Extragalactic jets from every angle
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A survey of X-ray emission from 100 kpc radio jets

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Abstract. We have completed a *Chandra* snapshot survey of 54 radio jets that are extended on arcsec scales. These are associated with flat spectrum radio quasars spanning a redshift range z=0.3 to 2.1. X-ray emission is detected from the jet of approximately 60% of the sample objects. We assume minimum energy and apply conditions consistent with the original Felten-Morrison calculations in order to estimate the Lorentz factors and the apparent Doppler factors. This allows estimates of the enthalpy fluxes, which turn out to be comparable to the radiative luminosities.

Keywords. (galaxies:) quasars: general, galaxies: jets, X-rays: jets, X-rays: quasars

1. Introduction

We have used the *Chandra* X-ray observatory (Weisskopf *et al.* (2002), Weisskopf *et al.* (2003), Schwartz (2014)) to carry out a survey for X-ray emission from the radio jets of 54 flat spectrum radio quasars (Marshall *et al.* (2005), Marshall *et al.* (2011)). The parent sample consisted of flat spectrum radio sources with 5 GHz flux density greater than 1 Jy, taken from Murphy, Browne, & Perley (1993) based on VLA observations, or with a flux density at 2.7 GHz greater than 0.34 Jy from ATCA observations by Lovell(1997). We considered only jets longer than $2''$ projected on the sky in order to resolve multiple regions with the half-arcsec resolution of the *Chandra* X-ray telescope. From that parent population we selected objects for which either we predicted an X-ray detection in a 5 ks observation, or which had a one-sided linear radio morphology. Those two selection criteria were motivated by the serendipitous *Chandra* observation of PKS 0637-752 (Schwartz *et al.* (2000), Chartas *et al.* (2000)), scaling the predictions of X-ray flux from the X-ray to radio jet ratio for that object, and considering that one-sided linear morphology might indicate bulk relativistic motion. Such a relativistically beamed jet was the basis of the interpretations of the PKS 0637 X-ray emission as inverse

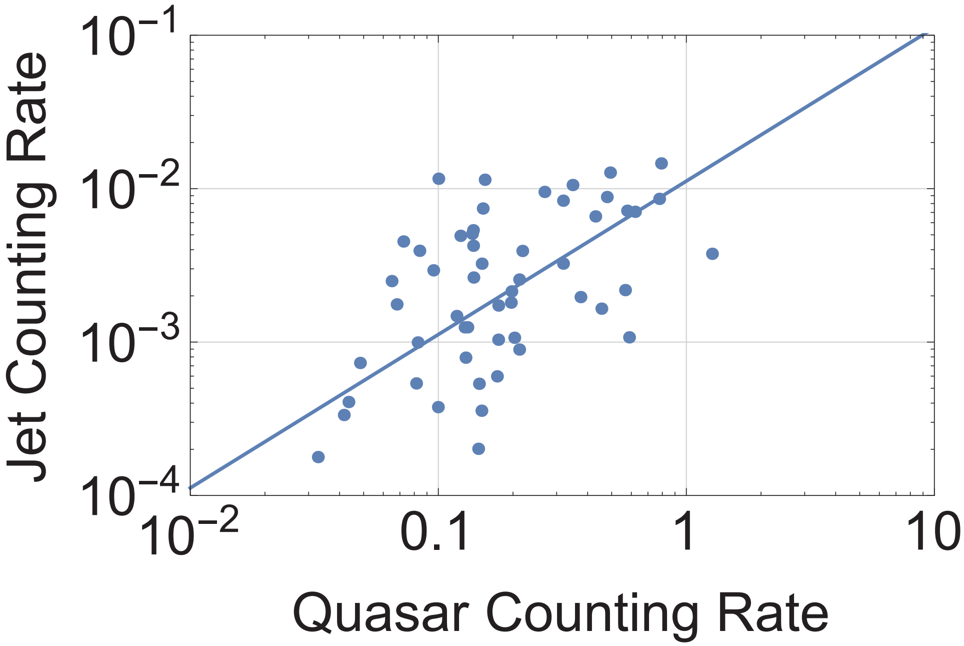

Figure 1. Raw X-ray counting rates s^{-1} from the jet and from the quasar. The data include only the initial "snapshot" observation, of 5 to 10 ks duration. Thirty-one of the 54 observations are considered a firm detection of X-rays from the jet.

Compton (IC) scattering of the cosmic microwave background (CMB) (Tavecchio *et al.* (2000), Celotti *et al.* (2001)).

The following section presents model independent correlations derived directly from the data. The final section examines what we can learn by modeling the jet X-ray emission as inverse Compton scattering of electrons by the cosmic microwave background in a relativistic jet beamed nearly at our line of sight. In both studies we consider only the straight portion of the jet from the quasar out to a large apparent angular bend (where typically the X-rays disappear), and do not include the terminal hotspot or radio lobe. Since the lifetimes of the jets are inferred to be relatively short, 10^{7-8} years, the regions we are sampling may be somewhat heterogeneous due to differing ages.

2. Correlations from the data

Figure 1 shows raw counting rates in the jet region vs. the quasar core region. All observations were targeted on ACIS-S3, and level 2 counts were taken in the 0.5 to 7 keV band. For photon power law spectral indices in the range 1 to 2, 1 count ks^{-1} is approximately 0.94 nJy at 1 keV, or 2.2×10^{-15} erg cm^{-2} s^{-1} in the 0.5 to 7 keV band. For the jet region we used a $2''$ wide rectangle drawn on a DS9 (Joye & Mandel (2003)) plot of an L, C, or K band radio image. The length was extended to include the straight part of the radio image but ended before any terminal hot spot or lobe. The quasar core was taken to be a circle of $1\overset{''}{.}26$ radius. The correlation shows a large scatter, with a correlation coefficient only 0.43, but which has a probability less than 10^{-4} of no correlation. One might expect that the power in the jet is correlated with the energy release at the black hole, hence explaining Fig. 1. However since these FR II jets are almost certainly relativistically beamed, their apparent radiative output will vary widely with the angle to our line of sight, and should not show a correlation to any isotropic

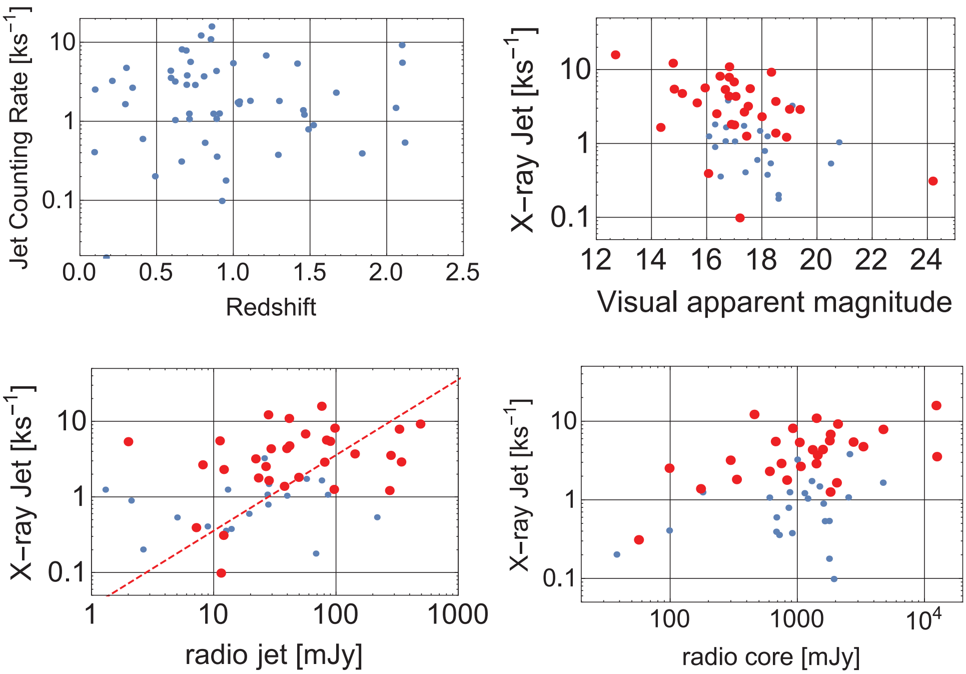

Figure 2. Correlations of the raw X-ray counting rates from the jets. Clockwise from upper left, the plots are against redshift, the quasar apparent magnitude, the radio core flux density, and the radio jet flux density. The larger (red in on-line version) points are the detected jets, the smaller (blue) points include all the observations. The dashed line in the lower left panel is the ratio observed for the jet in PKS 0637-752, and was used to select targets for this survey.

source of radiation. The X-ray to optical ratio for radio loud quasars has been known to be larger than for radio quiet quasars and even more so for flat spectrum radio quasars (Worrall *et al.* (1987)), so the present correlation may present new evidence that the quasar core has an X-ray component that is also beamed in the same direction.

A simple least squares fit of the jet counting rate to the quasar counting rate gives a mean proportionality constant 1.1% ± 0.3%, to 95% confidence, and with a scatter about a factor of 2.5. Even if both the jet and quasar core are beamed, the scatter would be expected to be large since the detailed emission mechanisms, (e.g., target photons from Compton scattering and/or contribution from synchrotron radiation) should be different.

Other relations to the X-ray flux are shown in Fig. 2. There does not appear to be any correlation with redshift or optical magnitude. The X-rays may correlate to the radio core flux density, but the present figure is dominated by the half dozen points at $\leqslant 100$ and $\geqslant 10^4$ mJy. Correlation would be expected simply from the fact that the quasar core X-ray flux increases with the radio (Worrall *et al.* (1987)). Although the predicted X-ray flux based on the ratio of the X-ray to radio jet in PKS 0637-752, (shown as the dashed line in the lower left panel) has served well to detect X-rays from $\approx 60\%$ of our jet sample, the scatter is very large with no obvious correlation.

3. Implications of the inverse Compton/cosmic microwave background interpretation

For almost every jet where optical data exist, the optical flux or upper limit does not allow the jet X-ray spectrum to be an extension of the synchrotron radio spectrum of the

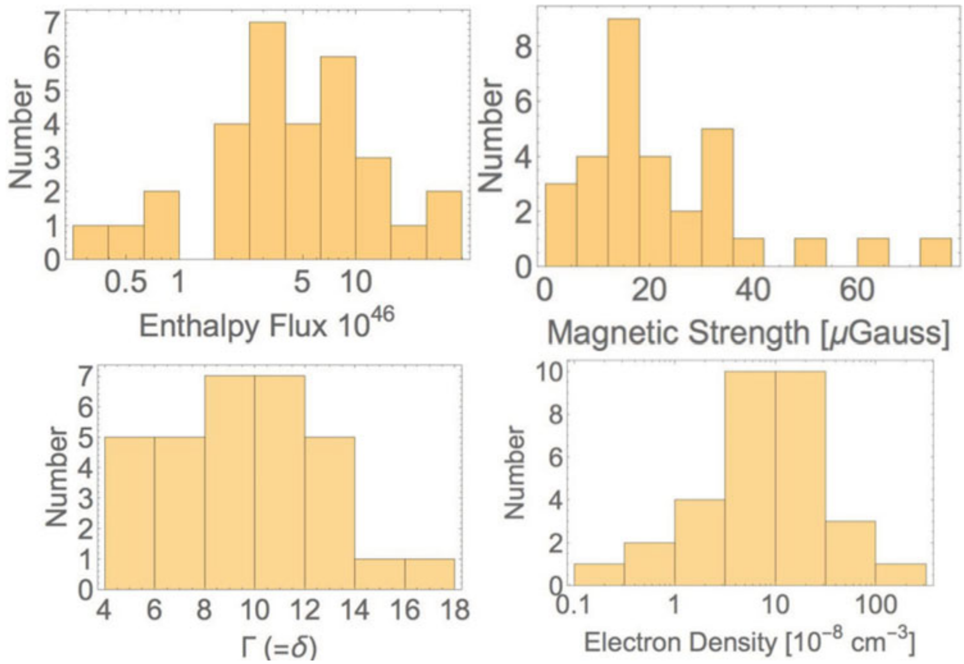

Figure 3. Jet properties derived assuming minimum energy, IC/CMB emission of X-rays, Doppler factor δ equal to the bulk Lorentz factor Γ, and charge neutrality via equal energy and density of protons and electrons. See text for other details. The magnetic field strength and electron density are in the jet rest frame. The enthalpy flux [10^{46} erg s^{-1}] and Lorentz factor are in the CMB frame, which is approximately the observer frame.

jet. Although exceptions exist, this has led to the general interpretation of the X-ray emission as inverse Compton scattering of the cosmic microwave background. We apply the formalism previously used by Schwartz *et al.* (2006), based on work by Felten & Morrison (1966) and Bicknell (1994). Briefly, we assume minimum energy conditions producing the radio synchrotron emission, with a low energy cutoff to the electron spectrum at Lorentz factor γ_{min}=30, and with relativistic beaming so that the energy density of the CMB is enhanced by a factor Γ^2 in the jet rest frame. We use the supersnapshot formalism discussed in Jester (2008) to calculate the rest frame volume as $V=V_{observed}/(\delta \sin\theta)$. Further assumptions must be made to break the degeneracy between the Doppler beaming factor, $\delta = 1/(\Gamma(1-\beta\cos\theta))$, the bulk Lorentz factor of the jet, Γ, and the angle θ to the observer's line of sight. The electron spectrum producing the radio synchrotron is assumed to extend to sufficiently low energies to produce the X-rays. Roughly, $\gamma \approx 1000/\delta$ produces 1 keV X-rays. For PKS 0637-752, Mueller & Schwartz (2009) show that $\gamma \leqslant 70$ to produce the lowest energy X-rays; consistent with our choice of γ_{min}=30. We assume homogeneity and isotropy for the particles and magnetic fields in the jet rest frame.

For an initial evaluation of the entire sample, we have taken δ=Γ. This places the jet at the largest allowed angle for the given value of δ, $\sin\theta$=$1/\delta$. For this case, the photons seen by the observer are emitted in the jet frame perpendicular to the direction of propagation of the jet, and $V=V_{observed}$. It also implies δ is half its maximum possible value of 2Γ, which is approached for large Γ and small θ. Fig. 3 summarizes the results for the 31 detected jets. For these values we have also assumed equal kinetic energy in relativistic protons, and equal number density of protons, which can both be satisfied

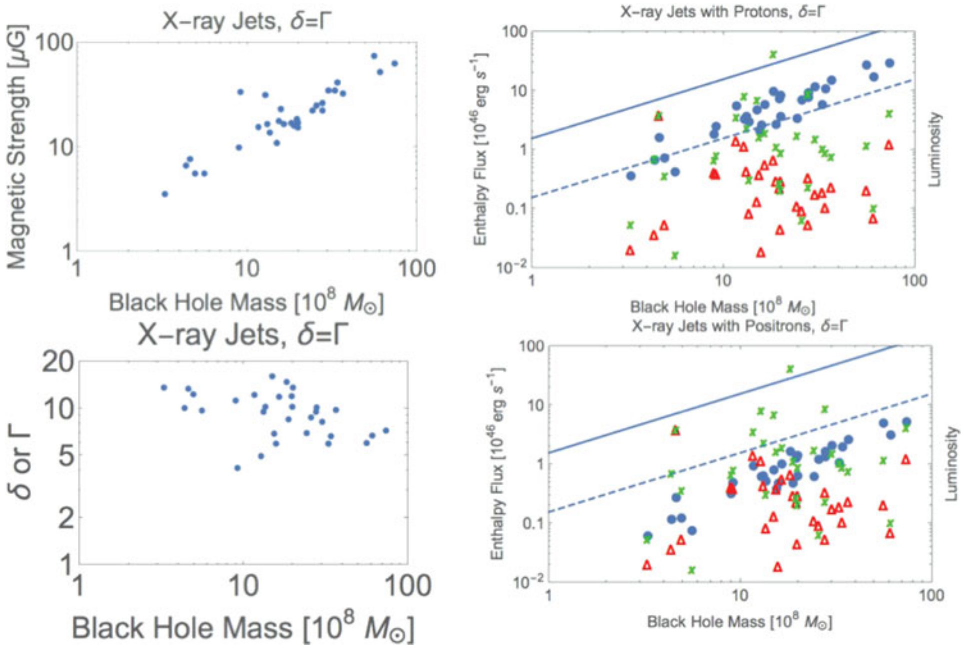

Figure 4. Derived jet properties plotted against a proxy for black hole mass. Clockwise from top left: Magnetic field strength, Enthalpy flux assuming proton density equals electron density, Enthalpy flux assuming proton density is zero, Bulk Lorentz factor of the jet. In each plot, the small (blue in on-line version) dots are the jet X-ray data. In the enthalpy plots, the (green) crosses are the optical luminosities of the quasar and the (red) triangles are the X-ray luminosities.

since we have no constraints on the proton spectral shape. We can summarize the sample properties as $\Gamma \approx 10$, magnetic field strength $\approx$ 10–20 μG (1–2 nTesla), electron density $\approx 10^{-7}$ cm^{-3} and enthalpy flux $\approx$ (5–10) $\times$ 10^{46} erg s^{-1}.

Fig. 4 plots the derived quantities vs. a proxy for black hole mass. The mass estimate is taken from the relation in Gültekin *et al.* (2009): $\mathrm{M}_\odot = 10^{0.19}\mathrm{L}_{r38}^{0.48}\mathrm{L}_{x40}^{-0.24}$, where L_{r38} is the radio luminosity of the quasar in units of 10^{38} erg s^{-1} and L_{x40} is the quasar X-ray luminosity in units of 10^{40}erg s^{-1}. The magnetic field strength, electron density (which is forced to be proportional to the magnetic field by the minimum energy assumption), and enthalpy flux are all proportional to the black hole mass proxy. This is partially due to the correlation of the jet and quasar X-ray flux, since the latter enters the equation for the mass proxy.

Assuming positrons, rather than protons, provide charge neutrality in the jet lowers the estimates of the enthalpy flux by a factor of about 5. In either case the energy flux carried by the jet is comparable to the radiative luminosity, or at least a significant component of the accretion energy budget. Other derived quantities depend only slightly on the positive charge carrier, typically decreasing about 20% from all protons (e.g., Fig. 3) to all positrons.

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