X-RAY JETS AND HOTSPOTS IN EXTRAGALACTIC RADIO SOURCES

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ABSTRACT

X-ray emission has now been detected from a large number of jets and hotspots of radio galaxies and radio-loud quasars. This paper asks, and attempts to provide answers to, a fundamental question: what are the emission mechanisms for these X-rays, and how do we know?

1. LOW-POWER JETS

The X-ray emission from low-power jets in Fanaroff- Riley class I radio sources is thought to be synchrotron. The primary motivation for this belief is the detection of optical synchrotron emission at a level that allows a smooth spectrum to be constructed through the radio, optical and X-ray data (e.g. Hardcastle et al. 2001). Synchrotron X-ray emission, in the typical fields estimated for a low-power jet, implies very highenergy electrons ($\gamma > 10^7$) and correspondingly short loss lifetimes (tens of years). Thus X-ray synchrotron emission traces the current location of high-energy particle acceleration. The fact that the X-ray emission is often associated with the region where the jet is decelerating suggests that the acceleration mechanism must involve the tapping of the jet kinetic energy. In Cen A, the brightest compact X-ray regions are associated with stationary radio knots, suggesting that we are seeing small internal shocks in the jets (Hardcastle et al. 2003). A more diffuse particle acceleration process is probably also required. There are still unanswered questions in this model: why do the overall spectra of jets resemble one-zone synchrotron models, although the acceleration mechanism must be very localized? And what determines the characteristic steep high-energy spectral index (α = 1.0–1.5)? But the basic picture seems clear: these low-power radio galaxies at least have synchrotron jets.

2. HIGH-POWER JETS

The situation is less clear for the jets in powerful FRII radio galaxies and quasars. The earliest new discoveries of X-ray jets in this type of object (e.g. Schwartz et al. 2000) were unlike the FRI jets in that their radio through X-ray spectra were not consistent with a one-zone synchrotron model: where optical constraints existed, they lay below a straight line connecting the radio and X-ray fluxes. This led to the widespread adoption of the beamed inverse Compton model for these jets (Tavecchio et al. 2000; Celotti et al. 2001). In this model the jets are travelling at highly relativistic speeds and the CMB's energy density in the jet frame is boosted by a factor $\sim \Gamma^2$, where Γ is the bulk Lorentz factor. In this model the electrons producing the X-rays by the inverse-Compton process have very low energies, and the electron spectrum must extend down to $\gamma \sim 10$. Typical bulk Lorentz factors needed to produce the X-rays are ~ 10, similar to what is observed on pc scales.

One problem with this model is that it is inconsistent with the existing constraints on the bulk speeds of the kpc-scale jets from beaming studies. These tend to give bulk speeds of $\sim 0.6c$ (e.g. Wardle & Aaron 1997, Hardcastle et al. 1999, Mullin et al. in prep.). The distribution of observed jet parameters is inconsistent with even moderately high jet speeds. If the core-dominated quasars that show X-ray jets are the same objects as the lobe-dominated radio galaxies that dominate the radio samples, then there must be some velocity structure in the jets, e.g. a fast central spine with $\Gamma \sim 10$ and a slower sheath with $v = 0.5c$. More recently some FRII sources have been shown to have jet X-ray components that are likely to be synchrotron in origin: examples include Pictor A (Hardcastle & Croston 2005) and 3C403 (Kraft et al. 2005). So it is clear that the X-ray emission in these sources can be synchrotron emission. In the beamed inverse-Compton model, perhaps the X-ray synchrotron emission originates in the slow sheath.

Is there any way of testing the beamed inverse-Compton model? One interesting approach comes from considering those jet X-ray sources that can be resolved into more than one jet X-ray component. The bulk Lorentz factor can then be calculated for each X-ray region, allowing us to plot quantities as a function of position along the jet. I have carried out this analysis for a small sample of objects from the literature (Hardcastle, 2005, MN submitted. Almost all of these show a systematic de-

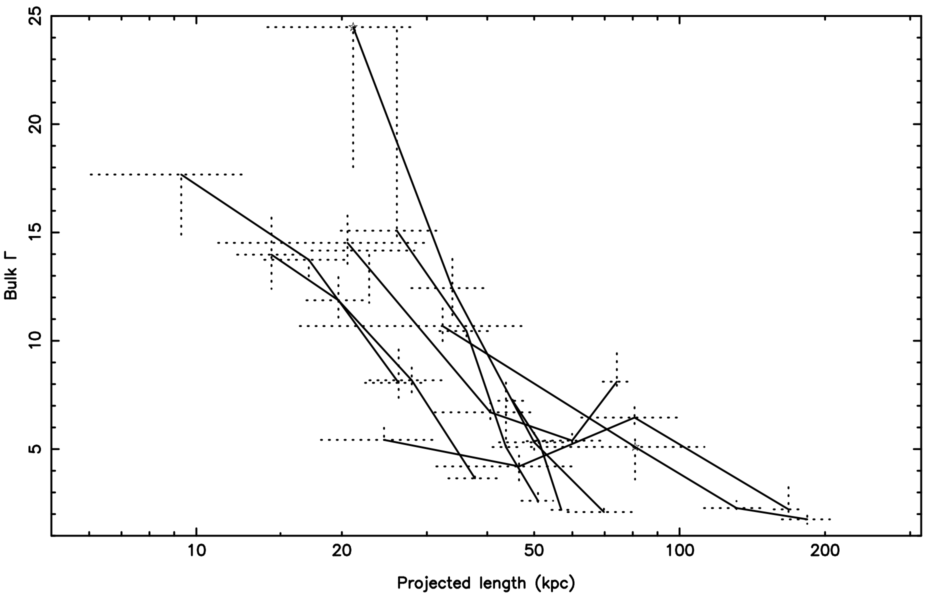

Figure 1. Bulk Lorentz factor as a function of projected distance for 9 X-ray jet sources, showing apparent jet deceleration.

crease in X-ray to radio ratio. It has already been pointed out (e.g. Georganopoulos & Kazanas 2004) that this obvious strong trend could be attributed to bulk deceleration: however, this has so far not been tested quantitatively against real data until now. My analysis (Fig. 1) shows that the required bulk Lorentz factor (for a fixed but reasonable choice of angle to the line of sight, 4°) systematically decreases as a function of distance along the source, not just in general, but also for most individual sources. The decrease in Γ is large, so that there are some interesting physical problems involved in getting the jet to decelerate (particularly as the deceleration must happen on scales of 100 kpc–1 Mpc). More importantly, there is no corresponding evidence for deceleration in the jets in radio galaxies on these scales – if the spine-sheath model discussed above were true, then we would expect the sheath to decelerate, with observable changes in jet prominence as a function of length, which are not seen.

If deceleration is not viable, what is? Possible ways to explain the radio/X-ray properties of these jets in the framework of the beamed IC model include changing magnetic field strength as a function of length and/or a synchrotron contribution to the inner part of the jet. Such a synchrotron model would not be a one-zone model, but we know (Jester et al. 2002) that the optical-UV spectrum of the best-studied object in this sample, 3C 273, is not described by a one-zone model anyway. There is some evidence for X-ray synchrotron emission in the hotspots of powerful sources (Hardcastle et al. 2004) although space restrictions preclude a detailed discussion here. At present we have to conclude that the emission mechanism for the jets in these sources is not clear, although inverse-Compton is a required process that must come to dominate at large redshifts. More work is needed before inverse-Compton jet X-ray emission can reliably used as a diagnostic of jet physical conditions.

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