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A high-energy view of radio-loud AGN

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Abstract. Seyfert galaxies and quasars were first discovered through optical and radio techniques, but in recent years high-energy emission, that can penetrate central gas and dust, has become essentially the defining characteristic of an AGN. AGNs with extended radio jets are of particular interest, since the jets signal source orientation. However, the jets extend into the cores, where they are faster and more compact. Special-relativistic effects then cause jet brightness and variability time-scales across the electromagnetic spectrum to be strong functions of jet orientation. Jet X-ray emission is confused, to varying degrees, with that from the central engine, but can be measured, at least in a statistical sense, through considerations of the multiwaveband spectrum and the level of intrinsic absorption. The rich high-energy structures found in jets which are resolved with *Chandra* and *HST* inform our interpretation of the inner structures. In particular, it is found that shocks are prevalent and don't necessarily disrupt jets, and that one-zone models of emission near shocks are an over-simplification.

Key words. galaxies:active – galaxies: jets – radiation mechanisms: non-thermal – X-rays:galaxies

1. Introduction

Now that it is known that massive or supermassive black holes are prevalent, if not ubiquitous, at the centres of galaxies, the line between active and non-active galactic nuclei has become harder to define. We must ensure that the perceived level of activity is not underestimated because radiation is obscured by gas and dust. Indeed it is often the case, and a prediction of unified schemes, that the central emission of an active galactic nucleus (AGN) must penetrate large columns of gas and dust. High-energy emission, since it is able to penetrate dust, and at the highest X-ray energies to penetrate gas, is now virtually the defining characteristic of an AGN. But the high-energy emission is complicated and there remain unanswered questions. Active galaxies with radio jets are arguably the most complicated AGN. To ascertain if and how the central engines differ from non-jetted AGN, we need to peel off the jet emission to reveal the central engines.

Here the *Chandra* X-ray Observatory (Weisskopf et al. 2000) has come into its own. The jet components it has resolved have informed our interpretation of the unresolved structures and allowed much interesting and important physics to be addressed. Since a complete discussion of the high-energy emission of radio-loud AGN is beyond the scope of this review, I'll concentrate mostly on one aspect, the extended components, since this has been a particular area of intense interest and study over the last few years.

2. Foundations

Back in the late 1970s, when the *Einstein* Observatory found a typical AGN to be a bright X-ray source, there were two important discoveries. Both were based on the total observed X-ray emission. Firstly, it was found that radio-loud quasars were brighter X-ray sources than radio-quiet quasars for a given optical luminosity (Ku et al. 1980; Zamorani et al. 1981). The dependence of X-ray luminosity and spectrum on beaming angle that was subsequently found was interpreted as evidence that the X-ray emission was composed of radio-quiet (i.e., accretion-flow related) and radio-loud components (Zamorani 1986; Browne & Murphy 1987; Worrall et al. 1987; Wilkes & Elvis 1987; Canizares & White 1989; Kembhavi 1993; Shastri et al. 1993). It was only speculation that the component related to the accretion flow might be the same in radio-quiet and radio-loud quasars, even though the quasar nature implied that the sources were all radiating with high Eddington accretion efficiency.

Secondly, a correlation of X-ray emission with core radio emission was found for radio galaxies (Fabbiano et al. 1984), i.e., sources presumed to be non-beamed counterparts of quasars and BL Lac objects. This was supported by *ROSAT* observations that largely separated the core X-ray emission from the thermal emission of the host galaxies and clusters (Worrall & Birkinshaw 1994; Canosa et al. 1999). The implications were either (a) that the central-engine X-rays were correlated with radio loudness or (b) that the X-rays were from an inner radio jet, and the central-engine X-rays were obscured or weak. In the 1990s, after our first such correlations using *ROSAT*, I pointed out (Worrall 1997) that the brightest features in the X-ray-resolved jets of the nearest radio galaxies, Cen A and M 87, fitted on the same correlation as the core emission from more distant radio galaxies. This gave support to interpretation (b), and implied that *Chandra* with its sub-arcsecond spatial resolution, should resolve jets in radio galaxies more distant than Cen A and M 87.

3. Resolved jets in the *Chandra* era

3.1. Low-power radio sources

Low-redshift sources provide the best linear spatial resolution, so it is interesting to look at them first. Naturally, these sources are biased towards having low radio power. Here resolved jet emission is seen in sources of all orientation, from two sided jets in 3C 270 (e.g., Chiaberge et al. 2003a; Zezas et al. 2004), where the jet emission is relatively faint and hard to see in contrast with X-ray emission from the host galaxy NGC 4261, to the stubby one-sided jets of BL Lac objects (e.g., Pesce et al. 2001; Birkinshaw et al. 2002) where it is believed that the jets are at small angle to the line of sight and we are seeing boosted emission from the relativistic jet pointed towards the observer. Typically jets are shorter in the X-ray than the radio. The X-rays are often associated with regions in which the jets are believed to be decelerating through entrainment of the ambient X-ray-emitting medium (e.g., Hardcastle et al. 2002). It is natural to consider shocks associated with this entrainment as being responsible for the knotty structures of many of the jets.

There are selection effects in the *Chandra*-observed sources, with a bias in favour of those where the kpc-scale radio emission is predominantly one sided, and known optical jet sources are over-represented. It has been normal to detect one-sided jet X-ray emission, and indeed there is better contrast with galaxy emission in the X-ray than in the optical to the depth of *HST* snapshot surveys (Worrall et al. 2001). A broken power law normally fits the radio, optical and X-ray spectrum, integrated over the entire X-ray-emitting region (e.g., Hardcastle et al. 2001; Böhringer et al. 2001; Birkinshaw et al. 2002). Typically model predictions for inverse Compton (iC) emission in the X-ray band fall short of the observations (e.g., Hardcastle et al. 2001) and the X-ray spectrum is, in any case, too steep to be iC from the electrons producing the radio synchrotron emission (e.g., Böhringer et al. 2001).

A synchrotron frequency can be related to a most probable energy for the emitting electron, given an adopted magnetic field strength, B. It is normal to adopt the value for B for which the source contains a minimum total energy in particles and magnetic field. Such minimum-energy values for B have been confirmed to within a factor of a few in most hotspots and radio lobes observed with *Chandra* and *XMM-Newton*, where B is measured through associating the X-ray emission with inverse Compton scattering of the population of electrons that is producing the radio synchrotron emission (e.g., Hardcastle et al. 2004; Brunetti et al. 2002; Isobe et al. 2002; Comastri et al. 2003; Bondi et al. 2004; Belsole et al. 2004; Croston et al. 2004). Minimum-energy values of B in low-power jets are typically around 100 μG. X-ray-emitting electrons then lose their energy in tens of years, which is less than the plasma travel time from the core, implying the need for *in situ* acceleration. It is natural to invoke the existence of shocks. The shocks presumably have a range of strengths, and the fact that the multiwavelength spectra and images are integrals over inhomogeneous regions may explain two observed features. Firstly, the size of the break in the spatially integrated multiwavelength spectrum is too large by $\Delta\alpha \sim 0.2$ for a simple continuous injection and energy-loss model (e.g., Birkinshaw et al. 2002). Secondly, in sub-regions there are often offsets between peaks of X-ray and radio emission, with the X-ray typically lying closer to the core (e.g., Hardcastle et al. 2001, 2003).

The greatest detail is seen in the closest radio galaxy, Cen A. In the X-ray the jet is intrinsically blobby, with an apparent filling factor of less than about 10 per cent. Here it has been proposed (Hardcastle et al. 2003) that, in at least some locations, shocks are the result of obstacles in the jet (gas clouds or high-mass-loss stars) such that both radio-emitting and X-ray-emitting electrons are accelerated in the standing shock ahead of the obstacle, and downstream a wake produces further acceleration of just the low-energy electrons that emit in the radio. The sort of radio-X-ray offset that this model describes, averaged over several knots, might explain the radio-X-ray offsets seen in more distant jets.

Polarization fraction and direction changes are a signature of shocks. Optical frequencies are particularly good for probing this, since Faraday rotation is negligible. In M 87 there is evidence for strong shock acceleration at the base of bright emitting regions in compressed transverse magnetic fields (Perlman et al. 1999). Multiwavelength variability studies provide another probe of acceleration and energy losses. Here again it is M 87 that has so far proved the best resolved jet for study in this way (Harris et al. 2003; Perlman et al. 2003).

The synchrotron jets in low-power sources thus provide test-beds for studies of particle acceleration. It appears that shocks are accelerating particles and changing magnetic field directions in regions where the jets, although slowing, can still be propagating at speeds more than a few tenths of the speed of light and are still well collimated. If this behaviour applies at higher speeds, it suggests that one-zone models should always be treated with caution, even imbedded in small-scale blazar jets.

3.2. High-power radio sources

High-power jets are rarer and so more distant. The beamed counterparts are the quasars. Observing them was not initially a high priority for *Chandra* since it was recognized that the cores were bright, and the likelihood of multiple photons arriving between CCD readouts was high, leading to distorted spectral measurements (so called 'pileup'). It was fortuitous that a radio-loud quasar was the chosen target for in-flight focus calibration, since this led to the detection of resolved jet emission from the $z = 0.651$ quasar PKS 0637-752 (Schwartz et al. 2000; Chartas et al. 2000). Major programs targeting the jets of core-dominated quasars followed (Sambruna et al. 2002, 2004; Marshall et al. 2004), with a detection success rate of roughly 50 per cent.

The generally favoured X-ray energy-production mechanism for the quasar jets has been inverse Compton (iC) scattering of cosmic microwave background (CMB) photons by a fast jet (with a minimum-energy magnetic field) which sees boosted CMB and emits beamed X-rays in the observer's frame (Tavecchio et al. 2000; Celotti et al. 2001). The mechanism requires the jets to have a highly-relativistic bulk flow and be at a small angle to the line of sight, as expected for core-dominated quasars. Although in PKS 0637-752 such a speed and angle are supported on the small scale by VLBI measurements (Lovell et al. 2000), the fast speed must persist up to hundreds of kpc from the core (after projection is taken into account) for the X-rays to be produced by this mechanism. Single-zone synchrotron self-Compton (SSC) models lead to an uncomfortably large departure from minimum energy (a factor of about 1000 in the case of PKS 0637-752). Optical emission falling below a spectral interpolation between the radio and X-ray has been used to rule out synchrotron radiation from a single population of electrons as the explanation of the spectral energy distribution for this source (Schwartz et al. 2000).

Clearly as long as jets remain fast out to hundreds of kpc from the core, the beamed iC-CMB mechanism produces X-ray emission at some level. Since the CMB energy density increases as $(1 + z)^4$, the surface brightness for this mechanism is constant with redshift, while the radio-synchrotron surface brightness decreases with redshift. But there is a difficulty with the beamed iC-CMB interpretation. Sharp gradients in X-ray surface brightness (sharper than in the radio) at the edge of knots (e.g., Chartas et al. 2000) or X-ray emission decreasing with distance along the jet while the radio increases (e.g., Sambruna et al. 2001, 2004; Marshall et al. 2001), sometimes with distinct radio-X-ray offsets (e.g., Siemiginowska et al. 2002; Jorstad & Marscher 2004) are not naturally explained, since with the beamed iC-CMB mechanism the X-rays are from low-energy electrons with long energy-loss lifetimes. This may suggest that jets are clumpy (Tavecchio et al. 2003), but in this case the SSC may be enhanced and the requirement for fast jets and the importance of beamed iC-CMB may diminish (Schwartz et al. 2000). It may suggest jet decelerations, with declining effectiveness of the iC-CMB process along the jet accompanied perhaps by magnetic-field compression that produces more radio synchrotron emission (Sambruna et al. 2001; Georganopoulos & Kazanas 2004). But, it remains possible that the X-rays are dominated by synchrotron emission, either from high-energy electrons whose efficiency in losing energy by inverse Compton scattering is decreased through being in the regime where the Klein-Nishina cross section applies (Dermer & Atoyan 2002), or from a separate electron population, perhaps due to transverse velocity structure in the jet (Jorstad & Marscher 2004).

To assess the importance of X-ray synchrotron emission in the resolved jets of powerful radio sources, it is beneficial to select some of the nearest powerful radio galaxies, where the jets should not be at the same small angles to the line of sight deduced for core-dominated quasars, thus de-emphasizing beamed iC-CMB emission. Good examples of such radio galaxies for which the case is made for X-ray synchrotron emission are 3C 403 (Kraft et al. 2004) and 3C 346 (Worrall & Birkinshaw 2004a). 3C 346 is of particular interest because offsets between radio and X-ray emission are seen in a bright knot where the jet makes a dramatic change in direction. The observations have been interpreted as due to an oblique shock in the wake of a companion galaxy's track though the host cluster, and predictions are made for a change in magnetic field direction that are testable with *HST* polarimetry.

There remains much to be learned about the X-ray emission mechanisms of powerful jets, and the relative importance of shocks in accelerating particles and shaping the morphologies. An extreme source which may advance understanding greatly though an upcoming programme of more sensitive multiwavelength measurements is PKS 1421-490 (Gelbord et al. 2005, in preparation). It has an undistinguished radio knot which is remarkably bright in the optical and X-ray, with multiwavelength properties that challenge straightforward emission models.

4. X-ray Cores

In highly boosted sources (e.g., core-dominated quasars and BL Lac objects) it is common to assume that jet emission dominates the continuum at all energies, including the X-ray, where it is assumed to swamp emission associated with the accretion flow (see section 2). One-zone SSC models, often including external photon fields, are commonly applied, typically implying emission regions of order 10^{16} cm in size and magnetic fields of order a Gauss (e.g., Ghisellini et al. 1998; Tagliaferri et al. 2003). Sometimes correlated multiwavelength flares support the presence of a dominant emission region (e.g., Urry et al. 1997; Takahashi et al. 2000), but in other cases uncertainties of size scales, geometries, and parameters for the competing processes of energy loss and acceleration force adoption of poorly-constrained models. On resolved scales we find evidence that shocks don't necessarily disrupt a fast flow and multiple synchrotron-emitting emission regions appear. This may suggest that one-zone models are an oversimplification for the inner jets.

The cores of non-boosted powerful radio galaxies are more difficult to study in the X-ray. Distance, and the obscuring torus invoked by unified models that should weaken their nuclear flux at low X-ray energies, gives *XMM-Newton* advantages over *Chandra* for their study. However, kpc-scale jet emission then appears in the unresolved cores (e.g., Belsole et al. 2004), complicating the issue of component separation.

Low-power sources are closer and the cores are more easily X-ray studied (e.g., Donato et al. 2004), but ideas are divided about the origin of this emission. Using NGC 6251 as an example, one school looks at spectral energy distributions and interprets the emission in terms of synchrotron and iC jet models (e.g., Chiaberge et al. 2003b). The other emphasizes the detection of variability or Fe-K line emission and models the sources in terms of an accretion disk (e.g., Gliozzi et al. 2004). However, there are least two sources which show spectral evidence for both components. The first (Evans et al. 2004) is Cen A. As our closest radio galaxy, the X-ray jet emission is better resolved out from the core than for any other source. There is strong Fe-line emission which the *Chandra* gratings resolve but find to be sufficiently narrow that it can be located at an obscuring torus, with $N_{\rm H} \sim 10^{23}$ cm^{-2}, responsible for absorbing the strong inner emission. Additional, somewhat less absorbed, X-ray emission can be associated with the inner radio jet. The second source is 3C 270 (Zezas et al. 2004), which is currently the best example of a two-sided X-ray jet source. The X-ray spectrum shows a strong contribution at low energies from unresolved galaxy gas, but a good model fit contains also Fe-K line emission and two power-law components, the more absorbed of which can be associated with the accretion flow and the other with the inner jets (for alternative interpretations of a single nonthermal component in this source see Chiaberge et al. 2003a; Sambruna et al. 2003; Gliozzi et al. 2003). In these sources, at the lowest X-ray energies the dominant component is interpreted by Evans et al. (2004) and Zezas et al. (2004) as associated with the inner radio jets. Since *ROSAT* was sensitive only to low-energy X-rays, this can explain the radio and X-ray correlations found by that satellite and discussed in section 2.

A new approach to studying the cores is to assume that they do indeed all host a moderately large obscuring torus of $N_{\rm H} \sim 10^{23}$ cm^{-2}, and find the upper limit to the luminosity of X-ray emission behind this column (Evans et al. 2004, in preparation). A typical value is 10^{41} ergs s^{-1}, which is similar to the luminosities of the obscured components measured in Cen A and 3C 270. Of course, if even higher obscuring columns are present, these cores could contain even more luminous components, and the maximum luminosity and column density are linked by the assumed structure of the obscuring torus.

5. Summary

This review has concentrated on the X-ray observations of the jets and cores of AGN, the emission mechanisms that have been ascribed to them, and the observed morphologies.

The resolved X-ray jets of low-power radio sources can be interpreted as synchrotron radiation in regions where the jets, although slowing by entrainment, are still believed to travel at significant bulk speed. Short electron energy-loss times then require *in situ* particle acceleration that is most naturally attributed to the presence of shocks. Although much detail is still to be explored and understood, such a picture can qualitatively explain observed spectral breaks in the radio, optical, and X-ray spectrum, and spatial offsets in X-ray and radio emission regions.

The origin of the X-rays in the resolved jets of high-power sources is more controversial. Synchrotron emission dominates in some cases, and again shocks may be important in particle acceleration. The situation is less clear in sources at high redshift, and where the jets are close to the line of sight. Here inverse Compton processes are expected to be more important, and may dominate.

What is defined as the core emission region depends on instrument resolution and source redshift. It is natural that some of this X-ray emission should be associated with the radio jets, and what is learned from the resolved jets can inform our interpretation of this component. What is less clear in many sources is how much X-ray emission is associated with the accretion flow, and whether or not a central structure obscures much central emission.

Over the past decade, it is not just the jet *emission mechanisms* that have been studied. Much has been learned about other physics of the resolved components, particularly through relating properties of the jets to those of the X-ray-emitting medium through which they propagate, and which provides sufficient pressure to be dynamically important. A discussion of this physics is out of the scope of this paper, but see Worrall & Birkinshaw (2004b) for a recent review and discussion of outstanding issues.

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