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Quasar Cores & Jets

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X-ray and Optical Properties of Radio Jets

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Abstract. Over the last few years the high-quality imaging and spectroscopic data from *Chandra* and XMM-Newton have added greatly to our knowledge of the physics of radio jets. Supported by optical data, we are now able to understand much about jet energetics. Here I review the current state of knowledge.

1. Introduction

Chandra, XMM-Newton and HST have revitalized the study of active-galaxy radio jets. Studies using only radio data reach a natural limitation. The emission is known to be of synchrotron origin, and thus an inseparable function of the magnetic-field and electron energy densities. To progress further, the usual assumption has been that a source is "in equipartition", with these two energy densities equal, which is roughly equivalent to the source radiating at minimum energy. But this assumption was largely untested.

The electron population producing radio synchrotron emission must also lose energy by scattering ambient photons to higher energies via the inverse Compton process. If this process dominates the production of the higher-energy radiation that is measured, the electron population is probed directly. Both the electron energy density and magnetic field strength can then be estimated, and the equipartition assumption can be tested. The ambient photons may be the radio synchrotron emission itself (synchrotron self-Compton), the cosmic microwave background (CMB) radiation, or photons from the nucleus of the active galaxy.

Inverse Compton scattering is not the only mechanism which may produce radiation at energies above the radio. An electron spectrum that extends to sufficiently high energy will produce high-energy synchrotron radiation. The highest-energy electrons have correspondingly fast energy losses, and *in situ* particle acceleration may be required to ensure their supply.

Thus, once the emission mechanism of the X-ray and optical radiation is unraveled, the underlying physical processes provide insights not readily available from measuring the radio synchrotron emission alone.

X-ray detection has a further important role in probing the physics of active-galaxy radio jets, since the medium through which jets propagate is X-ray emitting. The new X-ray data provide unprecedented information on the hydrodynamical interactions between the jet and gaseous medium. This can help us understand jet content and models for jet propagation.

The high spatial resolution of *Chandra* has been key to the study of X-ray jets, and the large throughput of XMM-Newton has assisted studies of the X-ray-emitting environments. While historically the search for optical jet emission has been carried out using ground-based telescopes, a major problem has often been one of low contrast with light from the host galaxy. HST's sharp focus helps to overcome this difficulty, and it is playing a particularly important role in polarization studies.

2. Resolved X-ray Jets

For high-power radio sources, if we discount hot-spot emission, which is thought to arise from sub-relativistic flows at jet termination (but see Georganopoulos & Kazanas 2003), resolved X-ray jets are detected with *Chandra* mostly in quasars (e.g., Schwartz et al. 2000; Marshall et al. 2001; Sambruna et al. 2001, 2002; Siemiginowska et al. 2002, 2003), with the bright radio sources Pictor A and Cygnus A (Wilson et al. 2001a,b) being the galaxy exceptions. The quasar X-ray jet emission is one-sided, always on the same side as the brighter radio jet, implying that relativistic beaming is important. Two-sided X-ray emission, such as that in the quasar 3C 9 (Fabian et al. 2003) most likely does not imply the presence of counter-jet emission, but rather the more isotropic lobe, hot-spot, or cluster-related emission expected at some level in all sources and detected in many (e.g., Worrall et al. 2001b; Hardcastle et al. 2002a). Tests, using lobe and hot-spot X-ray inverse Compton emission, have generally found magnetic field strengths within a factor of a few of their equipartition (minimum energy) values (e.g., Brunetti et al. 2002; Hardcastle et al. 2002).

Currently there are at least 24 quasar X-ray jet detections. They have mostly been found through targeted programs to observe bright, prominent, one-sided radio jets. In most cases there has been no pre-existing reported optical jet detection, but there has been reasonable success in subsequent detection. The level of many detections lies below an interpolation between the radio and X-ray spectra, and so the optical flux densities are key in showing that the X-rays do not arise from synchrotron emission of a single power-law distribution of electrons (e.g., Schwartz et al. 2000; Sambruna et al. 2002). In order to avoid the total energy in particles and magnetic field being orders of magnitude above its minimum value, as would arise from a simple synchrotron self-Compton explanation, the most widely favored model is that the X-rays are produced by inverse Compton scattering of CMB photons by the electrons in a fast jet that sees boosted CMB radiation and emits beamed X-rays in the observer's frame (Tavecchio et al. 2000a; Celotti et al. 2001). The model can produce sufficient X-rays with the jet in equipartition, but only if the bulk motion is highly relativistic (bulk Lorentz factor, $\Gamma \approx 5-20$) and the jet at small angle to the line of sight. Although such a speed and angle are supported on the small scale by VLBI measurements, at least for the source which has guided this work, PKS 0637-752 (Lovell et al. 2000; Schwartz et al. 2000), the jet must remain highly relativistic hundreds of kpcs from the core (after projection is taken into account) for the X-rays to be produced by this mechanism. This conclusion, based on multi-wavelength data, has been something of a surprise, since earlier statistical studies of the structures of powerful radio sources suggested that jet velocities average only about $0.7c$ at distances of tens of kpc from the core (Wardle & Aaron 1997; Hardcastle et al. 1999).

Whether high-power jets are electron-positron, or have a significant proton content, is still somewhat unclear. For example, Tavecchio et al. (2000b) argue, based on near-equipartition models applied to the emission from quasar sub-pc-scale inner jets, that a significant proton contribution may be required to boost the kinetic power sufficiently to match the total radiated power. In contrast, Hardcastle et al. (2002a) find cases where the radio lobes would be over-pressured with respect to the ambient X-ray-emitting medium if a proton contribution were included.

Resolved X-ray jets in active galaxies with *low* radio power are detected with *Chandra* in sources covering the whole range of orientation suggested by unified schemes, suggesting that beaming is less important than in their more powerful counterparts. The more than 18 detected sources range from beamed jets in BL Lac objects (Pesce et al. 2001; Birkinshaw et al. 2002) to two-sided jets in radio galaxies (Chiaberge et al. 2003; Hardcastle et al. 2003), with most X-ray jets corresponding to the brighter radio jet (e.g., Hardcastle et al. 2001, 2002b; Harris et al. 2002a,b; Marshall et al. 2002; Worrall et al. 2001a, 2003). Several of the observations have been targeted at sources already known to have optical jets, from ground-based work or HST. However, it's easier to detect X-ray jets in *Chandra* observations than to detect optical jets in HST snapshot surveys (Worrall et al. 2001a), because there is generally better contrast with galaxy emission in the X-ray band than in the optical.

Inverse Compton models for any reasonable photon field suggest an uncomfortably large departure from a minimum-energy magnetic field in most low-power X-ray jets (e.g., Hardcastle et al. 2001). Synchrotron emission from a single electron population, usually with a broken power law, is the model of choice to fit both the radio, optical, and X-ray flux densities and the relatively steep X-ray spectra (e.g., Böhringer et al. 2001; Hardcastle et al. 2001). X-ray synchrotron emission requires TeV-energy electrons which lose energy so fast that they must be accelerated *in situ.*

It has been known for some time that the minimum pressure in low-power jets (calculated assuming an electron-positron plasma) is typically below that of the external X-ray-emitting medium (e.g., Morganti et al. 1988; Killeen et al. 1988; Feretti et al. 1995; Worrall & Birkinshaw 2000). However, this cannot be used simply to infer that the jets are launched as an electron-proton plasma to give them the extra required pressure component. Low-power jets are believed to slow down to sub-relativistic speeds within kpc distances, via significant entrainment of thermal material (e.g., Bicknell 1994), and even the most detailed hydrodynamical modeling, such as that which has been applied to 3C 31 by Laing & Bridle (2002), does not decide the issue of primary jet content.

3. Centaurus A and Particle Acceleration

The above arguments, applied to the bright northeast jet of the nearest radio galaxy, Centaurus A, find in favor of X-ray synchrotron emission (e.g., Kraft et al. 2002), and the proximity of Cen A allows us to probe its acceleration sites in the greatest possible detail. Unfortunately the dramatic dust lane spanning the galaxy masks any optical jet emission. The source is the subject of a detailed, continuing, X-ray and radio study using *Chandra*, XMM-Newton, the VLA, and the ATCA, and here I report some of the results from Hardcastle et al. (2003).

Looking first at the radio measurements, when we compare our new VLA map with archival data from 1991, we find proper motion of order 0.5c in some knots. Given that the proper motion is also apparent in the diffuse emission, we conclude that it is bulk motion rather than a pattern speed. If the jet is at about 50 degrees to the line of sight, as parsec-scale properties and other considerations suggest is reasonable, then the sub-luminal proper motion means that the strong jet-counterjet asymmetry seen on kpc scales is intrinsic and not due to beaming.

In the X-ray, we see both diffuse jet emission and much resolved structure, including substructure in some knots. Some bright X-ray knots have only weak radio emission with no indication of proper motion, but with the radio emission brightening down the jet in the direction away from the nucleus. While the radio association confirms that these X-ray knots are indeed jet related, the emission profiles are not what are expected from a simple toy model where the electrons are accelerated and then advect down the jet, with the X-ray emitting electrons losing energy faster than the radio-emitting electrons. Instead, we propose a model where there are obstacles in the jet (gas clouds or high-mass-loss stars). Both radio and X-ray-emitting electrons are accelerated in the standing shock of this obstacle, and a wake downstream causes further acceleration of the low-energy, radio-emitting, electrons. The resulting radio-X-ray offsets, averaged over several knots, could give the radio-X-ray offsets seen in more distant jets (e.g., Hardcastle et al. 2001).

What observations might help us to learn more about the acceleration processes in low-power jets? Optical polarization is one way. In M 87, Perlman et al. (1999) found evidence for strong shock acceleration at the base of bright emitting regions, in compressed transverse magnetic fields. Perlman is now leading an HST program to extend these polarization studies to other low-power radio galaxies. Variability is also an important probe of energy losses, and we are monitoring the resolved jet of Cen A in the X-ray and radio. A knot in the jet of M 87 has been observed to vary in the X-ray and optical on the time-scale of months, consistent with shock acceleration, expansion, and energy losses (Harris et al. 2003; Perlman et al. 2003).

4. Jet interactions with the X-ray-emitting medium

Most results on the interaction between jets and the X-ray-emitting medium obtained so far are for low-power sources. For example, Laing & Bridle (2002) have extended the modeling of Bicknell (1994) and use radio-jet sidedness to deduce a velocity model for twin radio jets. This model predicts the mass entrainment needed for their deceleration, and thus a density and pressure model in the ambient medium. They have applied this to 3C 31, and find that *Chandra* observations of the galaxy atmosphere (Hardcastle et al. 2002b) give an excellent match to the predicted pressure profile.

There is much current interest in the possibility of radio sources heating the interstellar and inter-cluster medium. Such heating would help to explain the weakness or absence of lines from gas cooling below 1 keV in the densest central

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regions of the atmospheres, as seen in reflection-grating observations with XMM-Newton (e.g., Peterson et al. 2001). The first definitive evidence for heating by a supersonically-expanding lobe is found in the inner regions of Cen A, where a rim of gas that is significantly hotter than the surrounding medium is found to cap the inner southwest radio lobe (Kraft et al. 2003). From the density and temperature measurements, we infer that gas is heated as it crosses the bow shock in front of the lobe, and then adiabatically cools from about $kT = 6.8$ keV to the $kT = 3$ keV shell that is seen. The kinetic energy in the shell exceeds the thermal energy in the nearby ambient interstellar medium, so that when the shell dissipates it will have a major effect on the interstellar medium and provide distributed heating.

There have been several reported examples where radio-emitting plasma appears to be shoving away X-ray-emitting gas, most notably Perseus A (Böhringer et al. 1993) and Hydra A (McNamara et al. 2000). 3C 66B is an interesting new example in which we see direct evidence of associated heating, as measured with XMM-Newton (Croston et al. 2003). Firstly, the group X-ray gas is hotter than expected based on a temperature-luminosity relationship for similar groups void of radio sources. Secondly, there is a region of gas which appears to have been compressed by the eastern radio lobe, and which is measurably hotter than the overall atmosphere.

5. Conclusions

The new results on radio jets which have resulted from complementary X-ray and optical observations have brought some surprises. Firstly, synchrotron X-ray jets are common in low-power sources, which implies that the intrinsic electron spectrum continues to TeV energies, and requires substantial *in situ* particle acceleration. Secondly, the detection of so many quasar X-ray jets, interpreted as due to beamed CMB photons, means that highly relativistic bulk flows exist far from the cores. This was not expected based on earlier statistical studies of radio sources. Jet theory has had some pleasing successes, such as the agreement of the X-ray pressure profile with the prediction from a hydrodynamical model for 3C 31.

There is still much observational work to be done. Firstly, there is considerable bias in the jets which have been observed in the X-ray, and we need observations of unbiased samples over broader luminosity and redshift ranges. Secondly, we need more deep X-ray observations (and refined theory) to understand jet-lobe/inter-cluster medium interactions. Finally, to study acceleration sites and processes, more detailed knot mapping and temporal monitoring is required. In combination with multi-frequency polarization measurements, such data could map the spatial distributions and follow the acceleration of the electrons responsible for the radiation in the radio to X-ray bands.

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