart to any of the extended radio or X-ray features. The X-ray core exhibits interesting spectral properties, including an Fe Kα emission line (Gambill et al. 2002).

1136–135: Two X-ray knots are detected at 4.5″ (A) and 6.7″ (B) from the nucleus; both have a bright optical counterpart in our HST images. Knot A has an extremely weak radio counterpart; knot B, the brightest in X-rays, has a relatively weak radio counterpart (Saikia et al. 1989). Overall, after knot B, the X-ray and radio brightnesses along the jet behave oppositely, with the X-rays peaking at ~ 7″ from the core, in correspondence to a secondary peak in the radio, while the radio emission peaks at 10″ at knot C, for which we can set only an upper limit in X-rays.

1150+497: The X-ray jet has at least three bright knots at 2.1″ (A), 4.3″ (B), and 7.9″ (C) from the core. The final knot coincides with a terminal hot spot in the radio image. As shown by the PA in Table 2, the X-ray jet wiggles by ∆PA ~ 20 degrees, following closely the radio (Owen & Puschell 1984). All the three X-ray knots have an optical counterpart in our HST images.

1354+195: This spectacular, well-collimated X-ray jet is also the longest one in our sample, extending up to 27″ (145 kpc projected length). It consists of a string of nine X-ray knots, closely tracing the radio morphology (Murphy, Browne, & Perley 1993). X-ray emission is also present from the southern radio hot spot (knot I), which appears misaligned with respect to the jet axis by ∆PA ~ 10 degrees, and off-center by 2″ with respect to its
radio counterpart. Only inner knots A and B have optical counterparts in our HST images. Knot I is off the HST field of view and its optical counterpart is not known.

Table 3 gives multiwavelength information for the jets, in the form of radio (5 GHz), optical (5852 Å), and X-ray (1 keV) fluxes for the various knots, and the derived broad-band spectral indices: radio-to-optical $\alpha_{ro}$, optical-to-X-ray $\alpha_{ox}$, and radio-to-X-ray $\alpha_{rx}$. Fluxes at radio and optical wavelengths were extracted using the same $1''$ circular regions as for the X-rays. The X-ray fluxes were obtained from the the counts in Table 2 assuming a power law with photon index $\Gamma = 2.0$ and absorbing column density fixed to the Galactic value. No correction for reddening was applied to the optical fluxes; however, this correction is negligible compared to the large uncertainties of the optical fluxes. We also list 3$\sigma$ upper limits (see discussion above) for the radio knots that were not detected at optical or/and X-rays, and for the counterlobes (CL).

4. Interpretation

4.1. General constraints from the radio and X-ray morphologies

X-rays from extended radio jets in AGN can derive from different processes. Non-thermal mechanisms, suggested by the presence of relativistic electrons necessary to account for the radio emission, include synchrotron radiation (from the high-energy end of the electron population), or inverse Compton scattering processes, with the seed photons provided by the synchrotron photons themselves (SSC) or by external radiation fields. Recently, Tavecchio et al. (2000) and Celotti et al. (2001) showed that if the plasma is still relativistic on large (10 kpc or more) scales, the dominant source of seed photons is the cosmic microwave background (CMB). In fact, the CMB radiation density is amplified in the comoving frame of the emitting plasma by a factor $\Gamma^2$, where $\Gamma$ is the bulk Lorentz
factor of the jet. The resulting X-ray emission is strongly beamed. As shown by Dermer (1995; see also Brunetti et al. 2001) the emission cone of this radiation is narrower than that of the synchrotron emission. In this case the relative importance of the X-ray emission depends on the viewing angle, being greater for small angles.

In this IC/CMB model, we expect the X-ray and radio morphologies of the jet to be generally similar, as emission at both wavelengths is produced by electrons in similar, relatively low, energy ranges ($\gamma_X \sim 100$, $\gamma_{\text{radio}} \sim 1000$). However, differences in the X-ray-to-radio brightness ratio can arise from, and give information on, changes in magnetic field and/or bulk Lorentz factor (deceleration) along the jet.

If X-rays are due to synchrotron emission, the radiating electrons must have very high energies, a factor $\simeq 10^4$ larger than those emitting in the radio and with correspondingly shorter lifetimes by the same factor. Thus, electrons producing X-rays may cool rapidly after the acceleration region, while radio electrons can survive and diffuse in regions further away from the acceleration sites. The expectation for the jet morphology is then that the X-ray emission should peak before the radio. Inspection of Figure 1–4 shows that, in the cases of 0723+679, 1150+497, and 1354+195, the X-ray and radio morphologies are very close, suggesting that the X-ray emission from these jets is due to IC/CMB. The fourth jet, 1136–135, is a complex case. Knot A is bright at X-rays and in optical, but does not have a strong radio counterpart. Knot B is bright at all three wavelengths, while knot C at the end of the jet is bright only at the longer wavelengths. This suggests that different emission processes for the X-rays may dominate at different locations along the 1136–135 jet.
4.2. Spectral Energy Distributions

Complementary and more easily quantifiable information is provided by the spectral energy distributions (SED) of bright emission regions in the jet. These can be derived for a given knot extracting fluxes from the same spatial region around the knot at the various wavelengths.

In interpreting the SED, a critical role is played by the optical flux. Specifically, if the optical emission lies on the extrapolation between the radio and X-ray fluxes or above it, the SED is compatible with a single electron spectrum extending to high energies; instead, if the optical emission falls well below the extrapolation, it argues for different spectral components (and therefore different mechanisms unless two electron populations are hypothesised) below and above the optical range (e.g., synchrotron and IC respectively). Thus, in all knots where IC/CMB dominates the X-ray emission, we expect an up-turn of the spectrum in the X-ray band with respect to the radio-optical extrapolation and thus an optical-to-X-ray index $\alpha_{ox}$ flatter than the radio-to-optical index $\alpha_{ro}$. Conversely, when synchrotron dominates we expect $\alpha_{ro} \lesssim \alpha_{ox}$, with the inequality holding when radiative losses are important in the X-ray band.

Figure 6 shows the plot of the broad-band indices, $\alpha_{ro}$ versus $\alpha_{ox}$, from the data in Table 3. The dotted line marks the locus of points for which $\alpha_{ro} = \alpha_{ox}$. It can be seen that most knots lie in the region $\alpha_{ro} > \alpha_{ox}$, except for knot A in the jet of 1136–135 (Table 3). This behavior is well consistent with the morphological properties discussed above.

To investigate more quantitatively the jet physical properties, we computed synchrotron and IC/CMB emission models reproducing the SEDs of the most conspicuous knots. We note that with only three observed fluxes the models are underconstrained. Following the procedure of Tavecchio et al. (2000), we assume the flux extraction radius is the size of the (spherical) emission region and compute for what values of the magnetic field, $B$, and of the
beaming factor, $\delta$, it is possible to reproduce the radio and X-ray fluxes. As an example, the results for 1150+497 (knot B) are shown in Figure 7a. The dotted line represents the condition of energy equipartition between high-energy electrons and magnetic field, as derived from the synchrotron radio emission, which is the same for all models. The dashed and continuous lines represent the appropriate values of $B$ and $\delta$ for the SSC and IC/CMB models, respectively. It is clear from Figure 7a that SSC models require either no beaming or substantial debeaming (implying a very high power of the jet) and come close to equipartition only for very large values of $B$ and large debeaming, while IC/CMB models meet the equipartition line at reasonable values of $B$ and moderate values of $\delta$. We thus favor the latter and adopt equipartition as an additional constraint to fix the model univocally.

In the cases where X-rays are attributed to direct synchrotron emission, there is no “independent” constraint from the X-ray flux and only the equipartition assumption survives. In Fig. 7b we show the synchrotron constraints for knot A of 1136–135. We also plot the radiative lifetime of the X-ray emitting electrons as an additional criterium (see below).

Guided by the above parametric analysis, specific models were computed to reproduce the SEDs of X-ray knots A and B of each detected jet with synchrotron plus IC/CMB emission and assuming equipartition. The results are shown in Figure 8 and the derived parameters, for the electron spectrum, the beaming factor, $\delta$, and the magnetic field, $B_{\text{equip}}$, are reported in Table 4. The upper and lower limits of the electron spectrum, $\gamma_{\text{max}}$ and $\gamma_{\text{min}}$, determine the high energy cut-off of the synchrotron component and the

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$^4$The beaming factor $\delta$ is here defined as $\delta \equiv \left[\gamma(1 - \beta \cos \theta)\right]^{-1}$, where $\beta$ is the bulk velocity of the plasma in units of the speed of light, $\gamma = (1 - \beta^2)^{-1/2}$ the corresponding Lorentz factor, and $\theta$ the angle between the velocity vector and the line of sight.
low energy cut-off of the IC/CMB component, respectively. These two cut-offs are crucial in determining the SED in the intermediate IR-optical-UV-soft X-ray ranges, a region presently not constrained by the data. In all cases we used $\gamma_{\text{min}} = 10$.

For three of the X-ray jets (0723+679, 1150+497, and 1354+195) the favored X-ray emission process is IC/CMB. Optical emission can be attributed either to synchrotron or to IC/CMB processes, depending on the value of $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$. Clearly, only the optical spectrum can constrain these two parameters and discriminate between the synchrotron and IC/CMB models. Observations with HST at different wavelengths are needed to this purpose.

In the case of knot A of 1150+497 and knots A and B of 1354+195, we reproduce optical emission with the synchrotron component, while for knot B in 1150+497 we assume that the dominant process is IC. Consider the case of 0723+679. We have only an upper limit for the optical emission which constrains the synchrotron component to cut off before the optical range. Any optical emission at the level of the present upper limit could be due either to the high-energy tail of the synchrotron component (slightly higher $\gamma_{\text{max}}$) or to the low-energy end of the IC component (slightly lower $\gamma_{\text{min}}$).

The case of 1136–135 is different. As discussed above, this jet appears to have a “mixed” morphology, and indeed the SEDs of the two brightest X-ray knots differ (Fig. 8). For knot A, where $\alpha_{\text{ro}} \lesssim \alpha_{\text{ox}}$, we suggest that synchrotron emission is a plausible emission process. Still, the emitted radiation should be beamed ($\delta \sim 7$ for $B_{\text{equip}} \sim 10 \mu\text{Gauss}$; Table 4), or the magnetic field would be implausibly high and/or the relativistic plasma far from equipartition (Fig. 7b). Assuming a magnetic field of $B = 10 \mu\text{Gauss}$, the cooling time of the electrons in the knot is $\sim 10^{11}$ s. This is consistent with the light-crossing time for knot A, assuming its radius is 1". Thus, high-energy electrons can cool before they reach knot B, in agreement with the SED. Note that the associated IC/CMB component is only a factor
\[ \approx 3 \] below the synchrotron one.

For knot B in the same jet, clearly \( \alpha_{ro} > \alpha_{ox} \) and IC/CMB should be the main emission process. The X-rays fading further out and the increasing radio brightness should then be attributed to a deceleration of the relativistic plasma and to a compression of the magnetic field, as expected at the outer boundary of jets (e.g., Gómez 2001).

In summary, for the knots of the 0723+679, 1150+497, and 1354+195 jets, the IC/CMB scenario is the favored process for the X-ray emission, both from the comparison of the radio and X-ray morphologies and a more quantitative analysis of the SEDs. The model is consistent with equipartition for moderate values of the beaming factor (\( \delta \sim 5 - 6 \)), with \( B_{\text{equip}} \sim (2 - 10) \times 10^{-5} \) G. The SSC model requires in general conditions very far from equipartition and larger intrinsic powers in the jet (\( P_j > 10^{49} \) erg s\(^{-1}\)). On the other hands, the 1136–135 jet shows that various emission processes may dominate the X-ray production at different locations in the jet. This could be due to a different maximum energy to which the electrons are accelerated.

### 4.3. Jet Power

The last two columns of Table 4 list the jet intrinsic power, calculated assuming the parameters from the models, and the total radiated jet power, i.e., the observed power integrated over the whole solid angle (e.g., Sikora et al. 1997). Comparison of the two powers shows that only a small fraction of the jet kinetic power is dissipated into radiation. This implies small radiative efficiencies and that most of the energy extracted from the central black hole is stored in the bulk motion of the plasma. There have been suggestions (e.g., Ghisellini & Celotti 2001) that jet radiative efficiency decreases with increasing jet luminosity. While based on a very limited sample,
it is interesting to note that, with the exception of 1136–135, the X-ray detected jets lie at the higher-luminosity end of the distribution of jet radio luminosity in Table 1. Clearly, confirmation of this result awaits completion of our survey.

4.4. The non-detections

Two radio jets of the survey, 1055+018 and 2251+134, were not detected at either X-rays and optical (Fig. 5). Since their radio fluxes are comparable to those of the 4 detected jets, there must be some intrinsic differences responsible for their low X-ray emission.

A possible explanation could simply be an overall steeper electron spectrum. This idea could be easily verified by acquiring multifrequency radio observations. Alternatively, their large scale jets may be non-relativistic or seen at larger angles. Note that indeed the radio maps do not appear strongly asymmetric and the upper limits to their jet-to-counterjet ratios are smaller than in the other four cases (Table 1). However, it is also true that their core-to-extended radio flux ratio is very high, suggesting that the core is beamed. It is tempting to suggest that in these objects the jet decelerates not far from the core so that it is relativistic on pc scale but non-relativistic on larger scales. In this case, since a large part of the jet power must be dissipated in the inner part of the jet, one naturally expects that the outer jet is faint, contributing to enhance the value of the core-to-extended radio flux ratio. High-resolution, multi-epoch radio observations could in principle verify this scenario by providing a measure of the apparent bulk speed in the jet inner regions.
5. Discussion

As stressed above, the IC/CMB model works only if the plasma still has bulk relativistic motion ($\Gamma >> 1$) on kpc scales and the viewing angle is small ($\theta \lesssim \Gamma^{-1}$). Independent evidence for large bulk velocities on kpc scales in the jets of our sample where the IC/CMB process works at X-rays is provided by the radio, for which the 4 X-ray detected jets have especially large ratios of the jet-to-counterjet flux (Table 1). Some previous jet studies with ultra-deep VLA observations have provided statistical evidence that jets generally decelerate on kpc scales, with $\delta \sim$ a few (Wardle & Aaron 1997). Our results, however, are not necessarily in disagreement, because our selection criteria biases us toward the more beamed jets and, as Table 4 shows, only moderate beaming is required from our models. A picture where jets have a fast “spine” which produces the X-ray radiation, and slow walls from which the longer-wavelength radiation originates, as advocated by many authors (e.g., Sol, Pelletier, & Asseo 1989; Laing 1993; Owen et al. 1997; Wardle & Aaron 1997; Chiaberge et al. 2000), may be more realistic. While more complex emission models should then be used, the present data would be insufficient to constrain them.

Another possible scenario for the X-ray production from jets (Celotti et al. 2001) is IC scattering of the beamed emission from a blazar nucleus, which according to unification models is harbored by every radio-loud AGN (Urry & Padovani 1995). However, this process is likely to be unimportant if the jet plasma is still relativistic on large scales. In fact, in this case, the beamed photons from the inner jet appear redshifted in the plasma rest-frame, thus energetically unimportant.

On the other hand, IC scattering of the nuclear radiation could be important for the X-ray emission from radio lobes where the plasma reaches slower terminal velocities (Brunetti et al. 1997). This process could possibly explain the X-ray emission from the counterlobe of 0723+679, where a marginal detection is obtained from the short Chandra
exposure (Table 2 and Figure 1). In this model, since the up-scattered photons are beamed back toward the nucleus, only the counterlobe (i.e., the lobe opposite along the line of sight) is enhanced, as is indeed the case in 0723+679.

An alternative possibility for the production of X-rays from large-scale jets is the class of hadronic models, where the X-rays are direct synchrotron radiation of ultra-relativistic protons (Aharonian 2001). This model predicts a smooth optical-to-X-ray continuum spectrum if the protons are responsible for the longer wavelengths as well, which can be tested with future UV observations. It also requires much higher magnetic fields (∼mGauss) and much more efficient acceleration processes than in the leptonic models.

In conclusion, analysis of the SEDs of the various jet knots yields results which are consistent with the indications inferred from the radio/X-ray morphologies. Thus, the shape of the SEDs and the multiwavelength jet morphologies are powerful indicators of the physical mechanisms operating in the jet. Importantly, different processes may predominate at various locations in the jet for the production of X-rays, depending on the local physical conditions.

It is also worth remarking a few caveats affecting our analysis. First, the limited signal-to-noise ratio at both X-ray and optical wavelengths gives room to alternative interpretations of the SEDs. Second, a variety of conditions may exist within the relatively large extraction regions we used (1″, dictated by the Chandra resolution), for example if the emitting particle distributions are stratified or multiple shocks exist. While higher angular resolutions at X-rays await future generations of space-based telescopes, deeper follow-up X-ray and optical observations of the new jets of this survey with Chandra and HST can at least remedy the first limitation of our analysis, in providing higher quality images, smaller uncertainties on the fluxes, and X-ray and optical continuum spectra for individual knots. Note that optical observations are necessary to identify the mechanism
responsible for the X-ray emission. An additional important constraint will be provided by future IR observations with SIRTF, probing a poorly known region in the SEDs where the synchrotron peak is located.

6. Conclusions

In summary, we presented the detection of four new X-ray extragalactic jets with Chandra from our X-ray/optical survey, strengthening the evidence that X-ray emission from the kpc-scales of these structures is common. The new X-ray detections of jets imply the presence of relativistic bulk motion on very large scales, at tens to hundreds of kpc from the central black hole, setting new challenges for theoretical models. X-ray emission is produced in localized regions, likely shocks associated with the deceleration of the jet. Furthermore, our data show that different emission processes for the X-rays may dominate in the same jet at different locations, depending on the local physical conditions (e.g., the maximum electron energy, $\gamma_{\text{max}}$). Future deeper images at both X-ray and multiple optical frequencies will be essential to explore in greater detail the energetics and physical properties of the jets.

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Figure Captions

Figure 1: *Chandra* ACIS-S image in the 0.4–8 keV energy range of the newly discovered X-ray jet of 0723+679 (colors). Overlaied are the radio contours from archival VLA data. Both the colors and the contours are plotted logarithmically, in steps of factor 2. The *Chandra* image is smoothed with a Gaussian of width $\sigma=0.3''$, yielding a resolution of 0.86'' FWHM. The radio image was restored with a circular beam with FWHM=0.86''. The base level for the radio contours is 0.6 mJy/beam. In the image, 1'' corresponds to 5.5 kpc.

Figure 2: Same as for Figure 1, but for 1136–135. The base level for the radio contours is 0.8 mJy/beam. In the image, 1'' corresponds to 4.9 kpc.

Figure 3: Same as for Figure 1, but for 1150+497. The base level for the radio contours is 0.7 mJy/beam. In the image, 1'' corresponds to 3.9 kpc.

Figure 4: Same as for Figure 1, but for 1354+195. The base level for the radio contours is 0.9 mJy/beam. In the image, 1'' corresponds to 5.4 kpc.

Figure 5: *Chandra* ACIS-S images in the 0.4–8 keV range of 1055+018 and 2251+134, for which no X-ray or optical jet was detected. Overlaied are the radio contours from archival VLA data. Both the colors and the contours are plotted logarithmically, in steps of factor 2. The *Chandra* images were smoothed with a Gaussian of width $\sigma=0.3''$, yielding a resolution of 0.86'' FWHM. The radio maps were restored with a circular beam with FWHM=1.5'' for 1055+018 and 0.86'' for 2251+134. The base level is 0.5 mJy/beam and 1 mJy/beam for 1055+018 and 2251+134, respectively. In the images, 1'' corresponds to 5.6 kpc for 1055+018 and 5.3 kpc for 2251+134.

Figure 6: Radio-to-optical index, $\alpha_{ro}$, versus the optical-to-X-ray index, $\alpha_{ox}$, for individual knots in the four newly detected X-ray jets. The dotted line marks the division between knots where inverse Compton dominates over synchrotron for the production of X-rays.
Most X-ray knots are unlikely to be due to synchrotron emission from the high-energy tail of the radio-emitting electron distribution.

Figure 7: (a) Allowed values of magnetic field and Doppler beaming factor for knot B of 1150+497. Solid line: allowed values if the X-rays come from inverse Compton scattering of cosmic microwave background photons (the IC/CMB model). Dashed line: allowed values of $B$ and $\delta$ if the observed X-ray emission is produced by a synchrotron self-Compton model. Dotted line: allowed values of $B$ and $\delta$ under the assumption of equipartition between radiating particles and magnetic field assuming that the low energy cut-off of the electron distribution is $\gamma_{\text{min}} = 10$. The IC/CMB emission can clearly be consistent with equipartition assumption for moderately large values of the Doppler factor ($\delta \sim 6 - 7$). (b) Allowed values of magnetic field and Doppler beaming factor for knot A of 1136–135 from the synchrotron model. Solid line and left vertical axis: Values of the Doppler factor $\delta$ as a function of the magnetic field $B$ assuming equipartition between emitting electrons and magnetic field. Dashed line and right vertical axis: Cooling time for synchrotron emission of electrons producing 1 keV photons for different values of the magnetic field and assuming the equipartition value for $\delta$.

Figure 8: Radio-to-X-ray Spectral Energy Distributions (SEDs) for the brightest X-ray knots in the four new X-ray jets of Figure 1–4. In all panels, the left-handed vertical axes are in units of observed flux, $\nu F_\nu$, while the right-handed axes are in units of luminosity, $\nu L_\nu$. Typical uncertainties on the fluxes are 33% or larger. The X-ray flux is always above the extrapolation from the radio-to-optical continuum, except for knot A in 1136–135, suggesting a general dominance of inverse Compton for the production of X-rays. In knot A of 1136–135, synchrotron is likely the dominant process. The solid lines are the best-fit models (sum of all components), with the parameters reported in Table 4.
Table 1: The Sample

| Source     | Alt name | z   | Type      | logP_{core} | logP_{jet} | R_i | J | N_{Gal}^{HI} |
|------------|----------|-----|-----------|-------------|------------|-----|---|--------------|
| 0723+679   | 3C 179   | 0.846 | FSRQ      | 33.88       | 33.56      | 0.5 | > 21        | 4.31         |
| 1055+018   | 4C +01.28| 0.888 | FSRQ/BL   | 34.76       | 33.15      | 16.5| > 3         | 3.40         |
| 1136–135   | PKS      | 0.554 | FSRQ      | 33.50       | 33.46      | 0.30| > 10        | 3.59         |
| 1150+497   | 4C +49.22| 0.334 | FSRQ      | 33.04       | 32.39      | 2.30| > 16        | 2.05         |
| 1354+195   | 4C +19.44| 0.720 | FSRQ      | 34.35       | 33.43      | 2.80| > 56        | 2.18         |
| 2251+134   | 4C +13.85| 0.673 | QSO       | 33.81       | 33.29      | 1.13| > 14        | 4.98         |

**Explanation of Columns:**
1=Source IAU name; 2=Alternate name; 3=Redshift; 4=Optical/radio classification of core.
FSRQ: Flat Spectrum Radio Quasar; BL: BL Lac; QSO: Lobe-dominated Quasar; 5=Log of the core power at 5 GHz (in erg s\(^{-1}\) Hz\(^{-1}\)); 6=Log of the jet power at 5 GHz (in erg s\(^{-1}\) Hz\(^{-1}\)); 7=Ratio of core to extended radio power at 5 GHz, corrected for the redshift (observed value divided by (1+z)); 8=Ratio of the jet-to-counterjet radio flux (see text for references); 9=Galactic column density in 10\(^{20}\) cm\(^{-2}\).
Table 2: Chandra observations

| Source   | Exposure | Knot | Distance | PA | Counts |
|----------|----------|------|----------|----|--------|
| 0723+679 | 9334     | A    | 4.3      | 263| 6 ± 4  |
|          |          | B    | 6.3      | 274| 18 ± 5 |
|          |          | CL\(^a\) | 8.0 | 75 | 4 ± 3  |
| 1055+018 | 9314     | ⋮    | ⋮        | ⋮  | ⋮     |
| 1136–135 | 8906     | A    | 4.5      | 295| 22 ± 6 |
|          |          | B    | 6.7      | 295| 59 ± 9 |
| 1150+497 | 9294     | A    | 2.1      | 210| 72 ± 22\(^b\) |
|          |          | B    | 4.3      | 190| 27 ± 6 |
|          |          | C    | 7.9      | 195| 17 ± 5 |
| 1354+195 | 9056     | A    | 1.7      | 162| 135 ± 40\(^b\) |
|          |          | B    | 3.6      | 160| 10 ± 4 |
|          |          | C    | 6.2      | 167| 6 ± 4  |
|          |          | D    | 8.8      | 168| 4 ± 3  |
|          |          | E    | 10.2     | 165| 4 ± 3  |
|          |          | F    | 13.2     | 165| 12 ± 5 |
|          |          | G    | 14.4     | 165| 12 ± 5 |
|          |          | H    | 16.8     | 163| 7 ± 4  |
|          |          | I    | 26.9     | 170| 11 ± 4 |
| 2251+134 | 9186     | ⋮    | ⋮        | ⋮  | ⋮     |

Explanation of Columns: 1=Source; 2=Net Chandra exposure time in seconds after data screening; 3=Knot detected at X-rays; 4=Distance of X-ray knot from core in arcsec; 5=Position Angle of X-ray knot in degrees; 6=Net X-ray counts in a 1\(^\prime\) apertures in 0.4–8 keV. Uncertainties include the local background (see text).

Notes: \(^a\)=Counterlobe; \(^b\)=Uncertainty is 30% the value of the count rates (see text).
Table 3: Jets broad-band emission

| Source  | Knot | F$_{5\,GHz}$ | F$_{5\,852\,\AA}$ | F$_{1\,keV}$ | $\alpha_{ro}$ | $\alpha_{ox}$ | $\alpha_{rx}$ |
|---------|------|--------------|------------------|-------------|-------------|-------------|-------------|
| (1)     | (2)  | (3)          | (4)              | (5)         | (6)         | (7)         | (8)         |
| 0723+679 A | 73 | < 0.06$^a$ | 0.4 | > 0.90 | < 0.81 | 1.07 |
| B       | 110 | < 0.06$^a$ | 1.1 | > 0.92 | < 0.65 | 1.04 |
| CL$^b$  | 285 | < 2.8$^a$  | 0.24 | > 1.0  | < 0.90 | 1.18 |
| 1055+018 ...$^c$ | 69 | < 0.06$^a$ | < 0.01$^a$ | > 2.27 | ⋯   | > 1.28 |
| 1136–135 A | 1  | 0.23 | 1.4 | 0.73  | 0.83  | 0.76 |
| B       | 41  | 0.24 | 3.7 | 1.04  | 0.68  | 0.92 |
| C$^d$   | 190 | < 0.6$^a$ | 1.23 | > 0.87 | > 1.11 |
| CL$^b$  | 520 | < 11   | < 0.01$^a$ | > 0.93 | ⋯   | > 1.15 |
| 1150+497 A | 56 | 0.63 | 3.9 | 0.99  | 0.83  | 0.93 |
| B       | 36  | 0.02 | 1.3 | 1.24  | 0.44  | 0.97 |
| C       | 74  | 0.08 | 1.0 | 1.19  | 0.71  | 1.02 |
| CL$^b$  | 45  | < 7.0 | < 0.01$^a$ | > 0.76 | ⋯   | > 1.06 |
| 1354+195 A | 57 | 0.3  | 8.2 | 1.05  | 0.60  | 0.90 |
| B       | 23  | 0.04 | 0.24 | 1.15  | 0.68  | 0.98 |
| C       | 13  | < 0.06$^a$ | 0.37 | > 1.07 | < 0.83 | 0.98 |
| D       | 16  | < 0.06$^a$ | 0.25 | > 1.08 | < 0.89 | 1.02 |
| E       | 6   | < 0.06$^a$ | 0.25 | > 1.00 | < 0.89 | 0.96 |
| F       | 12  | < 0.06$^a$ | 0.72 | > 1.06 | < 0.72 | 0.94 |
| G       | 13  | < 0.06$^a$ | 0.61 | > 1.07 | < 0.74 | 0.95 |
| H       | >1  | < 0.06$^a$ | 0.43 | > 0.84 | < 0.80 | 0.83 |
| I       | 87  | ⋯$^c$ | 0.67 | ⋯   | ⋯   | 1.06 |
| CL$^b$  | 149 | < 9.0   | < 0.01$^a$ | > 0.84 | ⋯   | > 1.10 |
| 2251+134 Jet | 178$^f$ | < 1.6 | < 0.01$^a$ | > 1.89 | ⋯   | > 1.33 |

Explanation of Columns: 1=IAU name of source; 2=Knot (see text); 3=Radio flux in mJy; 4=Optical flux in $\mu$Jy; 5=X-ray flux in nJy; 6=Radio-to-optical spectral index; 7=Optical-to-X-ray spectral index; 8=Radio-to-X-ray spectral index.
Notes: a=3σ upper limit; b=Counterlobe; c=Average from two positions along the radio jet at 8.8", PA=174 deg, and 6.2", PA=175 deg; d=Radio/optical knot at 10" from the core; e=Off the HST field of view; f=Integrated on both radio lobes (see Figure 2).
Table 4: Parameters of Model Fitting to SEDs $^a$

| Source/Knot | Model | $\gamma_{max}$ | $n$ | $B$ | $K$ | $\delta$ | $\Gamma$ | $P_{jet}$ | $P_{rad}$ |
|-------------|-------|----------------|-----|-----|-----|--------|----------|----------|----------|
| 0723+679 A  | CMB   | $5 \times 10^4$| 2.6 | 14  | 1.5 | 5      | 3        | 47.05    | 42.23    |
| B           | CMB   | $5 \times 10^4$| 2.6 | 10  | 4.8 | 5      | 3        |          |          |
| 1136–135 A  | Sync  | $5.7 \times 10^7$| 2.5 | 1   | 0.1 | 7      | 5        | 46.47    | 43.12    |
| B           | CMB   | $3.5 \times 10^5$| 2.6 | 4   | 1.0 | 7      | 5        |          |          |
| 1150+497 A  | CMB   | $6 \times 10^5$ | 2.6 | 2.5 | 1.8 | 6      | 3.5      | 47.26    | 42.60    |
| B           | CMB   | $1 \times 10^5$ | 2.6 | 2.8 | 0.8 | 6      | 3.5      |          |          |
| 1354+195 A  | CMB   | $2.5 \times 10^5$| 2.6 | 3.6 | 5.7 | 6      | 4        | 47.88    | 43.70    |
| B           | CMB   | $2.5 \times 10^5$| 2.6 | 5.6 | 0.8 | 6      | 4        |          |          |

Explanation of Columns: 1=Source and Knot; 2=Model used to model the SED of the knot. Sync: synchrotron; CMB: Inverse Compton scattering off the microwave background photons (see text); 3=Maximum electron energy; 4=Index of the electron power law distribution ($N = N_0 \gamma^{-n}$); 5=Magnetic field (in $10^{-5}$ Gauss); 6=Normalization of the electron power law distribution in $10^{-4}$ ($N = N_0 \gamma^{-n}$); 7=Doppler factor; 8=Bulk Lorentz factor; 9=Log of the intrinsic jet power (erg s$^{-1}$); 10=Log of the radiated jet power (erg s$^{-1}$).

Notes: $^a$=In all cases a region size $R = 5 \times 10^{21}$ cm and minimum electron energy $\gamma_{min} = 10$ was assumed.
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1136–135 – knot A

![Graph showing the relationship between \( \log \delta_{eq} \) and \( \log t_c \) against \( \log B \) (G)].
0723+679

Log $\nu F(\nu)$ [erg cm$^{-2}$ s$^{-1}$] vs. Log $\nu$ (Hz)

- knot A
- knot B
