Chandra reveals a double-sided X-ray jet in the quasar 3C9 at $z = 2.012$

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**ABSTRACT**

A Chandra observation of the radio-loud quasar 3C9 at redshift $z = 2.012$ has revealed extended X-ray emission coincident with the radio jet. Of particular interest is the appearance of both jet and counterjet, which argues against the X-ray emission being highly beamed. We present the properties of the jets and discuss possible scenarios for the X-ray emission, contrasting them with the single sided jet found in PKS 0637-752, which has a similar X-ray luminosity. The jet X-ray emission in 3C9 is likely to be due to either nonthermal emission from a sheath with bulk Lorentz factor less than 1.5, or thermal emission from shocked cold gas surrounding the quasar. The thermal possibility implies a high mass for the cold gas unless it is highly clumped.

**Key words:** galaxies: active - galaxies: jets - galaxies: quasars: individual: 3C 9 - radiation mechanisms: non thermal - X-ray: galaxies.

1 INTRODUCTION

While the detection of X-ray emission coincident with radio jet structures is not unprecedented (e.g. Cen A, Schreier et al 1979; M87, Biretta, Stern & Harris, 1991; 3C273, Harris & Stern 1987; Röser et al. 2000), the Chandra X-ray Observatory (CXO) is providing an increasing quantity of high spatial and spectral resolution data on jetted structures associated with Active Galactic Nuclei (AGN).

The first Chandra observation of a radio-loud quasar, PKS 0637–752, showed the presence of X-rays extending for $\sim 10$ arcsec (Chartas et al. 2000; Schwartz et al. 2000), having close spatial overlap with the known radio structure. Since then several jets observed with Chandra have shown associated X-ray emission (e.g. Pictor A, see Sambruna et al. 2002; and Worrall, Birkenhaw & Hardcastle 2001; Pesce et al 2001; Siemiginowska et al 2002; Hardcastle et al 2002). It is important to stress that such features have been detected in both radio-galaxies and blazars (i.e. objects observed at a small angle with respect to the inner jet direction).

When multifrequency data are available (radio and optical images) interesting clues on the properties of the emitting plasma are obtained, such as different trends with distance from the core in different bands (an intensity decrease is often seen with X-rays whereas the radio often shows the opposite trend); displacements in the peak emission and different spatial extensions are sometimes visible in the images in different bands in the detailed comparison of individual knot emission. Broad band information on spatially resolved structures have also been studied: the local broad band spectral energy distributions are often not straightforward to interpret, since in several cases the level of the X-ray emission is higher than what simple models predict (e.g. Chartas et al. 2000; Schwartz et al. 2000, Röser et al. 2000, Harris & Krawczynski 2002).

Models involving synchrotron, inverse Compton scattering of the synchrotron, Cosmic Microwave Background (CMB) and nuclear hidden blazar radiation to produce X-rays on such scales have been proposed (e.g. Celotti, Ghisellini & Chiaberge 2001) as well as models invoking synchrotron radiation from ultrarelativistic protons (Aharonian 2000). The most satisfactory model, involving inverse Compton scattering on the CMB, remarkably requires the presence of relativistic bulk flows on scale of 100 kpc. Such an emission process also implies that the X-ray surface brightness of jets is constant with redshift, as pointed out by Schwartz (2001). Furthermore, structures in the jet velocity field, typically the presence of a relativistic core and a slower moving outer ‘layer’ – as already suggested on several other grounds – have been proposed to account for the varied phenomenology of both blazars and radio-galaxies (e.g. Celotti et al. 2001).

While much consensus of the above general scenario has accumulated, X-ray structures with looser morphological similarity to the radio jets have been found and proposed to be of thermal origin. In particular recent data from the radio galaxy PKS 1138-262 at $z = 2.2$ appear to support the view that a significant fraction of the detected X-ray
counterjet correspond to 18 and 12, respectively. While this jet is seen to the W of the nucleus and in a ‘spur’ above the SE. Some possible additional extended X-ray emission is also X-ray structure corresponds well to the radio jets (Fig. 2). The illumination of the ACIS-B3 chip. The data clearly show extensions to both sides of the core. In this paper we present the data (Section 2) and discuss the likely origin of the emission (Section 3).

2 OBSERVATIONS AND DATA ANALYSIS

3C 9 is a powerful quasar at redshift $\sim 2$ with extended radio emission (e.g. Bridle et al. 1994), classified as FR II. We observed it with Chandra for 16,235 s (cleaned of back-ground flares) on 2001 June 10. 3C9 was imaged on the back-illuminated ACIS-B3 chip. The data clearly show extensions to the NW and SE of the nucleus point source (Fig. 1). The X-ray structure corresponds well to the radio jets (Fig. 2). Some possible additional extended X-ray emission is also seen to the W of the nucleus and in a ‘spur’ above the SE jet.

Excluding the central region the counts in the jet and counterjet correspond to 18 and 12, respectively. While this of course does not allow any detailed spectral study, a simple power-law fit to the spectrum (grouped to a minimum of 10 ct per bin) gives a formal spectral index $\Gamma_s = 1.6 \pm 0.6$ (with a normalization of $K = (2.8 \pm 0.9) \times 10^{-20}$ ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$) assuming the Galactic value for $N_H = 4.2 \times 10^{20}$ cm$^{-2}$. Uncertainties are quoted at the 90 per cent confidence level. The X-ray flux (0.4–5 keV) amounts to $1.23 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ and the corresponding jet + counterjet luminosity is $\sim 2.4 \times 10^{44}$ erg s$^{-1}$ in the 2–10 keV band (rest frame) (assuming $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$). A thermal (MEKAL) fit to the spectrum yields a minimum (quasar rest frame) temperature of 4.1 keV (at the 90 per cent confidence level) with no constraint on the upper temperature.

The nucleus suffers mild pile-up (at the 4 per cent level). Spectral fitting of a power-law continuum gives a photon index $\Gamma_s = 1.58 \pm 0.1$ (similar to that of the extended emission) and a flux of $1.45 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ in the 0.2–3.5 keV band.

3 DISCUSSION

High resolution VLA radio imaging of 3C 9 shows two jets (Bridle et al. 1994). As can be seen in Fig. 1 the comparison of the radio and X-ray images shows that the X-ray extensions roughly coincide with the jet features, although apparently only in its inner parts before the jet bends (especially in the S structure).

In order to determine the origin of the large scale X-rays in 3C 9, assuming it is non–thermal radiation from the radio emitting plasma, let us first compare its properties with those of PKS 0637-752, at $z = 0.654$. The total low frequency radio flux (at 408 MHz) of the two systems are similar, while the extended X-rays are a factor $\sim 10$ lower in 3C 9 (Schwartz et al. 2000). Also the nuclear (blazar-like) X-ray emission of PKS 0637-752 also exceeds that of 3C 9 by a similar factor ($\sim 10 - 50$, Wilkes et al. 1994).

This implies that both the X-ray extended jet emission and (especially) the blazar core in 3C 9 are less prominent, with respect to the presumably isotropic extended radio, than in PKS 0637-752. The differing prominence of the
blazar component could be simply ascribed to a difference in the angle between the (core) jet and the line of sight, as envisaged by unification schemes.

This is indeed supported by the flat radio spectrum of PKS 0637-752 compared to a steep spectrum in 3C 9 ($\alpha \sim 1$). Furthermore for PKS 0637-752 supernovae light curves indicate bulk Lorentz factors (relative to the core jet) $\Gamma_b > 17$ and an angle between the jet axis and line of sight $\theta < 6$ deg (Lovell 2000). On the other hand for 3C 9 we can consider another crucial point, namely the jet/jet-counterjet ratio, in the radio and X-ray bands. They are $\sim 3.3$ in the radio (assuming only the straight part) and in the range 0.9-2.6 in X-rays. These are remarkably similar and imply that on the extended scales $\Gamma_b < 1.5$ even for an angle of 80 deg (note that uniform models would suggest 45 deg as a limit for a quasar). We conclude from these elements that 3C 9 is presumably observed at a larger viewing angle.

What can we then infer on the dominant radiation mechanism for the extended X-ray emission? On the one hand the energy density in the CMB radiation field is about a factor 10 higher in 3C 9. On the other, however, the nuclear X-ray luminosities (considered indicative of the blazar emission) of the two objects is of the same order, differing only by a factor $\sim 2.5$. While these two facts appear to suggest that also in 3C 9 the most likely photon field seed of the inverse Compton emission is the CMB radiation, if one takes into account the significant difference in viewing angle and thus of beaming, the blazar in 3C 9 can consistently be an order of magnitude larger (as seen at small angles). Together with the limit on $\Gamma_b$ on the extended scales, this suggests that the energy density associated with the nuclear emission might dominate over the energy density in the CMB field and thus in 3C 9 we probably observe emission from a slow (jet layer?) component (with respect to the case of PKS 0637-752) scattering the blazar radiation. Such a possibility is supported by the morphology of the emission, as in 3C 9 the X-ray extended structure is (within the limits of resolution) closer to the nucleus up to $\sim 100$ kpc (for the whole jet), indeed disappearing from detection after the jet bending, while in PKS 0637-752 it peaks in the large distance knots, at several hundred kpc. Note that in this situation of low relativistic speed we do not expect a large effect, e.g. on the jet/jet-counterjet ratio, due to the anisotropic scattering of the close and distant jets.

While the evidence discussed so far might be reasonably convincing, an alternative view could ascribe the majority of the X-ray flux to thermal emission, as suggested by Carilli et al. (2002), from gas heated via shocks produced by the jet propagation and able to confine the jet itself. Indeed the quality of the morphological similarity between the radio and X-ray spatial distribution – even the evidence of a (spatially coincident) knot (in the S jet) – cannot distinguish between these possibilities. Similarly the spectral analysis cannot constrain the nature of the emission. Note also that the jet/jet-counterjet ratio, in principle a powerful diagnostic for discriminating between the thermal and non-thermal scenarios, is consistent (due to the paucity of counts) with a similar, isotropic emission from the two jet sides.

Additional information for X-ray emission models is the extended Lyman $\alpha$ nebula around 3C9 found by Heckman et al (1991), with a tentative detection in Lyman $\alpha$ of a structure coincident with brighter part of the SE jet. This means that there is extensive ionized gas around the quasar, possibly at high gas pressure, as inferred from the redshifted $\mathrm{H}\alpha$ and [OII] observations reported by Wilman, Johnstone & Crawford (2000). If the extended X-ray emission is thermal bremsstrahlung then, assuming an emission temperature of 10 keV for the shocked gas and a volume of $10 \times 10 \times 50$ kpc$^3$, the electron density is about 0.5 cm$^{-3}$ meaning a pre-shock density of $\sim 0.1$ cm$^{-3}$. This is high if the pre-shock temperature is 1 keV or more, comparable only to that seen in the centres of strong cooling flows in nearby rich clusters. The Chandra data are inconsistent with the extensive intracluster medium of a rich cluster around the quasar. (Ignoring the weak temperature dependence, the emissivity of the pre-shock gas is 1/16 of that post-shock, so a volume 16 times that of the jet should have a similar flux which for a cylinder corresponds to a radius of about 4 arcsec; the data at this radius are however entirely consistent with the background.) The shock temperature must exceed about 2000 km s$^{-1}$ to agree with our lower limit on the gas temperature. The total mass of shocked gas (assuming unit filling factor $f$ of the volume assumed above) is about $10^{12} M_\odot$. Presumably there is much more gas beyond the region now shocked which occupies only a few per cent of the volume within the radius of the jet, raising the total gas mass to above $10^{13} M_\odot$. The mass varies as $f^{3/2}$, requiring a very low filling factor (say $f \sim 10^{-3}$ if the mass is to be significantly reduced).

Only if the gas is cooler can high pre-shock densities be present and consistent with observations. The difficulty is then accounting for such an extensive and massive atmosphere of relatively dense gas. It might have to be in the form of many small dense cold clouds in order to minimise the mass. Perhaps both the X-ray and Lyman $\alpha$ emission are due to shocks and photoionization of a substantial mass of cold gas clouds which are remnants of galaxy formation and mergers.

Clearly, it is of great relevance to distinguish between these scenarios with higher quality data, which will allow the nonthermal jet and thermal shocked gas possibilities to be distinguished, thereby constraining either the jet velocity field, dissipation and particle acceleration processes or the interaction of the jet with its confining mechanism.

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