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**MODELING X-RAY EMISSION OF A STRAIGHT  
JET: PKS 0920-397**

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We summarize a study of PKS 0920-397 using our 42 ks Chandra observation in conjunction with our ATCA 20GHz image, and HST/ACS F814W and F475W images. We investigate the hypothesis that the jet X-ray emission is due to inverse-Compton (IC) scattering on the cosmic microwave background (CMB) from the same population of relativistic electrons that give rise to the radio emission. To calculate parameters intrinsic to the source, one must finesse the fact that we do not know the true angle of the jet to our line of sight. Typical assumptions are that the Doppler factor equals the bulk Lorentz factor, or that the Lorentz factor takes some fixed numerical value. While giving useful estimates, neither assumption can be exact in general. We try different constraints to determine the jet quantities. It is plausible that the kinetic flux is constant along the jet, prior to a terminal hotspot or lobe, and with minimal bending of the jet. Alternatively, because PKS 0920-397 appears straight in projection on the sky, we might assume the jet maintains a constant angle to our line of sight. Either approach gives bulk Lorentz factors of 6 to 8, with kinetic energy flux of order  $10^{46}$  erg s<sup>-1</sup>, and with the jet at an angle 2° to 4° from our line of sight.

*Keywords:* Quasar jets; X-ray jets; jet emission mechanisms.

## 1. Introduction

Chandra has enabled the study of X-ray jets,<sup>1,2</sup> starting with the serendipitous detection of the jet in the quasar PKS 0637-751<sup>3</sup> during the very first pointed observation. While X-ray jet emission from FR I radio galaxies is normally explained via the synchrotron mechanism, the quasar jets initially presented a puzzle. Observations, or upper limits, to optical emission from quasar jets usually prohibit an extension of the radio synchrotron spectrum to the X-ray regime. However, estimates of the magnetic fields via minimum energy assumptions result in such large magnetic field strengths that inverse-Compton (IC) emission would not be expected to be significant. This dilemma was resolved by realizing<sup>4,5</sup> that if the jet was relativistically beamed with bulk Lorentz factor  $\Gamma$ , then the  $\Gamma^2$  increase of the cosmic microwave background (CMB) energy density in the jet rest frame<sup>6</sup> would allow the CMB to dominate the magnetic energy density and thus for IC/CMB to dominate the relativistic electron energy loss.

## 2. Images of PKS 0920-397

PKS 0920-397 is a quasar at redshift 0.591. We originally observed it with Chandra for 5 ks<sup>7,8</sup> as part of a survey<sup>7</sup> of flat spectrum quasars with good radio imaging.<sup>9,10</sup> Because it was clearly detected along the 10'' length of the radio emission, and because of its straight appearance, we proposed an additional 40 ks Chandra observation. We assumed that the straight morphology would allow us to use constant geometric factors along the jet, even though the angle to the line of sight was unknown. Figure 1 shows images of the quasar PKS 0920-397 (position noted

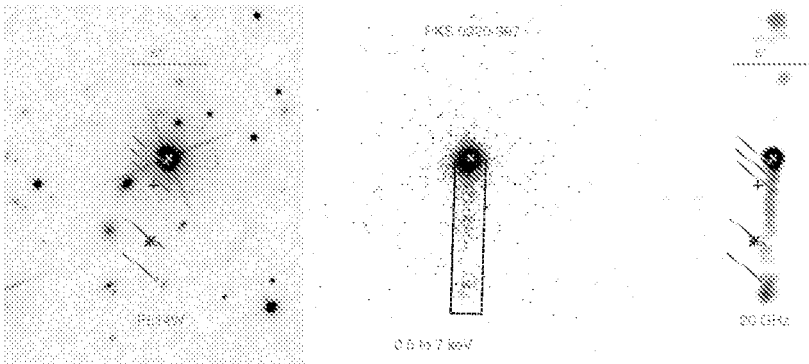


Fig. 1. Images of the PKS 0920-397 quasar and jet at 20 GHz (right panel) in the 0.5 to 7 keV X-ray band (middle panel) and with the HST/WFC filter F814W (left panel). The X-ray image shows counts in a 0.2'' square bin, with the faintest color being one count. The rectangle shows the sky region used to project the radio and X-ray data in Fig. 2. Five distinct optical knots are detected along the radio jet (arrows in left and right panels). The “plus” and “asterisk” in the left panel denote the regions 2.1'' and 5.9'' from the quasar for which the spectral energy distributions are constructed in Fig. 3.

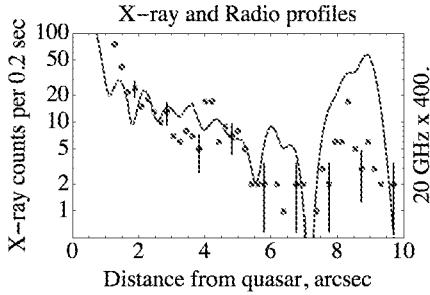


Fig. 2. Projection of the X-ray and radio data. Points plot the number of X-ray counts per 0.2'' bin. The solid line plots the 20 GHz data, arbitrarily multiplied by 350 to better compare with the X-ray profile. They are within a factor of 2 over a distance from 2'' to 5.5'' from the quasar. Representative statistical errors shown are the square root of number of X-ray counts.

by the cross) and its jet extending to the south. Both the ATCA 20.16 GHz image (right panel) and the 40 ks Chandra 0.5 to 7 keV image (center panel) show a gap past the end of the jet, followed by two hotspots in the southern lobe.

The radio and X-ray profiles appear very similar. Figure 2 compares those profiles, projected  $\pm 1''$  perpendicular to the jet, as a function of distance from the quasar. The bright quasar core contaminates the X-ray image out to about 2''. We arbitrarily renormalize the 20.16 GHz data to show that it tracks the X-ray flux within a factor of two out to at least 5.5'', which appears to be the end of the X-ray detected jet.

### 3. X-ray Emission Mechanism

Figure 3 presents the spectral energy distribution of the regions 2.1'' and 5.9'' from the quasar (indicated by the "+" and "\*" signs in the left panel of Fig. 1). We know that the radio emission is synchrotron because we measure polarization. It is evident that the 20 GHz flux density cannot be extrapolated to the X-ray region, since it would greatly exceed the HST measurements of optical flux density.

Given that the X-rays are not a continuation of the radio synchrotron emission, the simplest hypothesis is to add one single parameter, namely the bulk Lorentz factor  $\Gamma$ , which then enables the same electron population to emit X-rays via IC/CMB. Since we know the jets are in relativistic bulk motion from the fact that they are one-sided, it would take some fine tuning to keep  $\Gamma$  small enough to prevent IC/CMB.

While a synchrotron origin cannot be rejected absolutely, we also have additional observational arguments favoring IC/CMB, as follows. If the X-rays did result from synchrotron radiation, they would be emitted from an independent population of relativistic electrons which did not extend to low enough energies to radiate at GHz frequencies. In that case, the correlation of the radio and X-rays would be difficult to understand. The minimum energy estimates of magnetic field strength are of order 100  $\mu\text{G}$ , so that synchrotron X-rays would be produced by electrons

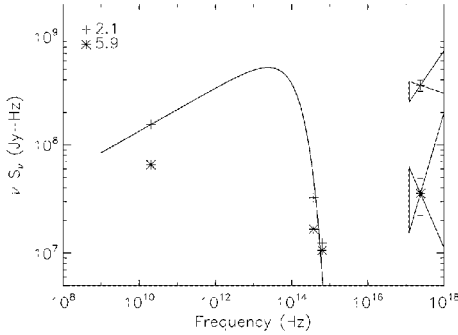


Fig. 3. Spectral energy distributions of the two regions 2.1'' and 5.9'' from the quasar. The solid line is an eyeball-fit of a power-law plus exponential cutoff, drawn to demonstrate that a synchrotron spectrum cannot be extended from the radio region to explain the X-ray emission. The “bowties” through the two X-ray points indicate the allowed range of the X-ray spectral index.

with Lorentz factors  $\gamma \approx 2 \times 10^7$ , and have lifetimes of order 100 years. Thus they would need to be accelerated continuously in space at the right intensity to match the independent population of radio emitting electrons.

#### 4. Calculation of the IC/CMB Emission

Figure 4 shows how we divide the jet into four spatially distinct cylindrical regions for analysis. For the present work, we make the same assumptions of Ref. 8, with the following modifications. We will calculate the minimum energy magnetic field by assuming intrinsic limits to the relativistic electron spectrum,  $\gamma_{\min} = 30$  to

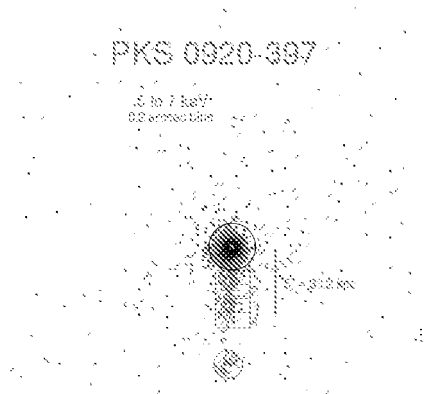


Fig. 4. Rectangular boxes define the distinct cylindrical regions for which the jet structure is calculated. Identical spatial regions are used for the X-ray and radio data. The large circle indicates the point response of the quasar, while the smaller circle is coincident with the southern radio lobe.

$\gamma_{\max} = 10^6$ , instead of limits to the radio spectrum received at earth.<sup>11</sup> The latter limits are not observable in a narrow jet by conceivable techniques, whereas  $\gamma_{\min}$  in principle could be detected by a low energy X-ray cutoff.<sup>12</sup> We use the super-snapshot special relativity transformations<sup>13</sup> which consider the relative time delay along the jet. Finally, we relax the assumption that the apparent Doppler factor,  $\delta = 1/(\Gamma(1 - \beta \cos\theta))$  equals the bulk Lorentz factor  $\Gamma$ .

With those refinements we have two possible ways to calculate the magnetic field in the jet rest frame. The minimum energy formalism gives

$$H_{\min} \propto \left( \frac{f_{\nu} \delta^{-2-\alpha} \sin\theta (\gamma_{\max}^{1-2\alpha} - \gamma_{\min}^{1-2\alpha})}{\theta_l \theta_r^2} \right)^{1/(3+\alpha)} \tag{1}$$

while the original IC/CMB calculation of  $H_{\text{FM}}$ <sup>14</sup> is modified to

$$H_{\text{CMB}} \propto \Gamma H_{\text{FM}} \tag{2}$$

where  $\theta_l$  and  $\theta_r$  are the angular length and radius of the jet element, assumed to be intrinsically cylindrical,  $z$  is the redshift,  $f_{\nu}$  and  $f_x$  are the radio and X-ray flux densities, and  $\alpha$  is the radio and X-ray spectral index. Equating (1) and (2) and with the definition of  $\delta$  gives two equations and three unknowns. This is where observers have usually assumed a fixed value for  $\Gamma$  or that  $\delta = \Gamma$ .

Instead we continue the calculation using  $\theta$  as an unknown free parameter. Figure 5 shows the result of the calculation of the kinetic energy flux applied to the four regions of Fig. 4. A plausible assumption is that the kinetic energy flux is constant along the length of the jet. This is based on the extreme inefficiency,  $10^{-4}$ - $10^{-5}$ , of the radiative energy losses.<sup>8</sup> A counter-argument is the known fact that quasars are variable on scales of years or months so their jet output need not be constant. Still, considering that the present X-ray angular resolution is averaging over elements that contain at least ten thousand years output, it may well turn out that the quasar accretion is a stationary process over that time-scale. From Fig. 5,

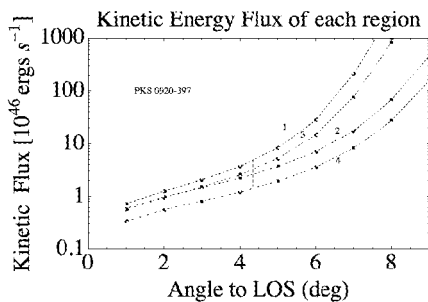


Fig. 5. Kinetic energy flux through the four regions defined in Fig. 4, as a function of the unknown angle to our line of sight. For angles less than  $4.5^\circ$  the four regions are statistically consistent (at 90% confidence level indicated by the vertical line) with a kinetic energy flux of  $3 \times 10^{46}$  erg  $s^{-1}$  or less.



the kinetic flux could be constant if the jet angle is less than  $4.5^\circ$  from our line of sight, while even 10 times variation would still require less than a  $6.5^\circ$  angle.

## 5. Summary

The X-ray emission from the jet in PKS 0920-397 most likely arises from inverse-Compton scattering on the cosmic microwave background. This is largely based on the tight correlation of the X-ray and radio profiles along the continuous portion of the jet, and the fact that the spectral energy distribution from radio through optical to X-ray rules out that the X-rays are synchrotron emission from a single power-law population of electrons that also produces the radio. Within the IC/CMB hypothesis, determination of  $\Gamma$ ,  $\delta$  and  $\theta$  are crucial to determine the structure and dynamics of the jet. We know that the hypothesis  $\Gamma = \delta$  cannot be exact. In this paper we showed that the assumption of constant kinetic flux along the jet gives a plausible fit to the observations. It results in a somewhat smaller value of the kinetic energy flux and requires that the jet be quite close to the line of sight. It therefore remains to be seen whether this approach gives consistent results when applied to a larger, well defined population of X-ray jets.

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