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AN X-RAY IMAGING SURVEY OF QUASAR JETS: TESTING THE INVERSE COMPTON MODEL

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ABSTRACT

We present results from continued *Chandra* X-ray imaging and spectroscopy of a flux-limited sample of flat spectrum radio-emitting quasars with jet-like extended structure. X-rays are detected from 24 of the 39 jets observed so far. We compute the distribution of α_{rx} , the spectral index between the X-ray and radio bands, showing that it is broad, extending at least from 0.8 to 1.2. While there is a general trend that the radio brightest jets are detected most often, it is clear that predicting the X-ray flux from the radio knot flux densities is risky, so a shallow X-ray survey is the most effective means for finding jets that are X-ray bright. We test the model in which the X-rays result from inverse Compton (IC) scattering of cosmic microwave background (CMB) photons by relativistic electrons in the jet moving with a high bulk Lorentz factor nearly along the line of sight. Depending on how the jet magnetic fields vary with z , the observed X-ray to radio flux ratios do not follow the redshift dependence expected from the IC–CMB model. For a subset of our sample with known superluminal motion based on VLBI observations, we estimate the angle of the kiloparsec-scale jet to the line of sight by considering the additional information in the bends observed between parsec- and kiloparsec-scale jets. These angles are sometimes much smaller than estimates based on the IC–CMB model with a Lorentz factor of 15, indicating that these jets may decelerate significantly from parsec scales to kiloparsec scales.

Key words: galaxies: active – galaxies: jets – surveys

Online-only material: color figure

1. INTRODUCTION

Many fundamental physical properties of quasar jets remain uncertain, such as the nature of the energy-carrying particles, whether the particle energy densities are in equipartition with the local magnetic field energy densities, and how much entrainment there is. From the observation of superluminal motion with the very long baseline interferometry (VLBI) technique, it is generally agreed that the parsec (pc)-scale jets of high power quasars are highly relativistic, with bulk Lorentz factors (Γ) of 10–30. However, it is not certain whether most jets at the kiloparsec (kpc) scale also have high Lorentz factors in bulk motion and whether the jets are oriented close to our line of sight, as inferred for PKS 0637–752 (Celotti et al. 2001; Tavecchio et al. 2000) because of its X-ray bright knots (Schwartz et al. 2000). The model posited by Celotti et al. and Tavecchio et al. involved inverse Compton (IC) scattering of photons from the cosmic microwave background (IC–CMB), in contrast to earlier synchrotron and synchrotron self-Compton models. For a review of relativistic jet physics and the role of X-ray observations, see Worrall (2009) and references therein.

It is now becoming evident that the simplest, single-zone IC–CMB model is inadequate in many cases (e.g., Kataoka & Stawarz 2005; Hardcastle 2006; Jester et al. 2006;

Siemiginowska et al. 2007). One concern with this model is that the lifetimes of the electrons responsible for the X-ray emission are orders of magnitude longer than those producing the radio emission, so the observed correspondence of radio and X-ray structures would not be expected (Tavecchio et al. 2003; Schwartz et al. 2006). Extra synchrotron components are proposed by others (Jester et al. 2006; Hardcastle 2006). In some cases it gets difficult to generate an adequate physical model (Siemiginowska et al. 2007). Currently, the field is in a fruitful phase of mutually driven theoretical and observational advances. Solutions seem to be as varied as the sources themselves, bolstering the need for more detailed case studies. This need provides the primary motivation for our X-ray imaging survey with *Chandra* (Marshall et al. 2005, hereafter Paper I). Our survey is similar to that undertaken by Sambruna et al. (2002, 2004) but the sample is somewhat larger and the exposures correspondingly shorter. This being a shallow survey, we leave detailed modeling of individual sources to later, follow-up analyses of deeper observations.

This paper is a continuation of Paper I and presents observations of another 19 quasars from the original sample of 56. We describe the sample properties in Section 2. In Section 3, we describe the *Chandra* observations and compare the X-ray maps to newly obtained radio images. In Section 4, we examine the sample properties in the context of beaming emission

models and test the IC–CMB model in a limited context, as examined previously by Cheung (2004) and Kataoka & Stawarz (2005). We use a cosmology in which $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. SAMPLE PROPERTIES

Sample selection was described in Paper I. Briefly, 56 sources were selected from 1.5 or 5 GHz Very Large Array (VLA) and ATCA imaging surveys (Murphy et al. 1993; Lovell 1997). The dominant selection criterion is on core flux density—as applied when creating the samples for the radio imaging surveys. We then use the flux density in extended emission, determined from imaging studies of the sample, as the primary criterion for inclusion in our sample. A few sources have somewhat indistinct morphology but most have double or triple structure and many have linear structure. Subsamples were defined in Paper I: the “A” list was a purely jet flux-limited sample, while the “B” list was selected on the basis of morphology with a bias toward one-sided and linear structure. The sample had 28 objects in each list, although many objects from the “A” list could qualify morphologically for the “B” list.

So far, 39 sources in the sample have been observed with *Chandra*. We reported results for the first 20 targets in Paper I, finding that 60% of the jets could be detected in short *Chandra* exposures. Here, we present results for another 19 quasars in the sample and present some ensemble properties for the 39 that have been observed with *Chandra*. Ten of the new images were obtained as part of the continuation of our survey and the other nine were taken from the *Chandra* archive. Some of these archival observations have somewhat longer exposures than we have used in our survey.

A significant fraction of the sample has been observed with VLBI: 22 of the 29 northern sources are in the MOJAVE survey.¹² An additional four targets with declinations in the -40° to -20° range have also been observed. Superluminal motions have been detected and measured for 22 of these 26 quasars; the distribution of the apparent velocities, $c\beta_{\text{app}}$, is comparable to those of the remaining MOJAVE sources, indicating that our sample and the MOJAVE sample have similar characteristics.

3. OBSERVATIONS AND DATA REDUCTION

3.1. Imaging Results

The observation dates and exposure times for the *Chandra* observations used in this analysis are given in Table 1. As in Paper I, events in the 0.5–7.0 keV range were selected for all analysis and to form the X-ray images, shown in Figure 1. The images of the brightest sources show readout streaks, which were avoided by selecting a suitable range of observatory roll angles.

Radio maps were obtained for all of the sources at the ATCA or the VLA archives. ATCA observations will be reported in detail in a separate paper. These maps were used for the image overlays in Figure 1 and Table 2 gives a log of the radio observations. We used these maps to determine radio flux densities for the jets. Images were registered as in Paper I.

We tested for the detection of X-rays from a jet using a simple Poisson test, as in Paper I, for counts in a rectangular region extending over a specific angular range (θ_i, θ_o) from the core at

Table 1
Chandra Observation Log

Target	<i>Chandra</i> Obs ID	Live Time (s)	Date (UT)	Ref. ^a
0234+285	4898	9032	2004 Jun 24	1
0454–463	4893	5775	2004 Jun 4	1
0820+225	4897	5617	2003 Dec 28	1
0923+392	3048	18638	2002 Oct 19	1
0954+556	4842	34404	2004 Jun 16	2
1040+123	2136	10401	2001 Feb 12	3
1055+018	2137	9314	2001 Jan 9	4
1055+201	4889	4693	2004 Jan 19	1
1116–462	4891	5623	2004 Mar 16	1
1251–713	4892	5974	2004 Mar 7	1
1354+195	2140	9055	2001 Jan 8	4
1421–490	4895	5472	2004 Jan 16	1
1641+399	2143	9055	2001 Apr 27	3
1642+690	2142	8326	2001 Mar 8	3
1928+738	2145	8392	2001 Apr 27	3
2007+777	5709	36046	2005 May 23	5
2123–463	4890	6473	2004 Mar 25	1
2255–282	4894	7127	2003 Nov 19	1
2326–477	4896	8298	2004 Jun 21	1

Notes. ^a References refer to previous X-ray imaging results: (1) this paper; (2) Tavecchio et al. 2007; (3) Gambill et al. 2003; (4) Sambruna et al. 2004; (5) Sambruna et al. 2008.

a specific position angle (P.A.) and appropriate width. The radio images were used to define the P.A.s and lengths of possible jets. Most jets are clearly defined as one-sided structure but in a few ambiguous cases, the pc-scale images were used to define the jet direction, when available. The parameters of the selection regions are given in Table 3. The width of the rectangle was $3''$ except for 0234+285, 0454–463, 1055+018, 1055+201, 1928+738, and 2007+777, where the jets bend substantially, so the rectangles were widened up to $4''$ – $10''$. Profiles of the radio emission along the jets are shown in Figure 2. In order to eliminate X-ray counts from the wings of the quasar core, a profile was computed at 90° to the jet and subtracted. The X-ray counts in the same rectangular region defined by the radio data were compared to a similar-sized region on the opposite side of the core for the Poisson test. We set the critical probability for detection of an X-ray jet to 0.0025, which yields a 5% chance that there might be one false detection in a set of 20 sources. Histograms of the X-ray emission along the jets are shown in Figure 3. The jet and counterjet P.A.s are compared, providing a qualitative view of the X-ray emission along the jets. In no case is a counterjet apparent in the X-ray images.

Jet X-ray flux densities (Table 3) were computed from count rates using the conversion factor $1 \text{ count s}^{-1} = 1 \mu\text{Jy}$. This conversion is accurate to within 10% for typical power-law spectra. The spectral index from radio to X-ray is computed using $\alpha_{rx} = -\log(S_x/S_r)/\log(\nu_x/\nu_r)$, where $\nu_x = 2.42 \times 10^{17} \text{ Hz}$ and ν_r depends on the map used. Due to the wide range of redshifts for the observed sample of 39 sources, the apparent 0.5–7.0 keV X-ray luminosities of the detected jets range from $10^{40} \text{ erg s}^{-1}$ to over $8 \times 10^{44} \text{ erg s}^{-1}$, with a median value of $8 \times 10^{43} \text{ erg s}^{-1}$. Excluding three sources with $z < 0.1$, the minimum detected jet luminosity is $9 \times 10^{42} \text{ erg s}^{-1}$ and the median is $1.3 \times 10^{44} \text{ erg s}^{-1}$.

Redshifts are still unknown for two objects in the sample for which we have X-ray images: PKS 1145–676 and PKS 1251–713. We excluded these two sources from sample analyses that require redshifts.

¹² See the MOJAVE Web site: <http://www.physics.purdue.edu/astro/MOJAVE/> and Lister et al. (2009a).

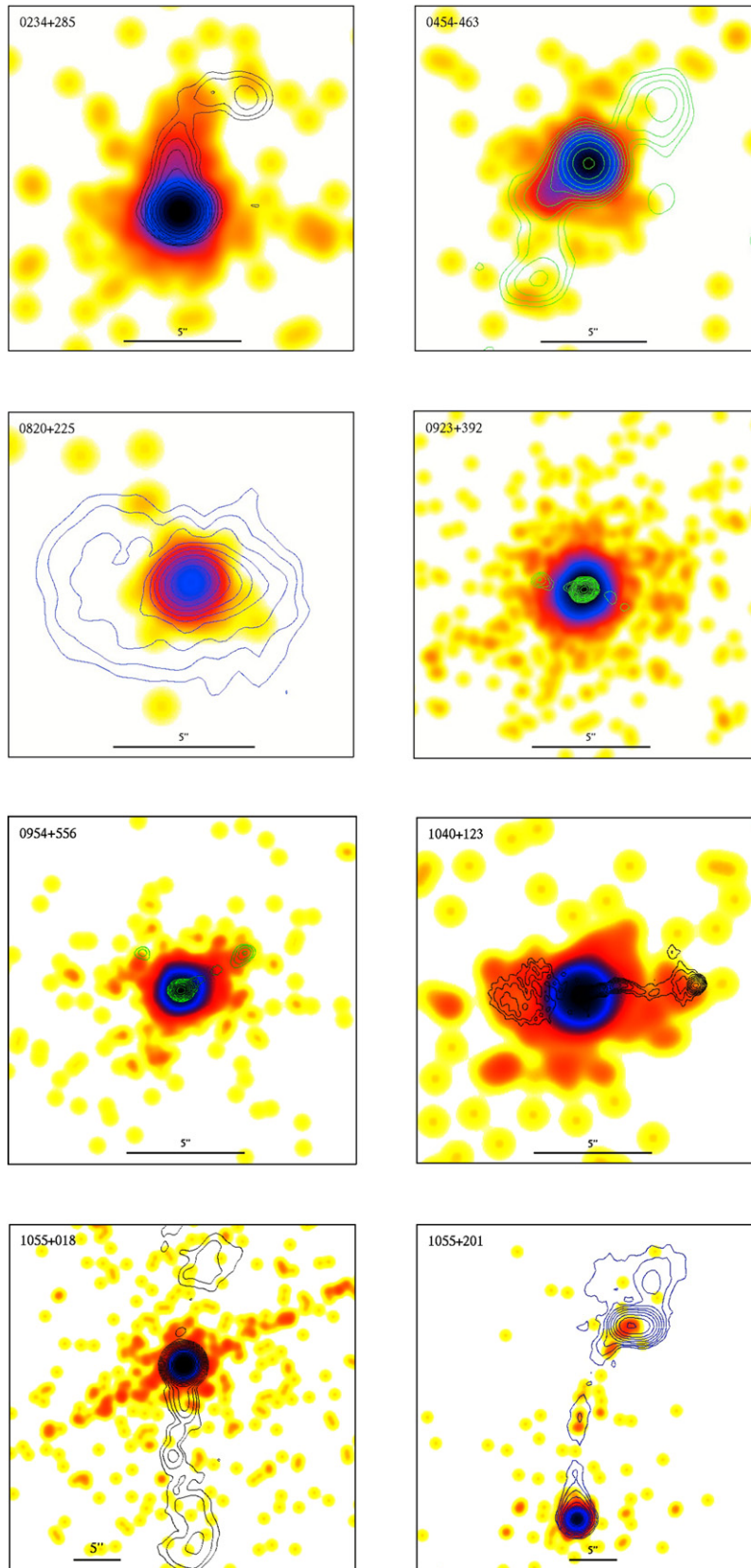


Figure 1. X-ray images obtained with the *Chandra* X-ray Observatory, overlaid by contours of radio emission obtained at the Australia Telescope Compact Array or the Very Large Array (VLA). The images appear in the following order: (a) 0234+285, (b) 0454–463, (c) 0820+225, (d) 0923+392, (e) 0954+556, (f) 1040+123, (g) 1055+018, (h) 1055+201, (i) 1116–462, (j) 1251–713, (k) 1354+195, (l) 1421–490, (m) 1641+399, (n) 1642+690, (o) 1928+738, (p) 2007+777, (q) 2123–463, (r) 2255–282, and (s) 2326–477. The radio surface brightnesses increase by $\times 2$ for each radio contour, starting at five times the rms noise (from Table 2). The X-ray images are convolved with $1''$ Gaussians and then binned at $0'.0492$. The color scales are the same in all images, ranging logarithmically from $0.5 \text{ counts beam}^{-1}$ (yellow) to $2500 \text{ counts beam}^{-1}$ (black). Notes on individual objects are given in the text. For sources with bright cores, a readout streak may be observed on both sides of the core, such as in 1055+018.

(A color version of this figure is available in the online journal.)

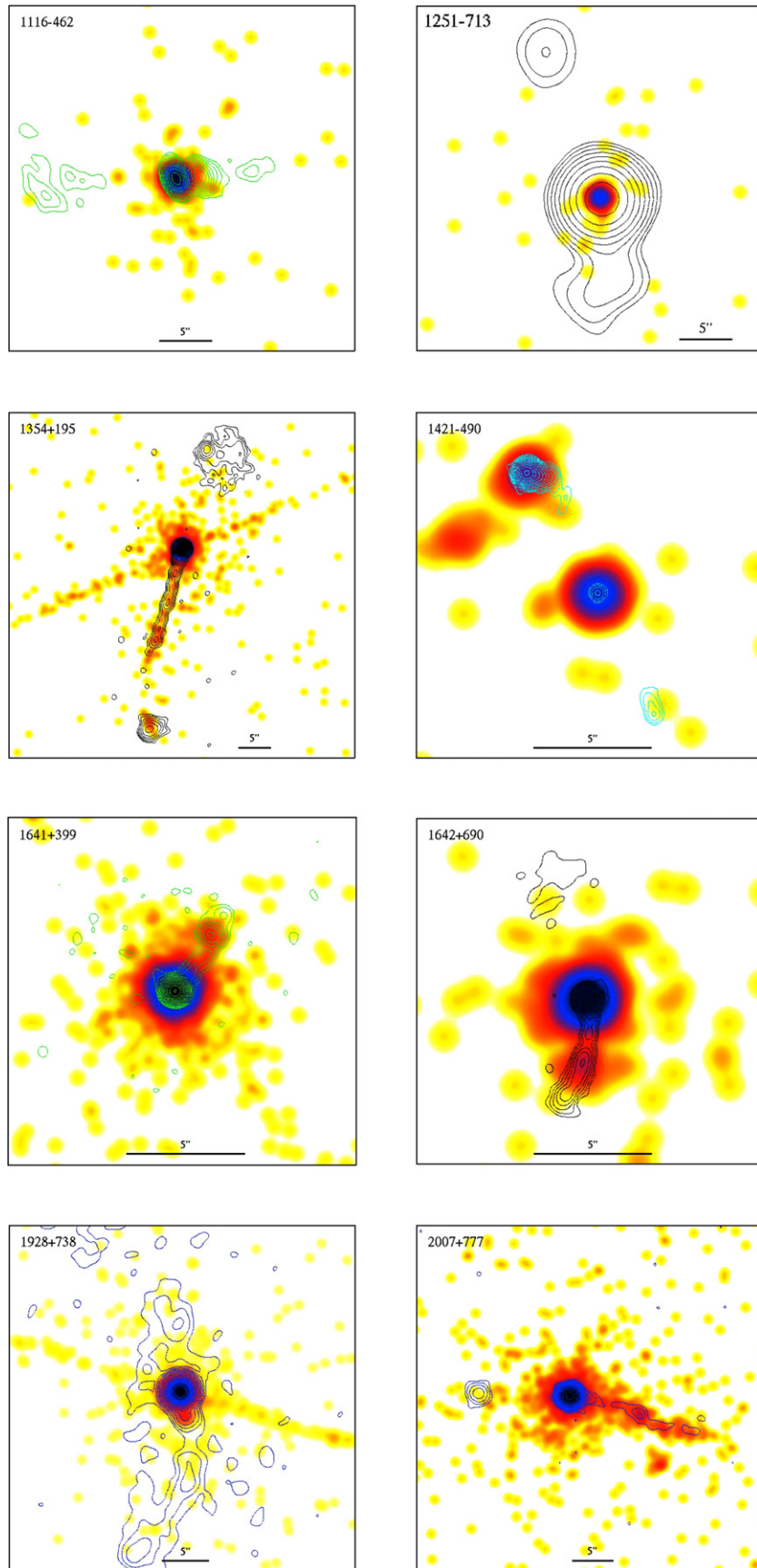


Figure 1. (Continued)

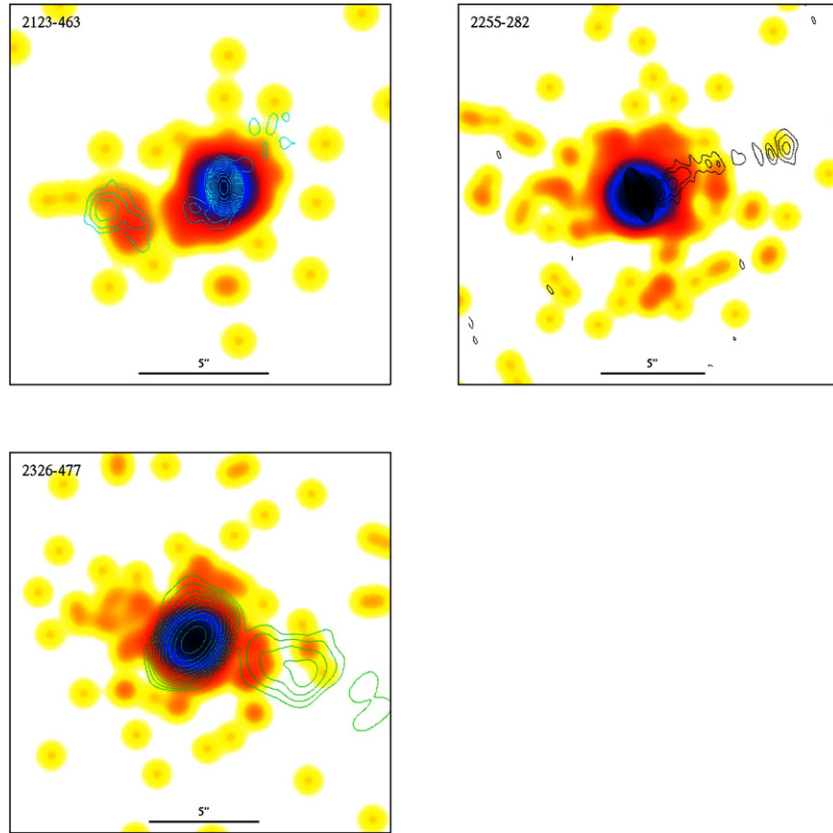


Figure 1. (Continued)

Table 2
Radio Observations

Target	Instrument	Date (UT)	Freq. (GHz)	$5 \times$ rms noise (mJy beam $^{-1}$)
0234+285	VLA	2000 Nov 5	1.42	3.74
0454 – 463	ATCA	2000 May 20	8.64	2.41
0820+225	VLA	2000 Nov 5	1.42	5.99
0923+392	VLA	2000 Nov 5	4.86	6.63
0954+556	VLA	2000 Nov 5	4.86	4.07
1040+123	VLA	1983 Sep 25	4.86	1.52
1055+018	VLA	1985 May 14	4.86	1.34
1055+201	VLA	1984 Dec 23	1.46	3.22
1116 – 462	ATCA	2002 Feb 4	8.64	1.48
1251 – 713	ATCA	1993 Jul 13	4.80	6.13
1354+195	VLA	1985 Apr 20	4.86	1.63
1421 – 490	ATCA	2004 May 9	17.73	1.12
1641+399	VLA	1985 Jan 31	4.86	3.78
1642+690	VLA	1986 May 6	4.86	1.92
1928+738	VLA	1996 Nov 23	1.42	1.98
2007+777	VLA	2000 Nov 5	1.42	1.70
2123 – 463	ATCA	2004 May 10	17.73	1.08
2255 – 282	VLA	2000 Nov 5	4.86	2.05
2326 – 477	ATCA	2002 Jan 31	8.64	1.43

3.2. Notes on Individual Sources

In this section, we present qualitative descriptions of the X-ray and radio morphologies shown in Figure 1 and describe the directions of any pc scale jets. Profiles of the radio and X-ray emission along the jets are given in Figures 2 and 3, respectively. All P.A.s are defined as positive when east of north with due north defining zero.

0234+285 (4C +28.07). On the pc scale, VLBI observations show two jet knots with P.A.s of about -15° and apparent speeds of about $12c$ (Lister et al. 2009a). The VLA image shows a jet about $6''$ long with an initial direction of due north but curving to a P.A. of -20° after which it bends sharply to a P.A. of -90° , and terminates within $3''$ at a bright component. X-ray emission is clearly detected up to the sharp bend. There is a marginal X-ray detection near the radio feature at the end of the detected jet.

0454–463 (PKS B0454–463). The ATCA data show hot spots placed somewhat asymmetrically $5''.9$ to the southeast and $4''.5$ to the northwest of the core. A $3''$ long jet extends to the southeast before bending to the south hot spot. There is no apparent VLBI structure (Ojha et al. 2004). The X-ray source appears extended along the jet direction to the southeast, coincident with the jet before it bends south. An X-ray source is found $1''$ beyond the southeast hot spot.

0820+225 (4C +22.21). Extended radio emission surrounds the source but is oriented predominantly along an east–west axis. A VLBI observation by Gabuzda et al. (2000) shows an S-shaped jet extending over 20 mas generally to the southwest. We consider the jet to be oriented due west for the purposes of this analysis because the radio emission is somewhat brighter in this direction on a scale of a few arcsec. We detect no associated extended X-ray emission.

0923+392 (4C +39.25). VLBA data show knots to the west of the core at a P.A. of -78° , moving with a maximum apparent speed of $2.9c$ (Kellermann et al. 2004; Lister & Smith 2000). Lister et al. (2009a), however, place the core differently (at position S instead of A in the Lister & Smith 2000 map, as suggested by Alberdi et al. 1997), with knots at a P.A. of about 100° , moving at up to $4.3c$. The 4.95 GHz map shows a $2''$

Table 3
Quasar Jet Measurements

Target	P.A. ($^{\circ}$)	θ_i ($''$)	θ_o ($''$)	S_r^a (mJy)	ν_r (GHz)	Count Rate (10^{-3} cps)	S_x^a (nJy)	$\alpha_{r,x}$	P_{jet}^b	X? ^c
0234+285	-20	1.5	10.0	66.0 \pm 4.5	1.42	5.20 \pm 1.15	5.2	0.86 \pm 0.01	<1e-10	Y
0454-463	150	1.5	8.0	62.4 \pm 2.2	8.64	10.39 \pm 1.70	10.4	0.91 \pm 0.01	<1e-10	Y
0820+225	-90	1.5	5.0	50.4 \pm 3.3	1.42	0.18 \pm 0.31	<1.1	>0.93	2.64e-01	N
0923+392	75	1.5	4.0	74.1 \pm 9.7	4.86	0.16 \pm 0.62	<2.0	>0.98	3.55e-01	N
0954+556	-60	1.5	5.0	108.0 \pm 7.1	4.86	1.40 \pm 0.27	1.4	1.03 \pm 0.01	<1e-10	Y
1040+123	-90	1.5	6.0	253.8 \pm 4.2	4.86	0.00 \pm 0.72	<2.2	>1.05	5.25e-01	N
1055+018	180	1.5	25.0	57.7 \pm 2.6	4.86	0.54 \pm 1.49	<5.0	>0.92	3.03e-01	N
1055+201	-10	1.5	20.0	137.8 \pm 4.1	1.46	3.41 \pm 1.48	3.4	0.93 \pm 0.02	2.76e-04	Y
1116-462	-85	1.5	4.0	126.2 \pm 0.6	8.64	0.89 \pm 0.73	<3.1	>1.02	4.26e-02	N
1251-713	180	1.5	10.0	35.7 \pm 2.6	4.80	0.33 \pm 0.63	<2.2	>0.94	2.56e-01	N
1354+195	165	1.5	20.0	109.4 \pm 2.3	4.86	4.97 \pm 1.39	5.0	0.95 \pm 0.02	<1e-10	Y
1421-490	30	1.5	8.0	2720.0 \pm 1.8	17.73	12.97 \pm 1.60	13.0	1.17 \pm 0.01	<1e-10	Y
1641+399	-30	1.5	5.0	295.9 \pm 5.1	4.86	3.20 \pm 1.18	3.2	1.04 \pm 0.02	4.89e-06	Y
1642+690	170	1.5	6.0	85.3 \pm 2.9	4.86	2.76 \pm 0.82	2.8	0.97 \pm 0.02	5.23e-08	Y
1928+738	170	1.5	20.0	80.5 \pm 3.0	1.42	6.79 \pm 1.75	6.8	0.86 \pm 0.01	<1e-10	Y
2007+777	-105	1.5	22.0	17.9 \pm 2.4	1.42	3.22 \pm 0.51	3.2	0.82 \pm 0.01	<1e-10	Y
2123-463	100	1.5	7.0	14.3 \pm 1.5	17.73	2.47 \pm 0.79	2.5	0.95 \pm 0.02	8.11e-08	Y
2255-282	-70	1.5	9.0	40.9 \pm 3.6	4.86	1.96 \pm 0.84	2.0	0.95 \pm 0.02	1.99e-04	Y
2326-477	-105	1.5	7.0	12.7 \pm 0.8	8.64	-0.12 \pm 0.73	<2.1	>0.79	6.22e-01	N

Notes.

^a The jet radio flux density is measured at ν_r for the same region as for the X-ray count rate, given by the P.A., θ_i , and θ_o parameters. The X-ray flux density is given at 1 keV assuming a conversion of $1 \mu\text{Jy}/(\text{count}/\text{s})$, which is good to $\sim 10\%$ for power-law spectra with low column densities and X-ray spectral indices near 0.5.

^b The quantity P_{jet} is defined as the chance that there are more counts than observed in the specified region under the null hypothesis that the counts are background events.

^c The jet is defined to be detected if $P_{\text{jet}} < 0.0026$ (see the text).

long jet extending along a P.A. of $+75^{\circ}$, which we take as the direction to examine for X-ray emission. We detect no associated extended X-ray emission, on either side of the core.

0954+556 (4C +55.17). This X-ray image was first published by Tavecchio et al. (2007) and is included in our analysis for completeness. The VLA image shows two distinct features, one at $5''$ from the core along a P.A. of -60° and the other at a P.A. of 45° , about $2''.5$ from the core. A MERLIN map at 5 GHz shows a jet at a P.A. of about -60° extending 150 mas to the WNW (Xu et al. 1995) and a 5 GHz map with the VLA shows a $5''$ long jet at the same P.A. as well as the knot $2''.5$ from the core at a P.A. of 45° . The $5''$ feature is detected in the X-ray image and is the more likely to be associated with a jet.

1040+123 (3C 245). This source was in the Sambruna et al. (2004) sample and is included in our analysis for completeness. We detect no significant extended X-ray emission associated with the western radio emission, which is the direction of the kpc-scale jet as well as optical knots (Sambruna et al. 2004). The eastern lobe appears to be detected, so our algorithm for detecting an X-ray excess on the jet side (by comparing the X-ray profile along the P.A. of the jet to a region 180° from it) may be failing in this case because the existence of what appears to be IC emission from the brighter radio lobe (see also Sambruna et al. 2004).

1055+018 (4C +01.28). This source was in the Sambruna et al. (2004) sample. It is included in our analysis for completeness. This source is another case where the pc-scale jet is strongly misaligned with the kpc-scale jet. Jet components are found from 1 to 10 mas from the core along a P.A. of -50° , moving at up to $11c$ (Lister et al. 2009a; Homan et al. 2009). The kpc scale jet is oriented generally to the south (Murphy et al. 1993; Figure 1). We detect no extended X-ray emission associated with

the radio emission on a few arcsec scale. The readout streak is very strong in the image shown in Figure 1.

1055+201 (4C +20.24). The radio and X-ray images show emission on a $20''$ scale to the north of the core. A detailed discussion of this source has been presented by Schwartz et al. (2006).

1116-462 (PKS B1116 - 462). The ATCA image shows a knot about $3''$ to the west of the core. We detect no associated extended X-ray emission.

1251-713 (PKS B1251 - 713). The ATCA image shows a knot about $10''$ to the south of the core. VLBI at 8.64 GHz shows no structure on the mas scale (Ojha et al. 2005). We detect no associated extended X-ray emission.

1354+195 (4C +19.44). This source was in the Sambruna et al. (2004) sample. The radio/X-ray jet is over $20''$ long and was the subject of a follow-up observation, which is used in a more in-depth analysis (see Schwartz et al. 2007, and D. E. Harris et al. 2011, in preparation). It is included here for completeness. The readout streak is very strong in the image shown in Figure 1. Based on VLBA observations from the 2 cm survey (Kellermann et al. 2004), the pc-scale jet of 1354+195 is relatively straight, at a P.A. of 143° . Several bright jet features appear to have motions of $160\text{--}240 \mu \text{ arcsec yr}^{-1}$ ($6.6\text{--}9.9c$; M. L. Lister et al. 2011, in preparation).

1421-490 (PKS B1421-490). This observation was published by Gelbord et al. (2005) and is included here for completeness. Magellan spectra show that component B (in the center of the image shown in Figure 1), which is the brightest optically and in the X-ray band, is the core of the quasar with $z = 0.662$. Because component A (to the northeast of component B and brighter in the radio band) has been resolved using VLBI (Godfrey et al. 2009), we now consider that component B is associated with

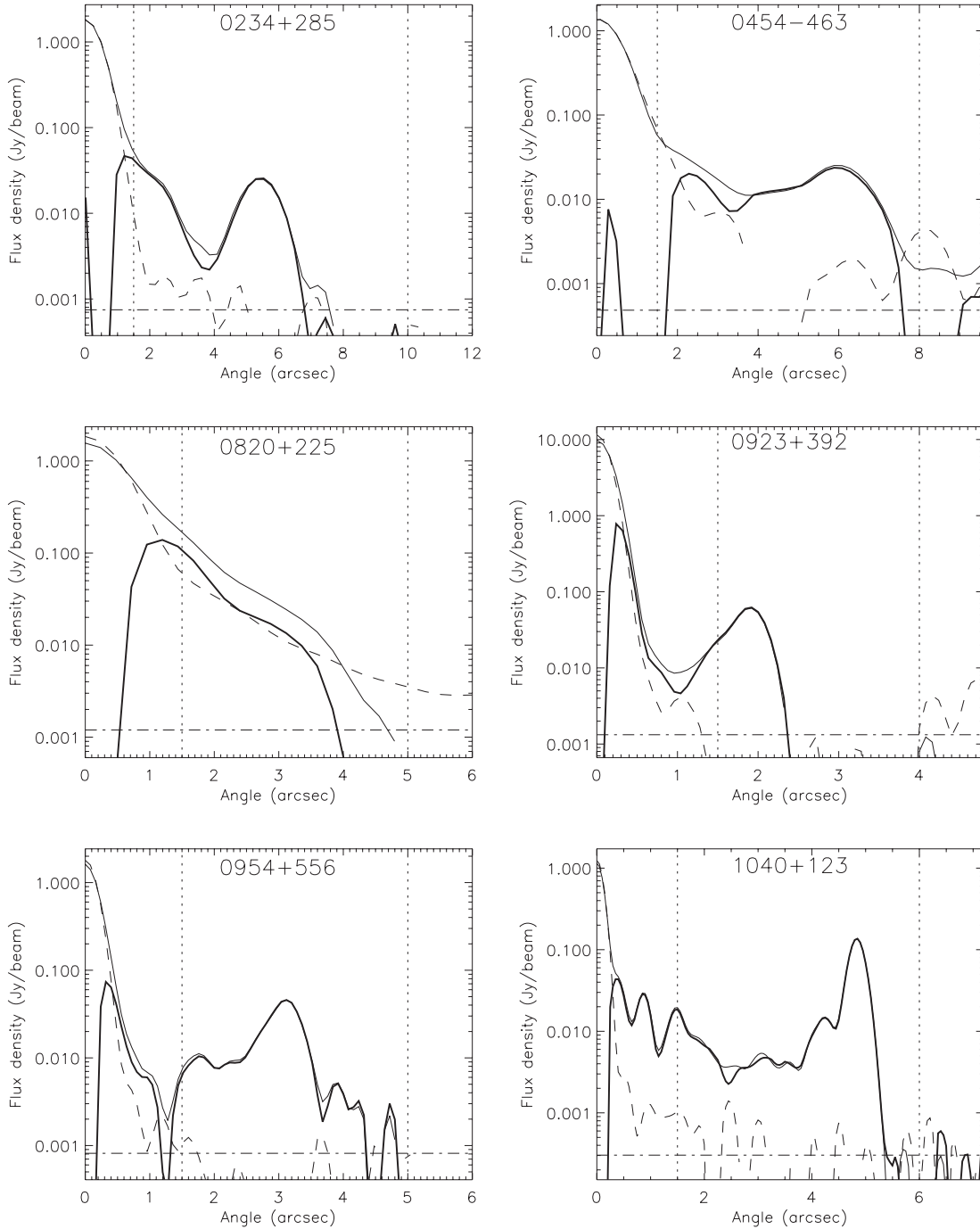


Figure 2. Profiles of the radio images. The solid, thin lines give the profiles along the position angles of the jets, as defined in Table 3 and used for measuring the X-ray profiles. The integrated flux densities are determined in rectangles given by parameters listed in Table 3. The dashed lines give the profiles at a position angle 90° CW from the jet to avoid any counterjets or lobes opposite the jet. The solid, bold lines give the difference between the profiles along the jet and perpendicular to it, so that the core is effectively nulled and the jet flux can be measured as a residual between the vertical dotted lines. The horizontal dash-dotted lines give the average noise level in the map.

the quasar core and that component A is a radio lobe with an exceptionally bright and compact hot spot. *1641+399* (*3C 345*). This source was in the Sambruna et al. (2004) sample and is included in our analysis for completeness. VLBA data show pc scale jet knots moving at about $12c$ along an average P.A. of -90° (Kellermann et al. 2004; Lister et al. 2009a). The jet curves north to a P.A. of about -45° about 4 mas from the nucleus (Lister et al. 2009a). The kpc-scale images (Figure 1) show an X-ray and radio knot about $3''$ from the core at a P.A. of -35° .

1642+690 (*4C +69.21*). This source was in the Sambruna et al. (2004) sample and is included in our analysis for completeness. The pc-scale jet is oriented along a P.A. of -162° and has a maximum apparent speed of $16c$ (Kellermann et al. 2004) while the kpc-scale jet points due south and curves to the east (O’Dea et al. 1988). There appears to be an X-ray excess associated with the brightest part of the extended jet, $\sim 3''$ from the core. *1928+738* (*4C +73.18*). This source was in the Sambruna et al. (2004) sample and is included in our analysis for completeness. The VLBA data show many knots moving non-radially, at $2-8c$

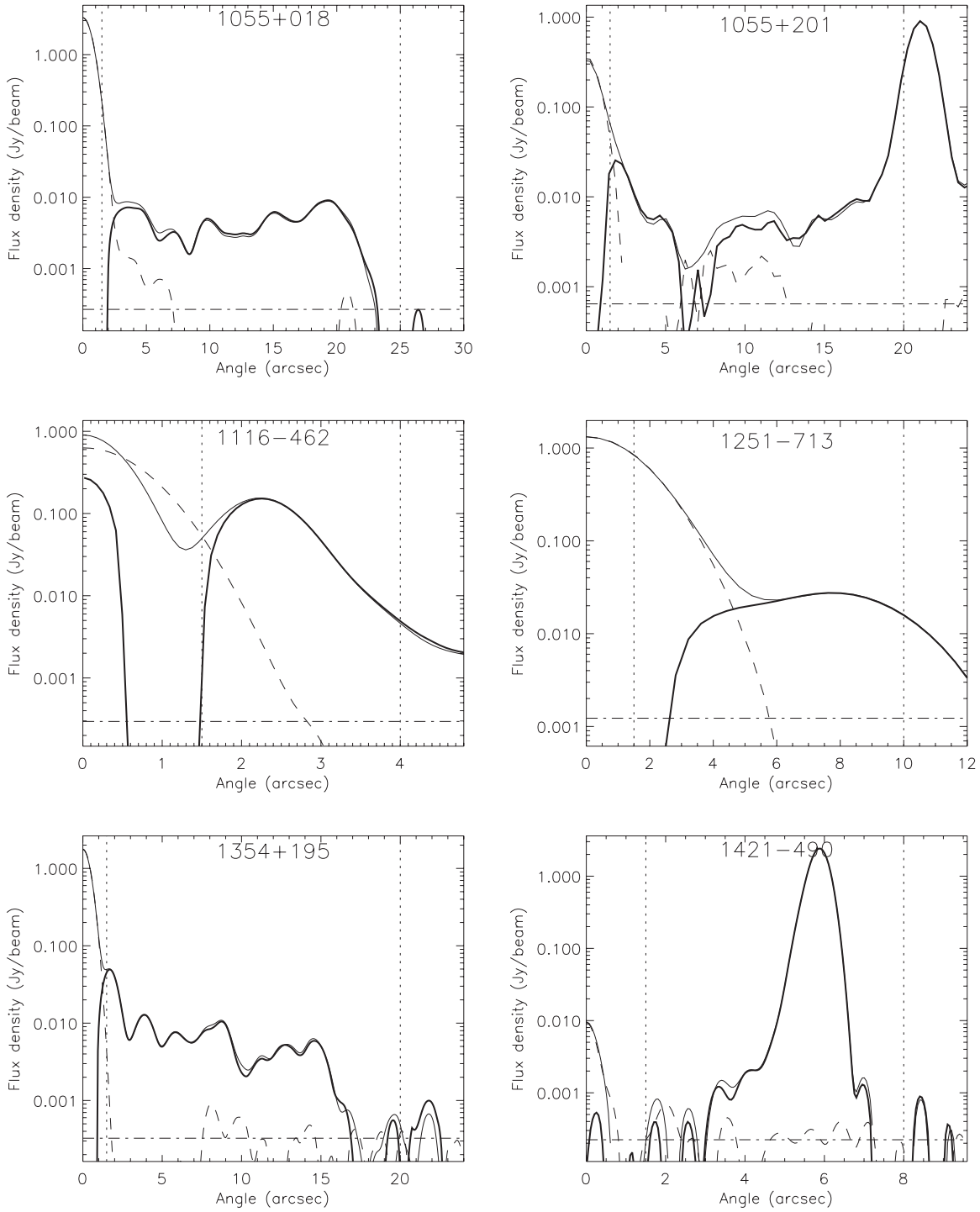


Figure 2. (Continued)

on an arc that extends over P.A.s 150° – 160° toward due south (Kellermann et al. 2004; Lister et al. 2009a), while the VLA data show knots in a jet that curves from P.A. -170° to the east between $5''$ and $10''$ from the core. In the X-ray image, the jet is detected most strongly at a P.A. of -170° out to $3''.5$ and is marginally detected for much of the remainder of the jet. The readout streak is visible in the image shown in Figure 1. *2007+777* (*S5 2007+77*). This active galaxy is considered to be a BL Lac object with hybrid FR I/II morphology (Gopal-Krishna & Wiita 2000). VLBI images show structure along a P.A. of -95° with a maximum apparent speed of $0.82c$, the only jet in

our sample where the fastest components are clearly subluminal (Lister 2001; Kellermann et al. 2004; Pérez-Torres et al. 2004). The VLA image shows a feature about $10''$ east of the core and a $20''$ long jet oriented at an average P.A. of -105° with some significant deviations from the average direction. The *Chandra* image shows that the jet is detected along almost its entire length and that the knot at the half-way point is particularly strong (Sambruna et al. 2008). *2123-463* (*PKS B2123-463*). The southeast edge of a radio feature $4''.5$ from the core at a P.A. of 110° is detected in X-rays. There also appears to be some X-ray emission about $1''.5$ from

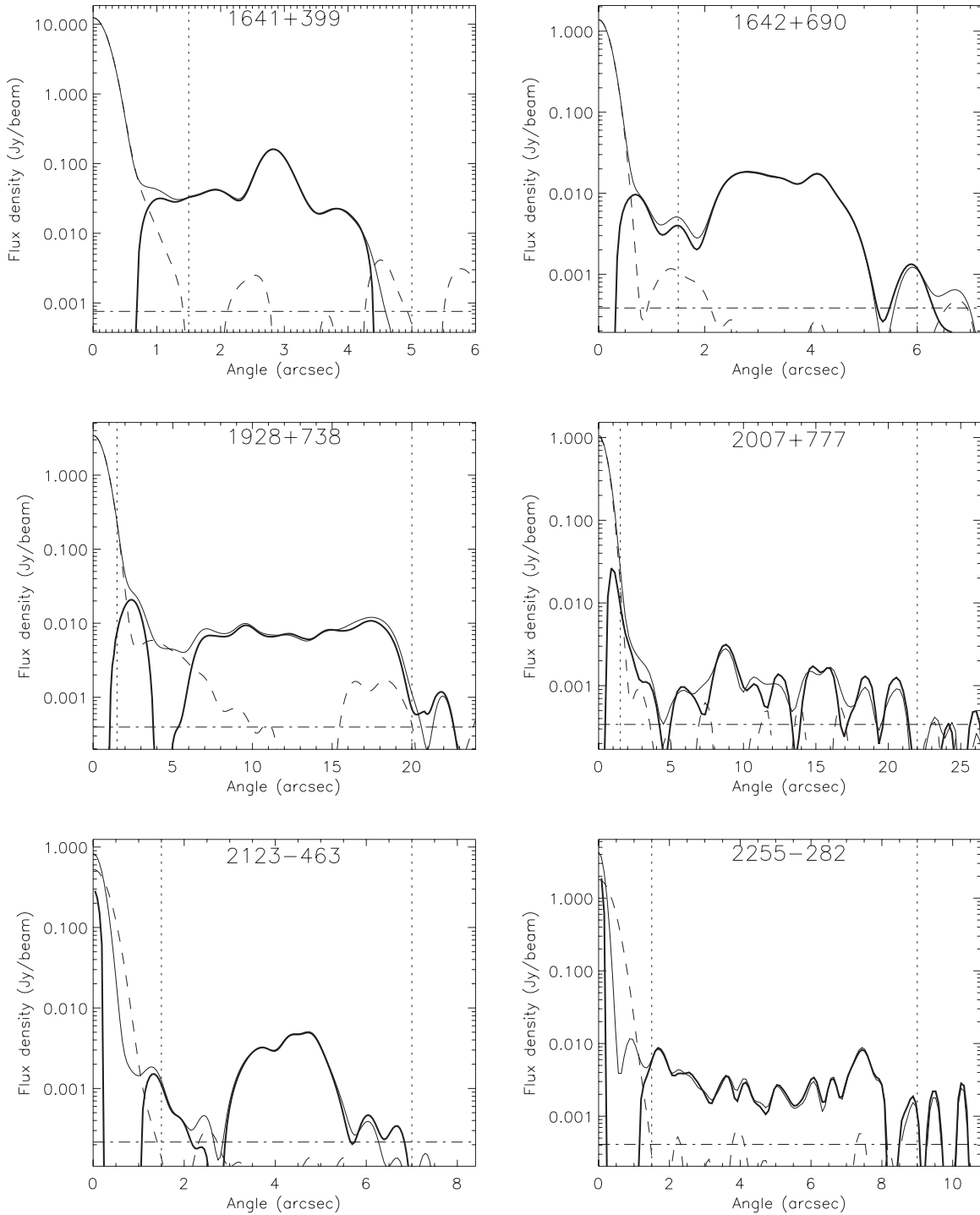


Figure 2. (Continued)

the core at a similar P.A., associated with a small-scale and bent radio jet. The adopted redshift (1.67) may be very uncertain or even incorrect (Jackson et al. 2002), being based on a unreliable objective prism spectrum.

2255–282 (*PKS B2255–282*). The 8'' long radio jet extends along a P.A. of -70° from the core. The VLBI images show jet emission without detectable superluminal motion (Piner et al. 2007) at a P.A. of -130 to -140° (MOJAVE Web site; Lister et al. 2009b). X-ray emission is detected along the first 4'' of the jet and as close as 1'' from the core (see Figure 3).

2326–477 (*PKS B2326–477*). A strong radio component is detected about 4.5'' from the core at a P.A. of -110° . VSOP imaging shows no jet at mas scales (Scott et al. 2004). We detect no associated extended X-ray emission along this P.A.

4. DISCUSSION

A hypothesis that bears testing with these data is that the X-ray emission results from IC–CMB photons off relativistic electrons and that the bulk motion of the jet is highly relativistic and aligned close to the line of sight. We have several lines of

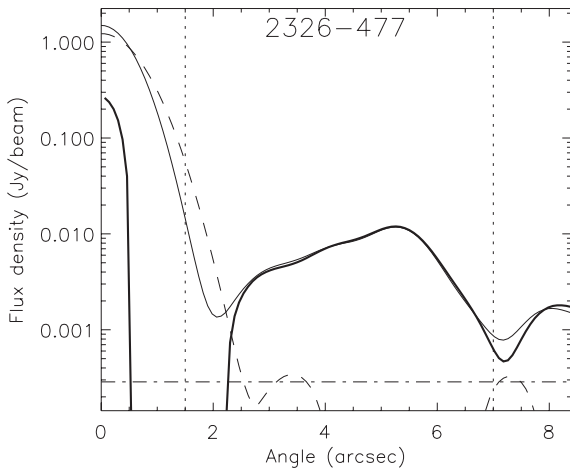


Figure 2. (Continued)

evidence that suggest that the jets in our sample are consistent with this interpretation.

4.1. Detection Statistics

We detected 12 X-ray emitting jets among the 19 targets observed, half of which were previously reported. Of these detections, nine were in the A subsample of 10 sources, while only three were in just the B subsample: 0234+285, 2007+777, and 2123-463. If detections were equally likely in both B and A samples, then the a priori probability that there would be <4 B detections would be 7.3%, so the hypothesis that the morphology selection is just as good as a flux selection is marginally acceptable. Of the aggregate of 39 sources from Paper I and this paper, 22 were in the A subsample. Jets were detected in 16 of the 22 images, for a 73% detection rate. This detection rate is similar to that obtained by Sambruna et al. (2004) and Marshall et al. (2005). The jet detection rate for the B-only subsample is not as high. Of all the B-only quasars, 7 of 17 jets are detected (41%). These rates could be biased, however,

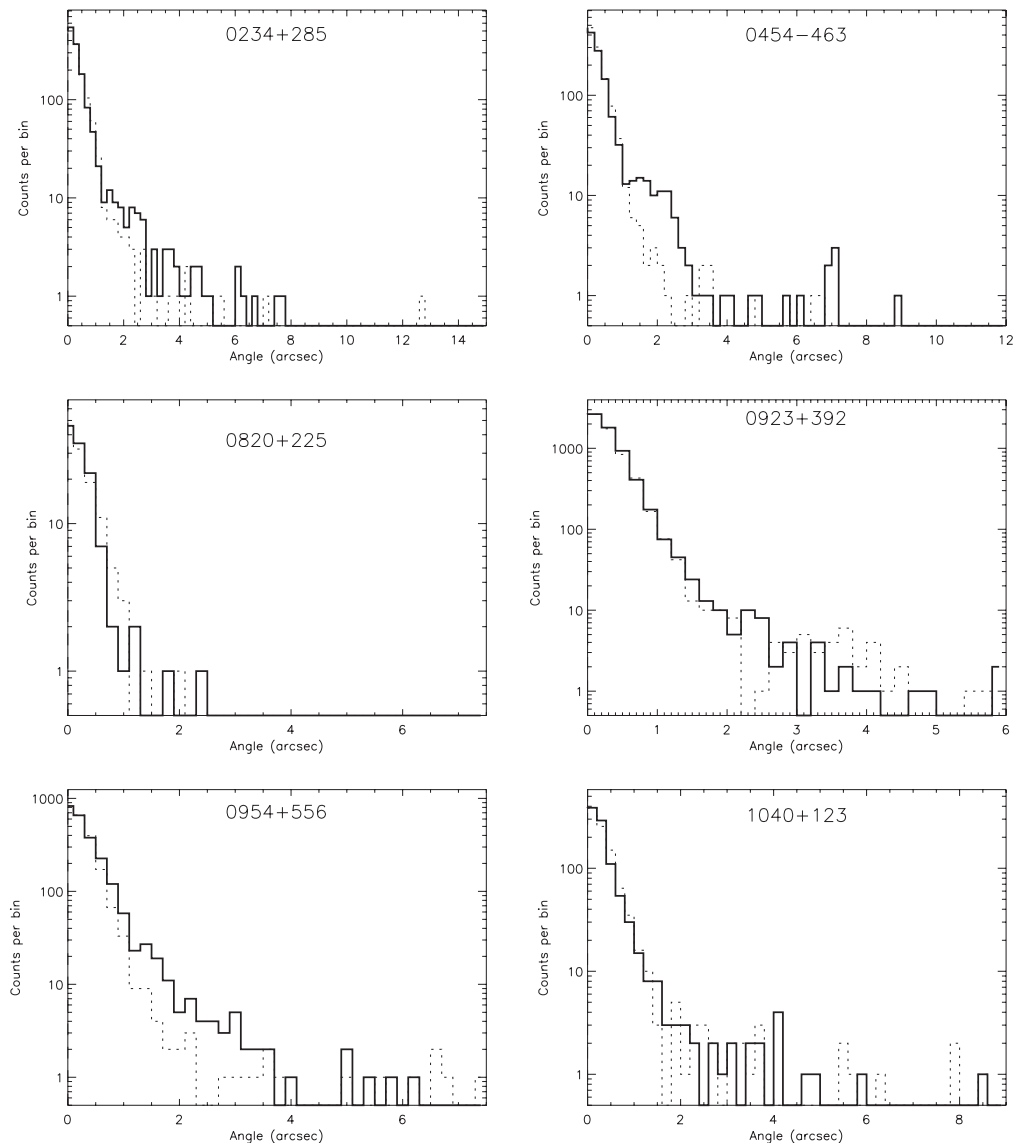


Figure 3. Histograms of counts from the X-ray images. The solid, bold lines give the profiles along the position angles of the jets, as defined in Table 3 and used in Figure 2. The dashed histograms give the profiles at a position angle 180° opposite to the jet—the counterjet direction. The counterjet profiles provide a measure of the significance of the X-ray emission from the jet because there are no clearly detected counterjets.

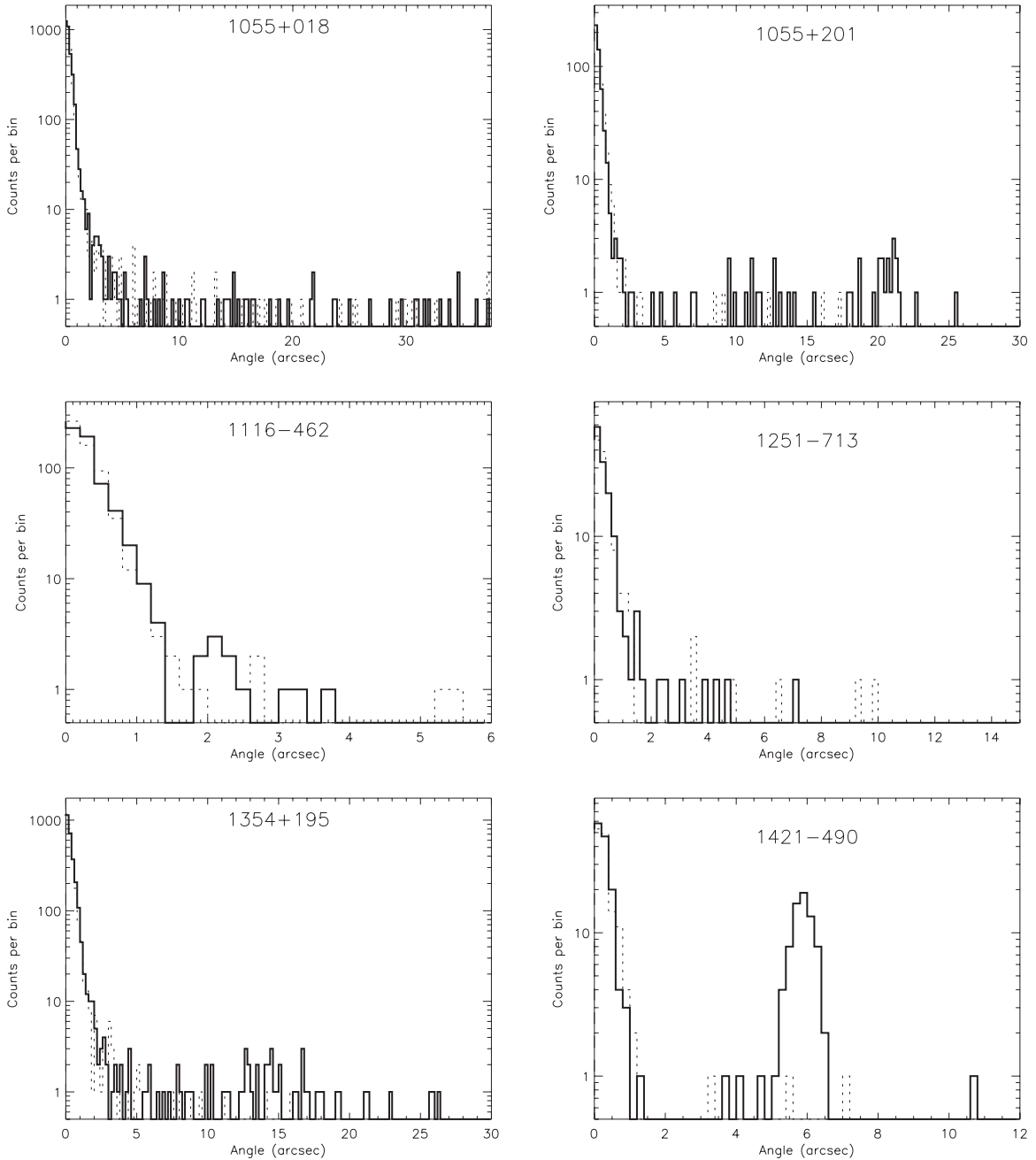


Figure 3. (Continued)

because those targets observed in other programs were generally the brightest A targets.

The typical X-ray flux densities of detected jets are greater than 2 nJy. Flux densities in the radio band were generally lower in B targets than in A targets while the X-ray flux limits are all about the same; consequently, the lower limits on α_{rx} are higher for the A targets (see Figure 4). However, Figure 5 shows that the distribution of α_{rx} is slightly shifted toward lower values of α_{rx} for B targets compared to A targets, indicating slightly larger X-ray flux densities relative to the jets' radio flux densities as a group. Thus, it appears that morphological selection may yield jets brighter in the X-ray band. However, the distribution differences are not statistically significant, due to small number of detected sources in the B subsample. Furthermore, due to the systematically higher redshifts of the B subsample, jet detection

rate differences between the two subsamples may result from redshift dependences.

4.2. Modeling the X-ray Emission

4.2.1. Distribution of α_{rx} and Redshift Dependence

As in Paper I, there are bright X-ray jets even in sources with weak extended radio flux, confirming that the ratio of the X-ray to radio flux densities has a wide range (see Figure 5). The $\pm 1\sigma$ width of the α_{rx} distribution is about 0.15—a factor of 15 in R , the ratio of the X-ray and radio flux densities (as extrapolated to a common frequency; see Appendix B). The jets' radio flux densities extend over a factor of almost 100 for the detected jets in our sample. While there is a general trend that the brightest jets are detected most often, it is clear that predicting the

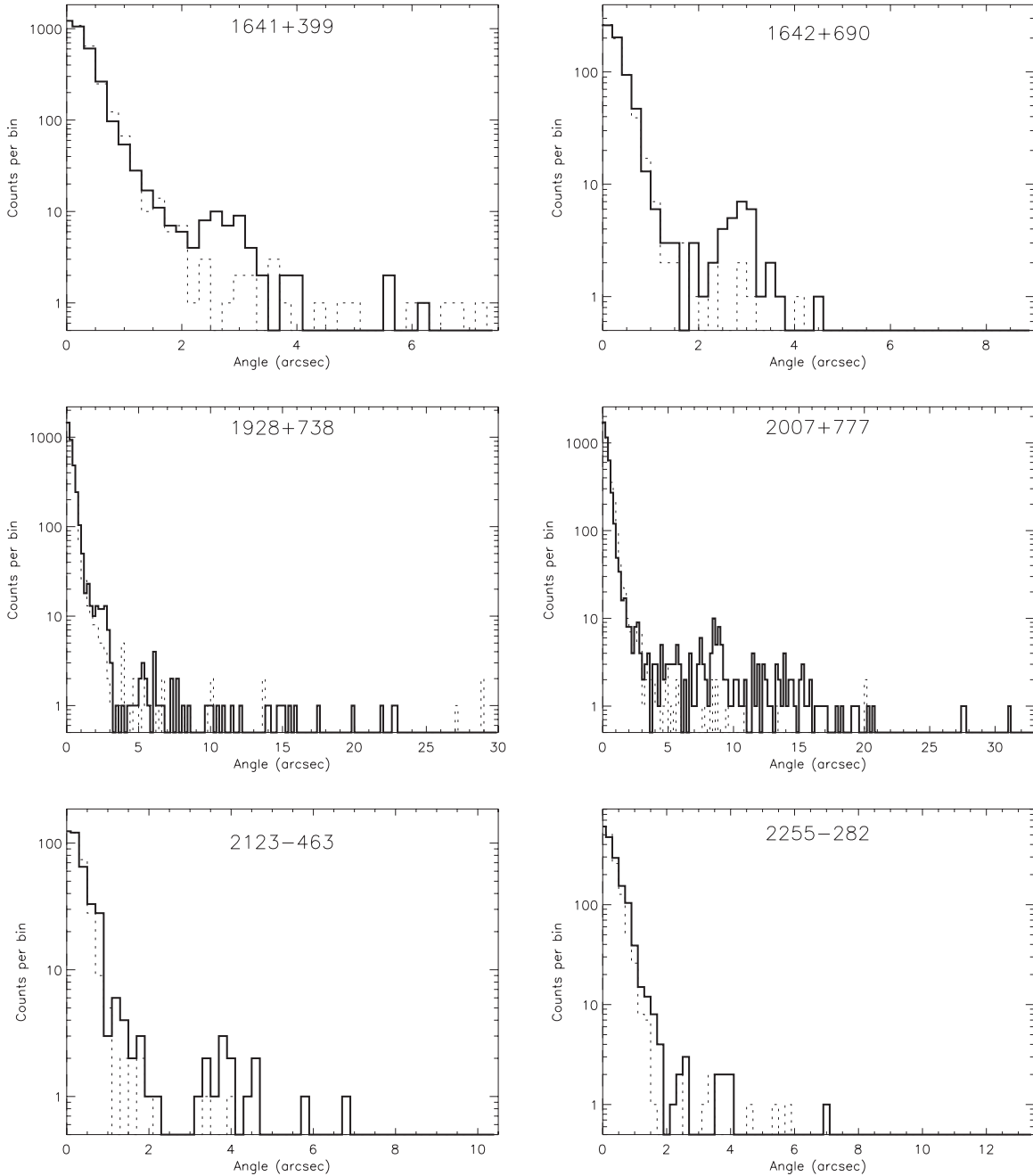


Figure 3. (Continued)

X-ray flux from the radio knot flux densities is risky, so a shallow survey is practically the only efficient means for finding jets that are X-ray bright. We note that the two jets detected out of four exposures longer than 10 ks would have been detected with just the first 10 ks.

Whereas detailed individual analyses of the brighter quasar jets can test physical models (e.g., Schwartz et al. 2006; Perlman et al. 2010), we explore here how even relatively short exposures can prove useful for statistical tests of the model in which the X-rays result from IC scattering of CMB photons by relativistic electrons in a jet moving with high bulk Lorentz factor nearly along the line of sight (the IC-CMB model). Particular support for this model arises in individual cases where the optical flux lies below the radio to X-ray interpolation,

indicating that synchrotron radiation from a single population of relativistic electrons cannot fit the spectral energy distribution. We note that our objective is comparable to that examined by Cheung (2004) and Kataoka & Stawarz (2005) but with a larger, more homogeneous sample of FR II quasars containing a much larger fraction of sources with $z > 1$. We limit our analysis to the 34 quasars in our sample with known redshifts greater than 0.1 so as to avoid the slight contamination by flat spectrum, core-dominated FR I radio galaxies.

Following Harris & Krawczynski (2002, HK02) and Paper I (see also Appendix B) in the context of the IC-CMB model, R can be related to the equipartition magnetic field in the absence of beaming, B_1 , derived from the radio flux and emitting volume, and beaming parameters $\Gamma = (1 - \beta^2)^{-1/2}$ and $\mu = \cos \theta$, where

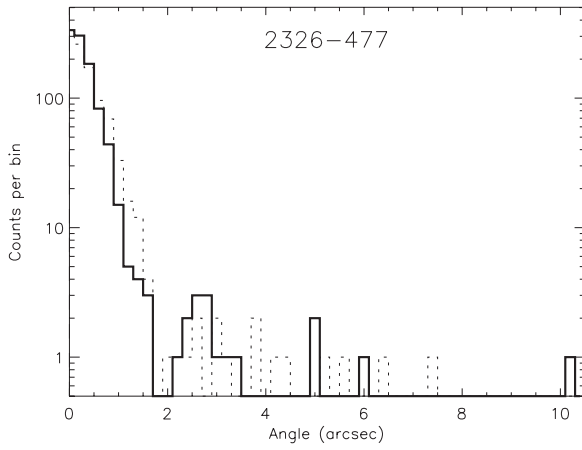


Figure 3. (Continued)

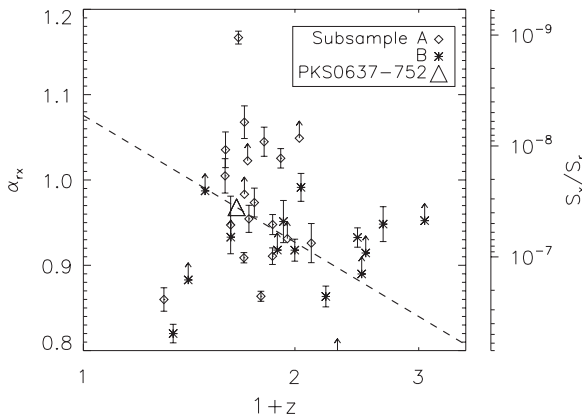


Figure 4. Plot of $\alpha_{r,x}$ against redshift. A value of $\alpha_{r,x}$ of 1.0 indicates that there is equal power per logarithmic frequency interval in the X-ray and radio bands. The right-hand axis gives the ratio of the X-ray to radio flux densities, assuming $\nu_r = 8.64 \times 10^9$ Hz and $\nu_x = 2.4 \times 10^{17}$ Hz. A change of about 0.13 in $\alpha_{r,x}$ results from a $\times 10$ change in the X-ray flux relative to the radio flux. The result for PKS 0637–752 is given for comparison. The dashed line gives the dependence of $\alpha_{r,x}$ on z under the assumptions that the X-ray emission results only from inverse Compton scattering off of the cosmic microwave background and that the beaming parameters for all jets are the same as those of PKS 0637–752, so that the X-ray to radio flux density ratio would increase as $(1+z)^{3+\alpha}$ (see Equation (1)). Clearly, there is a wide distribution of the observed values of $\alpha_{r,x}$, indicating that the beaming parameters vary widely.

θ is the angle to the line of sight, as

$$R = A \left(\frac{b}{B_1} \frac{(1-\beta)(1+\mu)}{(1-\mu\beta)^2} \right)^{(1+\alpha)} (1+z)^{3+\alpha}, \quad (1)$$

where $A = 6.9 \times 10^{-21}$ and $b = 38080$ G are constants and B_1 has units of G. The spectral index, α , defined by $S_\nu \propto \nu^{-\alpha}$, is assumed to be 0.8 for both the X-ray and radio bands. Equation (1) can be solved to give μ for an assumed value of β (Paper I) or for β for a given value of μ (Marshall et al. 2006; H. L. Marshall & T. Cheung 2011, in preparation). In Appendix B, we show that the HK02 approach is equivalent to the IC model developed by Dermer (1995) which was later written in a form independent of the system of units by Worrall (2009).

The quantity R depends on $\alpha_{r,x}$ via the relationship $R = (\nu_x/\nu_r)^{\alpha-\alpha_{r,x}}$, so $\alpha_{r,x}$ depends on quasar redshift in the IC–CMB model. No significant correlation of $\alpha_{r,x}$ with z is apparent in Figure 5. However, with such a broad distribution of $\alpha_{r,x}$ it would be difficult to discern such a trend. We tested the possibility

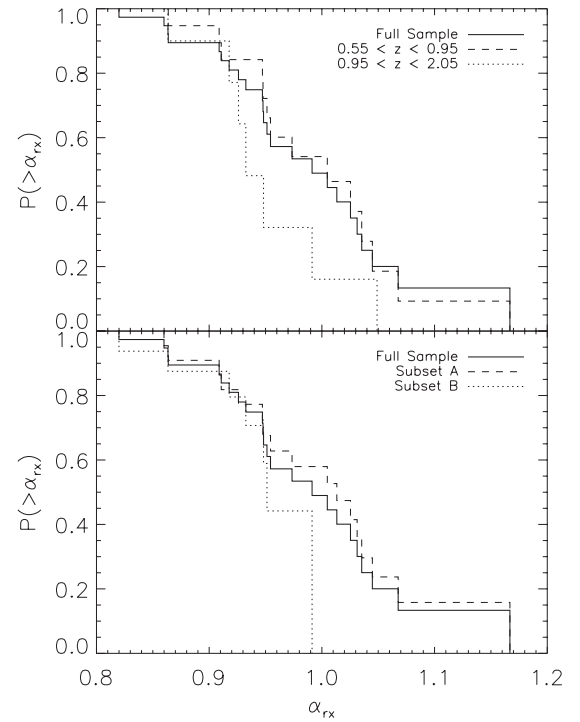


Figure 5. Distribution of $\alpha_{r,x}$ for 39 sources observed so far in our sample. Upper limits are handled by using the Kaplan–Meier method. Top: the sample is divided into two equal groups based on redshift (excluding those with unknown redshifts or $z < 0.1$). The high redshift subsample has marginally smaller values of $\alpha_{r,x}$, i.e., the jets’ X-ray flux densities are slightly larger relative to their radio flux densities. Bottom: the sample is divided according to the A or B selection criterion, where A represents a flux-limited subsample and B represents morphological selection only. The B subset shows slightly smaller values of $\alpha_{r,x}$ but the sample size is rather small.

that $\alpha_{r,x}$ depends on z by splitting the sample into two redshift ranges. For $0.55 < z < 0.95$, the average $\alpha_{r,x}$ is 1.001 ± 0.020 , compared to a value of 0.954 ± 0.019 for $0.95 < z < 2$. The difference is insignificant.

A more sensitive test is to explore the dependence of R upon z . We use the method developed by Marshall (1992) to fit R to the form $(1+z)^a$; details are given in Appendix A. However, B_1 is calculated from observations and depends on redshift according to model assumptions (as discussed below). Generally, we expect $B_1 \propto f(z)$, giving

$$R \propto (1+z)^{3+\alpha} [f(z)]^{-(1+\alpha)}. \quad (2)$$

In the simple case where the distribution of intrinsic magnetic fields is independent of redshift, then we may set $f(z) = 1$. The log likelihood for this case is shown in Figure 6, for which we find $a = 0.7 \pm 1.6$ at 90% confidence ($\Delta\chi^2 = 2.71$). The likelihood ratio test then rejects $a > 3.5$ at $> 99\%$ confidence, whereas we expect $a = 3.8$ for the IC–CMB model.

It is common to estimate the magnetic field in individual sources based on observations and assume minimum energy. We note that a simple dependence of B_1 calculated this way (Tables 4 and 5) with z is not readily apparent in our data (see Figure 7), but other factors entering the calculation of B_1 (particularly, the jet’s radio flux density and angular length) have a broad scatter and probably serve to mask any relationship.

A simple case to consider is one described by Worrall (2009). If source volume is estimated via angular sizes in two dimensions assuming that the path through the jet is independent of redshift, then the volume $V \propto d_A^2 \propto d_L^2/(1+z)^4$, where d_A

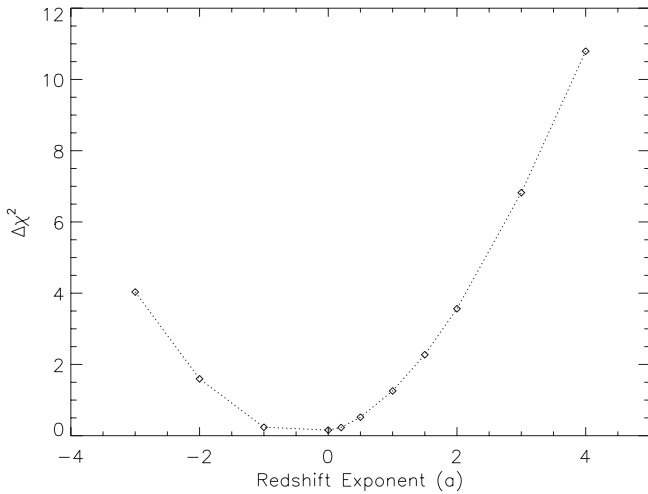


Figure 6. log likelihood dependence on a , where $S_x/S_r \propto (1+z)^a$ under the assumption that the distribution of intrinsic magnetic fields does not depend on redshift. In the IC–CMB model, $a = 3 + \alpha$; this dependence is ruled out at better than 99.5% confidence for $\alpha > 0.5$. Thus, if the IC–CMB mechanism is responsible for most of the X-ray emission from quasar jets, then other jet parameters such as the magnetic field or Lorentz factor must depend on z in a compensatory fashion.

and d_L are angular and luminosity distances, respectively.¹³ For minimum energy (or equipartition),

$$f(z) \propto \left[\frac{L_s(z)}{V(z)} \right]^{1/(\alpha+3)} \propto \left[\frac{(1+z)^{(\alpha-1)} d_L^2}{V(z)} \right]^{1/(\alpha+3)} \propto (1+z). \quad (3)$$

Here, we have assumed that the minimum-energy field is measured over fixed electron energies in the rest frame of the source. In the case of calculations over fixed frequencies in the observer’s frame (10^7 to 10^{15} Hz are actually adopted for B_1 in Tables 5 and 6) the result is similar, with exponent $2/7$ rather than $1/(\alpha + 3)$, where (as in Paper I) we assume that $\alpha = 0.8$. Combining Equations (2) and (3) gives

$$R \propto (1+z)^2 \quad (4)$$

which agrees with Equation (13) of Worrall (2009). Under this assumption for the jet volume, the fit value of a is consistent with the prediction of the IC–CMB model.

Alternatively, the volume can be estimated assuming that the jet is a cylinder of constant angular radius matched to *Chandra*’s resolution (as adopted in Paper I and used for the estimates of B_1 in this paper). Here, $V(z) \propto d_A^3$, so d_A does not cancel in the equations, giving

$$f(z) \propto (1+z) d_A^{-1/(\alpha+3)}. \quad (5)$$

In this case, $f(z)$ does not have a simple dependence on $(1+z)$ over the redshift distribution of our sources. Instead, we define a new quantity that is derived from the observed data for each source, $Q \equiv R B_1^{1+\alpha}$. In the IC–CMB model, $Q \propto (1+z)^{3+\alpha}$, while our fit to $Q \propto (1+z)^a$ gives $a = 1.35 \pm 1.36$ (at 90% confidence). Here $a = 3 + \alpha$ is rejected at better than

¹³ The values of the volume reported in Paper I were computed incorrectly, so we provide the correct values of V , B_1 , K in Table 5. The sense of the error is that the volumes in Paper I were too large, causing B_1 and K to be too small by about a factor of 10 in some cases, and θ to be about a factor of 2 larger than we now find.

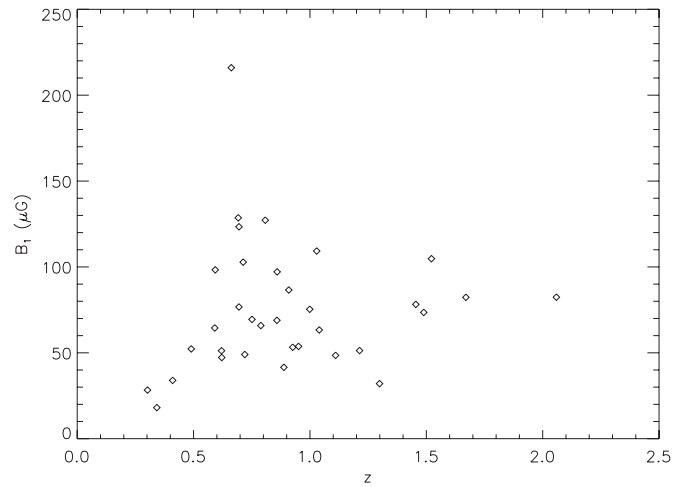


Figure 7. Estimated minimum-energy values of jet magnetic fields in the absence of beaming, B_1 , plotted against the redshift of the quasar. Although the calculation of B_1 depends on z , there is no apparent correlation, probably because of the wide scatter in other jet measurements (particularly radio flux and the jet’s angular length) that go into the calculation of B_1 .

99% confidence for $\alpha > 0.5$. The best fit resulted in a smaller index, $a = -0.37 \pm 1.35$, and $a = 3.5$ is still rejected at 99% confidence.

Thus, we have two circumstances where the IC–CMB model can be ruled out and one in which it is still viable, where the jet volume is computed using the assumption described above (Equation (4)). The circumstances involve different but plausible conditions dictating the dependence of the intrinsic magnetic field with redshift, so it is difficult to provide a definitive test using these data alone. The factors that go into estimating the magnetic field bear further investigation as source details are obtained in follow-up radio, X-ray, and optical observations in order to develop a refined test of the model. One source of uncertainty in our method of using the X-ray and radio emission for the entire jet rather than for individual knots is that the jet geometries are often complex. Furthermore, the termination knots may also be included in some cases, where it is unlikely that both the radio and X-ray emission regions are moving relativistically relative to the nucleus. This paper is concerned primarily with shallow observations and deeper individual analyses would be best suited to examine these more subtle issues.

4.2.2. Angles to the Line of Sight

As in Paper I, we computed the distribution of angles to the line of sight for these kpc-scale jets, under the assumptions that (1) X-rays arise from the IC–CMB mechanism and (2) all jets have a common Lorentz factor, Γ . Kellermann et al. (2004) estimated the intrinsic Lorentz factor distribution for a flux-selected set of core-dominated quasars, finding that it appears broad, with most values of Γ between 5 and 25 (see their Figure 9). For now, we assume $\Gamma = 15$ and find that θ ranges from 6° to 13° for the quasars in our sample (see Table 5). For these sources, the Doppler factor, δ , is in the range 3–8, compared with the assumed Lorentz factor of 15.

Because the jet surface brightness is not constant and the spatial variations between the radio and X-ray bands can differ, it is possible that systematic errors result from considering the entire jet. To estimate the effect of restricting attention to knots within the jets, we have computed X-ray and radio flux densities

Table 4
Quasar Knot Measurements^a

Target	P.A. (°)	θ_i (")	θ_o (")	S_r (mJy)	ν_r (GHz)	Count Rate (10^{-3} cps)	S_x (nJy)	α_{rx}	P_{knot}	X?
0234+285	0	1.5	3.5	35.6 ± 1.4	1.42	4.32 ± 0.88	4.3	0.84 ± 0.01	$<1e-10$	Y
0234+285	0	4.5	6.5	3.1 ± 1.4	1.42	0.44 ± 0.27	0.4	0.83 ± 0.04	$3.66e-03$	Y
0454-463	125	1.5	3.5	38.7 ± 0.8	8.64	10.91 ± 1.48	10.9	0.88 ± 0.01	$<1e-10$	Y
0820+225	-90	1.5	3.5	50.2 ± 2.0	1.42	0.00 ± 0.25	<0.8	>0.95	$6.32e-01$	N
0923+392	-80	1.5	3.5	-1.0 ± 7.1	4.86	-0.43 ± 0.58	<1.3	>0.91	$8.45e-01$	N
0954+556	-60	1.5	3.5	95.8 ± 4.4	4.86	1.34 ± 0.23	1.3	1.02 ± 0.01	$<1e-10$	Y
1040+123	-80	1.5	3.5	41.2 ± 2.3	4.86	0.00 ± 0.53	<1.6	>0.96	$5.34e-01$	N
1055+018	180	1.5	3.5	6.7 ± 0.3	4.86	0.11 ± 0.69	<2.2	>0.84	$4.40e-01$	N
1055+201	0	1.5	3.5	18.5 ± 0.8	1.46	0.21 ± 0.48	<1.6	>0.86	$3.23e-01$	N
1055+201	0	9.0	13.0	10.5 ± 1.1	1.46	1.07 ± 0.56	1.1	0.85 ± 0.03	$5.94e-04$	Y
1116-462	-85	1.5	3.5	110.8 ± 0.4	8.64	0.53 ± 0.64	<2.5	>1.03	$1.33e-01$	N
1251-713	180	1.5	3.5	1.7 ± 0.6	4.80	0.33 ± 0.33	<1.3	>0.79	$8.03e-02$	N
1354+195	163	2.0	4.0	24.3 ± 0.6	4.86	-0.55 ± 0.65	<1.4	>0.94	$8.95e-01$	N
1354+195	163	4.0	6.0	13.4 ± 0.6	4.86	0.44 ± 0.35	<1.5	>0.90	$3.35e-02$	N
1354+195	163	6.0	8.0	12.0 ± 0.6	4.86	0.33 ± 0.29	<1.2	>0.91	$5.26e-02$	N
1354+195	163	8.0	10.0	13.0 ± 0.6	4.86	0.22 ± 0.31	<1.2	>0.92	$1.85e-01$	N
1354+195	163	10.0	12.0	5.4 ± 0.6	4.86	0.44 ± 0.27	0.4	0.92 ± 0.04	$3.66e-03$	Y
1354+195	163	12.0	14.0	7.9 ± 0.6	4.86	0.99 ± 0.37	1.0	0.90 ± 0.02	$1.11e-07$	Y
1354+195	163	14.0	16.0	7.3 ± 0.6	4.86	0.77 ± 0.37	0.8	0.91 ± 0.03	$2.37e-04$	Y
1421-490	30	5.0	7.0	2704.6 ± 0.8	17.73	12.24 ± 1.52	12.2	1.17 ± 0.01	$<1e-10$	Y
1641+399	-35	1.5	3.5	263.0 ± 3.2	4.86	3.64 ± 0.99	3.6	1.02 ± 0.02	$<1e-10$	Y
1642+690	175	2.0	4.0	59.9 ± 1.6	4.86	2.88 ± 0.66	2.9	0.95 ± 0.01	$<1e-10$	Y
1928+738	-170	2.0	4.0	16.1 ± 0.5	1.42	4.65 ± 0.98	4.6	0.79 ± 0.01	$<1e-10$	Y
2007+777	-105	4.0	6.0	0.9 ± 0.5	1.42	0.50 ± 0.15	0.5	0.77 ± 0.03	$2.48e-08$	Y
2007+777	-105	7.5	9.5	3.3 ± 0.5	1.42	0.97 ± 0.17	1.0	0.79 ± 0.01	$<1e-10$	Y
2007+777	-105	11.0	13.0	1.2 ± 0.5	1.42	0.25 ± 0.09	0.2	0.81 ± 0.03	$1.11e-07$	Y
2007+777	-110	13.0	15.0	0.7 ± 0.5	1.42	0.22 ± 0.09	0.2	0.81 ± 0.03	$1.13e-06$	Y
2007+777	-105	15.0	17.0	1.3 ± 0.5	1.42	0.28 ± 0.10	0.3	0.81 ± 0.03	$1.00e-08$	Y
2123-463	112	1.5	3.5	2.6 ± 0.7	17.73	1.24 ± 0.58	1.2	0.89 ± 0.03	$2.92e-04$	Y
2123-463	112	3.0	5.0	8.0 ± 0.7	17.73	1.39 ± 0.51	1.4	0.95 ± 0.02	$1.11e-07$	Y
2255-282	-70	1.5	3.5	14.5 ± 1.5	4.86	1.26 ± 0.70	1.3	0.92 ± 0.03	$3.72e-03$	Y
2326-477	-110	1.5	3.5	-7.0 ± 0.4	8.64	0.48 ± 0.61	<2.3	>0.75	$1.46e-01$	N

Note. ^a All quantities are defined as in Table 3, except that knots are defined to be detected if $P_{\text{knot}} < 0.0062$, which gives a 20% chance of one false detection in 32 trials.

for a selection of $3'' \times 3''$ regions from the jets. Measurements are given in Table 4 and angles to the line of sight are given in Table 6. The angles usually decrease by a degree or less from the full-jet estimates. For the remainder of this section, we will only consider results for the entire jet, leaving analysis of individual knots to follow-up work which will require deeper X-ray observations with higher knot counts. See Section 3.2 for comments about individual sources and references to more detailed analyses, where available.

Many of these sources are in the MOJAVE program, which consists of VLBI observations of several hundred compact active galaxies and quasars used to measure pc-scale proper motions. Of the 22 sources in common with our sample, we have X-ray data for 14, as listed in Table 7. For all but one quasar of the 22, there is apparent superluminal motion. Values of β_{app} , the apparent velocity of the most rapidly moving pc-scale component relative to c , are given in the table. See the discussion of individual sources for references.

The population modeling by Cohen et al. (2007) based on the MOJAVE sample provides a basis for testing the IC-CMB model for our sample. As a first step, it is important to determine that our sample is a representative subset of the MOJAVE sample. For the flux-limited MOJAVE sample, Cohen et al. (2007) showed that $\sin \theta$ of the pc-scale jets are generally within 50% of $1/\beta_{\text{app}}$. Figure 8 shows that the distribution of $1/\beta_{\text{app}}$ for

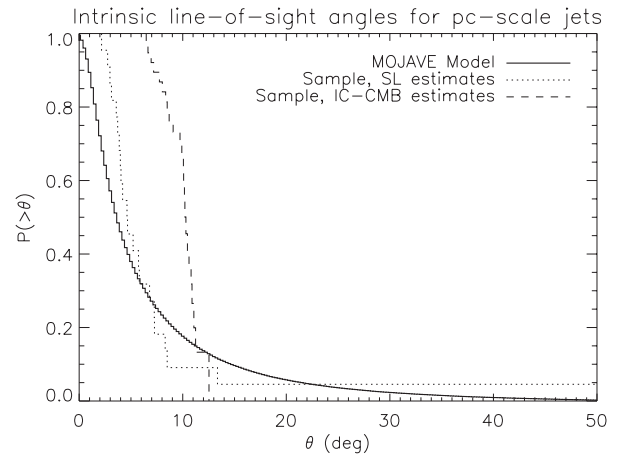


Figure 8. Cumulative distributions of angles to the line of sight, θ , for the model of the MOJAVE sample (Cohen et al. 2007) compared to the distribution of $\theta = 0.5/\beta_{\text{app}}$ for our sample based on superluminal (SL) motion on pc scales (dotted line, where β_{app} is taken from Table 7). The IC-CMB model is used to derive an angle to the line of sight as given by Equation (1).

our sample is as concentrated below about 5° as the MOJAVE sample. Also shown in this figure is the distribution of the values of θ for the large scale jets, as derived from the IC-CMB model. These angles are generally below 11° but systematically

Table 5
Jet Beaming Model Parameters

Target	z	A/B	α_{rx}	R_1^a (10^{-3})	V^b (pc^3)	B_1^c (μG)	K^d	θ^e ($^\circ$)
0208–512	0.999	B	0.92	132.8	1.0e+12	75.	23.6	9
0229+131	2.059	B	> 0.95	< 55.8	1.2e+12	82.	< 6.5	> 13
0234+285	1.213	B	0.86	300.5	2.2e+12	51.	20.4	9
0413–210	0.808	A	1.04	13.0	5.7e+11	127.	13.6	10
0454–463	0.858	A	0.91	149.8	1.3e+12	69.	27.0	8
0745+241	0.410	B	> 0.88	< 230.3	4.7e+11	34.	< 30.2	> 8
0820+225	0.951	A	> 0.93	< 83.3	7.7e+11	54.	< 13.7	> 10
0858–771	0.490	B	> 0.99	< 40.3	5.4e+11	52.	< 15.7	> 10
0903–573	0.695	A	1.07	10.1	6.4e+11	123.	13.1	10
0920–397	0.591	A	1.00	29.8	1.4e+12	64.	14.3	10
0923+392	0.695	A	> 0.98	< 38.8	4.0e+11	77.	< 17.2	> 10
0954+556	0.909	A	1.03	18.4	7.4e+11	87.	10.0	11
1030–357	1.455	B	0.93	103.0	3.9e+12	78.	13.8	10
1040+123	1.029	A	> 1.05	< 12.1	1.0e+12	109.	< 8.8	> 12
1046–409	0.620	A	0.95	80.0	6.2e+11	51.	18.9	9
1055+018	0.888	B	> 0.92	< 123.9	4.9e+12	42.	< 14.2	> 10
1055+201	1.110	A	0.93	92.2	4.5e+12	49.	11.1	11
1116–462	0.713	A	> 1.02	< 22.0	4.1e+11	103.	< 16.5	> 10
1202–262	0.789	A	0.86	335.5	1.2e+12	66.	43.7	7
1354+195	0.720	A	0.95	64.8	3.1e+12	49.	14.2	10
1421–490	0.662	A	1.17	2.4	9.8e+11	216.	10.8	11
1424–418	1.522	B	> 0.91	< 140.6	8.1e+11	105.	< 20.8	> 9
1641+399	0.593	A	1.04	15.4	4.6e+11	98.	15.1	10
1642+690	0.751	A	0.97	46.2	7.9e+11	69.	16.0	10
1655+077	0.621	B	> 0.93	< 94.7	4.9e+11	47.	< 19.1	> 9
1828+487	0.692	A	0.91	145.3	2.4e+11	129.	60.3	6
1928+738	0.302	A	0.86	321.3	7.4e+11	28.	35.9	8
2007+777	0.342	B	0.82	685.0	1.0e+12	18.	32.7	8
2052–474	1.489	B	> 0.89	< 214.4	6.7e+11	74.	< 18.9	> 9
2101–490	1.040	B	0.99	37.6	3.4e+12	63.	9.4	11
2123–463	1.670	B	0.95	87.6	1.5e+12	82.	11.1	11
2251+158	0.859	A	0.95	72.9	1.1e+12	97.	25.5	8
2255–282	0.926	B	0.95	68.5	1.6e+12	53.	12.5	10
2326–477	1.299	B	> 0.79	< 1111.1	1.4e+12	32.	< 24.4	> 9

Notes.

^a The ratio of the inverse Compton to synchrotron luminosities; see Paper I.

^b V is the volume of the synchrotron emission region. Note that the values reported in Paper I are incorrect and are corrected here.

^c B_1 is the minimum-energy magnetic field; see Paper I.

^d K is a function of observable and assumed quantities; large values indicate stronger beaming in the IC–CMB model. See Paper I for details.

^e The bulk Lorentz factor is assumed to be 15.

larger than the angles estimated for the pc-scale jets. This difference is not surprising because the pc-scale and kpc-scale jets are not aligned in projection on the sky but suggests that most misalignments are small. P.A. differences are given in Table 7.

We now attempt to quantify the comparison of the angles to the line of sight for the kpc-scale jets with information in the pc-scale jets. In Appendix C, we show how one may estimate the range of the kpc-scale angles to the line of sight by using only the values of β_{app} for the pc-scale jets and the P.A. differences. At the same time, intrinsic bend angles, ζ , are estimated and a probable range for these angles are computed. The results are given in Table 7 and shown in Figure 9, where it can be seen that these independent estimates are generally consistent. However, there are some notable exceptions, particularly where the angles from the IC–CMB calculation are of order a factor of two larger than those based on geometry and superluminal motion of the pc-scale jet. For these exceptions, one may infer that the jets decelerate substantially from pc to kpc scales.

5. SUMMARY

We have reported new imaging results using the *Chandra X-ray Observatory* for quasar jets selected from the sample originally defined by Marshall et al. (2005, Paper I). For the larger sample, we confirm many results in Paper I: (1) quasar jets can be readily detected in X-rays using short *Chandra* observations, (2) no X-ray counterjets are detected, and (3) the line-of-sight angles of the kpc-scale jets are small in the IC–CMB model in which the X-ray emission results from IC upscattering of CMB photons by relativistic electrons in a jet moving with large bulk Lorentz factor.

In addition, we have several new results: (1) depending on how the jet volume is computed, which determines how estimates of the intrinsic magnetic field may vary with z , S_x/S_r values do not increase with $1+z$ at the level expected in a simple IC–CMB model, and (2) the pc-scale jet speed and orientation indicate that some kpc-scale jets are oriented closer to the line of sight than inferred from the IC–CMB model, suggesting instead that these jets decelerate from pc to kpc scales. Other

Table 6
Quasar Knot Beaming Model Parameters^a

Target	$\alpha_{r,x}$	R_1 (10^{-3})	V (pc^3)	B_1 (μG)	K	θ ($^\circ$)
0234+285	0.84	461.6	509.	65.	32.9	9
0454-463	0.88	254.0	403.	84.	44.2	8
0820+225	>0.95	<57.3	440.	63.	<13.0	>12
0923+392	>0.85	<416.8	321.	37.	<30.7	>9
0954+556	1.00	24.8	424.	92.	12.6	12
1040+123	>0.96	<54.7	465.	82.	<15.2	>12
1055+018	>0.84	<461.5	415.	45.	<32.1	>9
1055+201	>0.88	<212.2	487.	59.	<21.3	>10
1055+201	0.85	363.9	975.	36.	17.8	11
1116-462	>0.75	<2466.4	331.	27.	<58.8	>7
1354+195	>0.94	<82.6	335.	60.	<19.9	>11
1354+195	>0.90	<158.2	335.	51.	<24.1	>10
1354+195	>0.91	<143.3	335.	49.	<22.1	>10
1354+195	>0.92	<127.0	335.	50.	<21.2	>10
1354+195	0.92	117.8	335.	39.	15.8	12
1354+195	0.90	179.2	335.	44.	22.2	10
1354+195	0.91	151.0	335.	43.	19.8	11
1421-490	0.75	2462.5	456.	72.	114.3	5
1421-490	>0.92	<138.9	456.	56.	<18.1	>11
1641+399	1.02	19.8	261.	112.	19.6	11
1642+690	0.95	68.6	352.	79.	22.8	10
1928+738	0.79	1102.5	80.	34.	84.8	6
2007+777	0.77	1823.9	102.	16.	48.7	8
2007+777	0.79	1115.7	102.	22.	51.5	8
2007+777	0.81	802.3	102.	16.	32.0	9
2007+777	0.81	810.3	102.	16.	31.0	9
2007+777	0.81	828.9	102.	17.	33.3	9
2123-463	0.85	423.0	540.	57.	18.6	11
2123-463	0.85	475.9	540.	57.	19.9	11
2255-282	0.92	124.5	430.	58.	18.9	11
2326-477	>0.75	<2525.8	522.	35.	<41.9	>8

Note. ^a All quantities are defined as in Table 5. Knots are defined in Table 4.

results also cast doubt upon a pure IC-CMB interpretation of the X-ray emission from kpc-scale jets (Uchiyama et al. 2006; Jester et al. 2006), tending toward an interpretation requiring a high energy population of electrons producing synchrotron emission observable in the optical to X-ray bands but undetected in the radio band. While we may not be able to verify this interpretation using these short X-ray exposures, our results do indicate that the large scale jets are likely to be seen in projection at small angles to the line of sight, as assumed in the IC-CMB model. In this case, in order to avoid substantial IC emission, the kpc-scale jets must have smaller Lorentz factors than their pc-scale counterparts.

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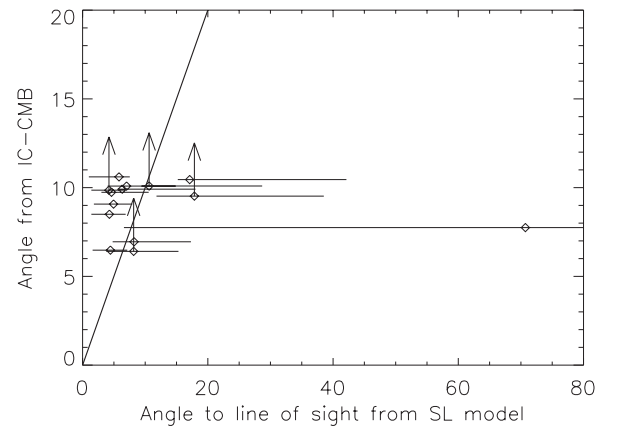


Figure 9. Comparison of angles of kpc-scale jets to the line of sight for two computation methods. The abscissa is determined from geometric constraints using the apparent speed of the superluminal (SL) components in the pc-scale jet, combined with the difference between the position angles of the pc-scale and kpc-scale jets by the method described in Appendix C. The IC-CMB model is used to derive an angle to the line of sight as given by Equation (1) to provide the ordinate. The solid line indicates where these two angles are equal. These independent estimates are generally consistent. However, there are some notable exceptions, particularly where the angles from the IC-CMB calculation are $\times 2$ larger than those based on geometry and SL motion of the pc-scale jet. For these exceptions, one may infer that the jets decelerate substantially from pc scales to kpc scales.

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Facilities: CXO(ACIS), ATCA, VLA

APPENDIX A

REGRESSION WITHOUT LIMITS

Here, we give the formal method for handling a linear regression where some of the data points have such large error bars that a logarithmic transformation is mathematically disallowed. One approach for handling such data is to degrade the poor measurements by assigning limits to them and then using a regression method developed by Avni & Tananbaum (1986). An alternative is to use the error bars and distinguish between the observation and the intrinsic quantities. A regression method using all error bar information was presented by Marshall (1992) that we shall use here. See that paper for a discussion of the approach.

Our objective is to determine a in the model

$$\log R = a \log x + b, \quad (\text{A1})$$

where $x \equiv 1 + z$. The data set is R_n, σ_n, x_n , where R_n are the estimated luminosity ratios that have uncertainties σ_n that may be large. Note that some R_n values may be negative due to large background and low intrinsic R values. Following Marshall (1992), we define the probability model for the true R , when given x and the model parameters as

$$p(R; x; a, b, s) = \frac{1}{(2\pi)^{1/2}s} \exp\left(-\frac{(\log R - a \log x - b)^2}{2s^2}\right), \quad (\text{A2})$$

where s is the standard deviation of the population about the trend line we are fitting. The likelihood for the observed

Table 7
Quasar Jet Orientations^a

Name	P.A.-kpc	P.A.-pc	β_{app}	Ref. ^b	θ_{kpc}			ζ^c			α_{rx}^d	θ^d
					min	mid	max	min	mid	max		
0106+013	-175	-120	26.50 ± 3.90	1	3.6	4.2	11.7	1.8	2.5	11.2	...	...
0234+285	-20	-10	12.27 ± 0.84	1	1.8	4.9	7.9	1.0	1.2	5.2	0.86	9.1
0707+476	-90	-20	6.74 ± 0.50	2	16.0	18.0	43.8	8.0	11.2	41.9	...	...
0745+241	-45	-60	7.90 ± 1.30	3	3.8	8.2	15.3	2.0	2.7	11.8	>0.74	6.4
0748+126	130	115	18.37 ± 0.82	1	1.8	3.5	6.7	1.0	1.2	5.1	...	...
0923+392	75	-78	4.29 ± 0.43	1	11.8	17.9	38.5	6.2	8.5	33.9	>0.97	9.5
0953+254	-115	-120	12.40 ± 0.40	3	1.0	4.7	6.1	0.6	0.6	2.6	...	...
1055+018	180	-63	11.00 ± 1.00	1	9.4	10.6	28.7	4.8	6.6	27.4	>0.92	10.1
1055+201	-10	-5	10.00 ± 4.30	3	1.0	5.8	7.5	0.6	0.7	3.2	0.91	10.6
1354+195	165	145	9.87 ± 0.06	2	4.0	7.0	14.9	2.0	2.8	12.5	0.95	10.1
1502+106	160	120	14.80 ± 1.20	1	5.0	6.3	16.6	2.6	3.5	15.5	...	...
1641+399	-25	-95	19.27 ± 0.52	1	5.6	6.3	18.0	2.8	4.0	17.3	1.04	9.9
1642+690	170	-166	16.00 ± 1.80	3	3.0	4.6	10.5	1.6	2.1	9.2	0.97	9.7
1655+077	-50	-40	14.40 ± 1.10	1	1.4	4.2	6.8	0.8	1.0	4.4	>0.97	9.9
1823+568	90	-161	20.86 ± 0.49	1	5.2	5.9	16.8	2.6	3.7	16.2	...	...
1828+487	-40	-30	13.66 ± 0.39	1	1.6	4.4	7.1	0.8	1.0	4.6	0.91	6.5
1928+738	-170	170	8.43 ± 0.34	1	4.8	8.2	17.3	2.4	3.3	14.5	0.83	6.9
2007+777	-105	-95	0.82 ± 0.50	3	6.6	70.7	96.3	9.4	13.2	46.5	0.82	7.7
2201+315	-110	-140	7.88 ± 0.41	1	7.4	10.2	24.4	3.8	5.1	22.1	...	...
2230+114	135	160	15.41 ± 0.65	1	3.2	4.9	11.3	1.6	2.2	9.9	...	...
2251+158	-50	-60	14.19 ± 0.79	1	1.4	4.3	6.9	0.8	1.0	4.5	0.95	8.5
2255-282	-70	-135	6.90 ± 1.00	2	15.2	17.1	42.1	7.6	10.6	40.2	0.95	10.5

Notes.

^a All angles are in degrees. Position angles (P.A.) are defined relative to north, positive to the east. The min, mid, and max values give the minimum, 50%, and 10% probability points for the given angle. *Chandra* data for some sources were not yet available.

^b References for values of β_{app} : (1) Lister et al. 2009a; (2) M. L. Lister et al. 2011, in preparation; (3) Kellermann et al. 2004.

^c The quantity ζ is the angle between the pc-scale and kpc-scale jets in the frame of the quasar. See Equation (C2).

^d From Table 5.

values, given this model and the (Gaussian) uncertainties on the measurements, is

$$L = \prod_n p'(R_n; x_n, \sigma_n; a, b, s) \\ = \prod_n \int_0^\infty p(R; x_n; a, b, s) \frac{1}{(2\pi)^{1/2} \sigma_n} e^{-\frac{(R_n - R)^2}{2\sigma_n^2}} dR \quad (\text{A3})$$

so that the minimization statistic that is distributed as χ^2 is $-2 \log L$. The integration interval is set by the physical condition that R cannot truly be less than zero.

APPENDIX B

THE DEPENDENCE OF R UPON BEAMING PARAMETERS

We have used the formalism of Harris & Krawczynski (2002, HK02) in Equation (1). We could just as well have used the derivation by Dermer (1995, D95). We now show that these two approaches yield the same dependence of R upon μ , β , and z .

Much of the reconciliation comes in the definition of terms. Translating from D95's notation to HK02 terms, $\beta_\Gamma = v/c$ becomes β , $\mu_e = \mu$ is the cosine of the emission angle in the rest frame of the relativistically moving jet knot and corresponds to μ'_j , while μ_{obs} is the cosine of the angle of the jet to the observer's line of sight and corresponds to μ . The identity cited by D95 just before Equation (7) is

$$\Gamma(1 + \mu) = D(1 + \mu_{\text{obs}})/(1 + \beta_\Gamma) \quad (\text{B1})$$

corresponds to the readily proved identity in HK02 notation

$$\Gamma(1 + \mu'_j) = \delta(1 + \mu)/(1 + \beta), \quad (\text{B2})$$

where D (in D95 notation) is $\delta = \frac{1}{\Gamma(1 - \beta\mu)}$, the Doppler boost factor in HK02 notation.

D95's Equations (7) and (8) define the IC-CMB flux, S_C , and the synchrotron flux, S_{syn} , so taking the ratio gives

$$R \equiv \frac{S_x(v/v_x)^{-\alpha}}{S_r(v/v_r)^{-\alpha}} = S_C/S_{\text{syn}} \\ = \frac{3u_{\text{iso}}^* D^{1+\alpha} \left[\frac{1 + \mu_{\text{obs}}}{1 + \beta_\Gamma} \right]^{1+\alpha}}{2u_B} (\epsilon_B/\epsilon^*)^{1-\alpha} \quad (\text{B3})$$

in D95 notation, where u_{iso}^* is the monochromatic, isotropic, radiation density in the host galaxy's rest frame; u_B is the magnetic field energy density in the knot rest frame; $\epsilon_B \equiv B/B_Q$ for $B_Q = 4.414 \times 10^{13}$ G; and ϵ^* is a dimensionless form of the photon energy of the isotropic radiation in the host rest frame. In general, $u_{\text{iso}}^* = u_{\text{iso},0}^*(1+z)^4$ and $\epsilon^* = \epsilon_0^*(1+z)$, where the subscript 0 indicates the corresponding quantities at the current epoch ($z = 0$). Equation (B3) is then the same as Equation (7) of Worrall (2009) who expresses it in a form fully independent of the system of units by using the gyrofrequency, ν_g , in place of ϵ_B .

When B is estimated using minimum-energy arguments, then $B = B_1/\delta$ (HK02). Substituting gives

$$R = \frac{C_0}{B_1^{1+\alpha}} \left[\frac{\delta^2(1 + \mu)}{1 + \beta} \right]^{1+\alpha} (1 + z)^{3+\alpha} \quad (\text{B4})$$

in HK02 notation, where $C_0 = 6\pi u_{\text{iso},0}^* (B_Q \epsilon_0^*)^{\alpha-1}$.

Substituting the identity from Equation (B2) and rearranging gives

$$\Gamma\delta(1 + \mu'_j) \propto B_1(R/R_0)^{1/(1+\alpha)} (1 + z)^{-(3+\alpha)/(1+\alpha)} \quad (\text{B5})$$

which has identical dependences on z , β , and μ as derived by HK02. The dependence on beaming parameters is also the same as given by Worrall (2009, Equation (13)). Worrall (2009) also pointed out that B_1 depends on z in a model-dependent way, so the dependence on z is not the same as derived here.

APPENDIX C

LIMITING ANGLES TO THE LINE OF SIGHT

We follow and extend the analysis of Conway & Murphy (1993), where they estimate jet bend angles. In their notation, θ is the angle of the jet to the line of sight before a bend, ζ is the magnitude of the jet bend, ϕ is a phase angle giving the rotation of the bent jet about the axis defined by the jet before the bend, and η is the apparent bend, as projected on the sky. For this definition,

$$\tan \eta = \frac{\sin \zeta \sin \phi}{\cos \zeta \sin \theta + \sin \zeta \cos \theta \cos \phi}. \quad (\text{C1})$$

We may solve this equation for ζ :

$$\tan \zeta = \frac{\tan \eta \sin \theta}{\tan \eta \cos \phi \cos \theta - \sin \phi}. \quad (\text{C2})$$

On the right hand side is the observable, η , the angle to the line of sight that may be estimated using $\sin \theta = 0.5/\beta_{\text{app}}$ (Vermeulen & Cohen 1994; Lister & Marscher 1997), and the unknown phase angle, ϕ . Taking a somewhat Bayesian view, we assume that this angle is uniformly distributed between 0 and 2π , so that one may assign a probability to possible values of ζ . For small θ and η , ζ is also small with high probability; in essence, it is unlikely that the intrinsic jet bends are large if the pc-scale jet is nearly aligned to the line of sight and the P.A. difference is relatively small. In practice, rather than setting $p(\theta) = \frac{1}{2\pi}$ and solving for $p(\zeta)$, we tabulate $\zeta(\phi; \theta, \eta)$, for each source and determine the points at which $p(> \zeta)$ equals 1, 0.5, or 0.10 to give the minimum, mid-range, and maximum values of ζ .

We extend this analysis by defining the angle of the jet to the line of sight after the bend to be ξ . We find

$$\cos \xi = \cos \zeta \cos \theta - \sin \zeta \cos \phi \sin \theta \quad (\text{C3})$$

so that, when given a value of ζ , one may determine ξ . We follow a similar procedure for determining the minimum, mid-range, and maximum values of ξ as was followed for determining the range of possible values for ζ .

REFERENCES

Alberdi, A., et al. 1997, *A&A*, **327**, 513
 Avni, Y., & Tananbaum, H. 1986, *ApJ*, **305**, 83
 Celotti, A., Ghisellini, G., & Chiaberge, M. 2001, *MNRAS*, **321**, L1

Cheung, C. C. 2004, *ApJ*, **600**, L23
 Cohen, M. H., Lister, M. L., Homan, D. C., Kadler, M., Kellermann, K. I., Kovalev, Y. Y., & Vermeulen, R. C. 2007, *ApJ*, **658**, 232
 Conway, J. E., & Murphy, D. W. 1993, *ApJ*, **411**, 89
 Dermer, C. D. 1995, *ApJ*, **446**, L63
 Gabuzda, D. C., Kochenov, P. Y., & Cawthorne, T. V. 2000, *MNRAS*, **319**, 1125
 Gambill, J. K., Sambruna, R. M., Chartas, G., Cheung, C. C., Maraschi, L., Tavecchio, F., Urry, C. M., & Pesce, J. E. 2003, *A&A*, **401**, 505
 Gelbord, J. M., et al. 2005, *ApJ*, **632**, L75
 Godfrey, L. E. H., et al. 2009, *ApJ*, **695**, 707
 Gopal-Krishna, & Wiita, P. J. 2000, *A&A*, **363**, 507
 Hardcastle, M. J. 2006, *MNRAS*, **366**, 1465
 Harris, D. E., & Krawczynski, H. 2002, *ApJ*, **565**, 244
 Homan, D. C., Kadler, M., Kellermann, K. I., Kovalev, Y. Y., Lister, M. L., Ros, E., Savolainen, T., & Zensus, J. A. 2009, *ApJ*, **706**, 1253
 Jackson, C. A., Wall, J. V., Shaver, P. A., Kellermann, K. I., Hook, I. M., & Hawkins, M. R. S. 2002, *A&A*, **386**, 97
 Jester, S., Harris, D. E., Marshall, H. L., & Meisenheimer, K. 2006, *ApJ*, **648**, 900
 Kataoka, J., & Stawarz, Ł. 2005, *ApJ*, **622**, 797
 Kellermann, K. I., et al. 2004, *ApJ*, **609**, 539
 Lister, M. L. 2001, *ApJ*, **562**, 208
 Lister, M. L., & Marscher, A. P. 1997, *ApJ*, **476**, 572
 Lister, M. L., & Smith, P. S. 2000, *ApJ*, **541**, 66
 Lister, M. L., et al. 2009a, *AJ*, **138**, 1874
 Lister, M. L., et al. 2009b, *AJ*, **137**, 3718
 Lovell, J. 1997, PhD Thesis, Univ. Tasmania
 Marshall, H. L. 1992, in *Statistical Challenges in Modern Astronomy*, ed. E. D. Feigelson & G. J. Babu (New York: Springer), 247
 Marshall, H. L., Jester, S., Harris, D. E., & Meisenheimer, K. 2006, in *Proc. The X-ray Universe 2005*, ed. A. Wilson (ESA SP-604; Noordwijk: ESA Publications Division), 643
 Marshall, H. L., et al. 2005, *ApJS*, **156**, 13 (Paper I)
 Murphy, D. W., Browne, I. W. A., & Perley, R. A. 1993, *MNRAS*, **264**, 298
 O’Dea, C. P., Barvainis, R., & Challis, P. M. 1988, *AJ*, **96**, 435
 Ojha, R., et al. 2004, *AJ*, **127**, 3609
 Ojha, R., et al. 2005, *AJ*, **130**, 2529
 Perlman, E. S., et al. 2010, *ApJ*, **708**, 171
 Pérez-Torres, M. A., Marcaide, J. M., Guirado, J. C., & Ros, E. 2004, *A&A*, **428**, 847
 Piner, B. G., Mahmud, M., Fey, A. L., & Gospodinova, K. 2007, *AJ*, **133**, 2357
 Sambruna, R. M., Donato, D., Cheung, C. C., Tavecchio, F., & Maraschi, L. 2008, *ApJ*, **684**, 862
 Sambruna, R. M., Gambill, J. K., Maraschi, L., Tavecchio, F., Cerutti, R., Cheung, C. C., Urry, C. M., & Chartas, G. 2004, *ApJ*, **608**, 698
 Sambruna, R. M., Maraschi, L., Tavecchio, F., Urry, C. M., Cheung, C. C., Chartas, G., Scarpa, R., & Gambill, J. K. 2002, *ApJ*, **571**, 206
 Schwartz, D. A., et al. 2000, *ApJ*, **540**, L69
 Schwartz, D. A., et al. 2006, *ApJ*, **647**, L107
 Schwartz, D. A., et al. 2007, *Ap&SS*, **311**, 341
 Scott, W. K., et al. 2004, *ApJS*, **155**, 33
 Siemiginowska, A., Stawarz, Ł., Cheung, C. C., Harris, D. E., Sikora, M., Aldcroft, T. L., & Bechtold, J. 2007, *ApJ*, **657**, 145
 Tavecchio, F., Ghisellini, G., & Celotti, A. 2003, *A&A*, **403**, 83
 Tavecchio, F., Maraschi, L., Wolter, A., Cheung, C. C., Sambruna, R. M., & Urry, C. M. 2007, *ApJ*, **662**, 900
 Tavecchio, F., Maraschi, L., Sambruna, R. M., & Urry, C. M. 2000, *ApJ*, **544**, L23
 Uchiyama, Y., et al. 2006, *ApJ*, **648**, 910
 Vermeulen, R. C., & Cohen, M. H. 1994, *ApJ*, **430**, 467
 Worrall, D. M. 2009, *A&AR*, **17**, 1
 Xu, W., Readhead, A. C. S., Pearson, T. J., Polatidis, A. G., & Wilkinson, P. N. 1995, *ApJS*, **99**, 297