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The X-ray Emission of Low-power Radio Galaxies

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Abstract. A low-power radio galaxy generally emits X-rays from a compact X-ray core, its brighter kpc-scale radio jet, and a galaxy atmosphere. The core emission is normally predominantly radio related. The kpc-scale jet emission is synchrotron from the radio to X-ray, requiring *in situ* particle acceleration. The similar integrated radio to X-ray jet spectra, and different radio and X-ray substructures, are best explained if the brightest X-ray regions are sites of strong acceleration, while weaker acceleration occurs throughout the jets, and the X-ray/radio displacements are due to a combination of particle acceleration, advection, diffusion and local ageing. Galaxy atmospheres with steep pressure gradients, such as would prevent disruption of jets where their bulk deceleration is believed to be large, are detected.

1. Components of X-ray emission

Low-power radio galaxies have jets which are believed to have slowed to bulk speeds of less than about 0.1c at kpc distances from the core, so that the effects of Doppler boosting, important on sub-kpc scales, can effectively be ignored. Unification models generally class the members whose small-scale jets are pointed to the observer as BL Lac objects. *Chandra*'s 1″ resolution has been essential to resolving kpc-scale structures in low-power radio galaxies.

Chandra observation of an unbiased sample (not just 'famous' sources or those with the brightest radio jets) is important to understanding the physics of the population. We are undertaking such a radio-galaxy survey using the B2 bright sample, which is well matched to BL Lac objects in isotropic properties. Typical observing times are between 5 and 20 ks. Our *Chandra* observations have already revealed a considerable richness of X-ray structure (Worrall, Birkinshaw, & Hardcastle 2001). A low-power radio galaxy generally contains (a) a compact X-ray core, (b) X-rays associated with the brighter, kpc-scale radio jet, and (c) galaxy-scale X-ray emitting gas. We complement the B2 X-ray survey with longer observations of low-power radio galaxies of specific interest.

X-ray Core: Although ROSAT was largely unable to distinguish between point-like X-ray emission and the small-scale gas whose presence was inferred from the structure of the outer atmosphere, a trend for the compact emission to correlate with the radio core strength was used to argue that at least part of the compact X-ray emission is associated with the pc and kpc-scale radio jets (Worrall & Birkinshaw 1994; Canosa et al. 1999). With *Chandra* we typically resolve a significant fraction (10-90%) of the emission previously associated with an unresolved core. Statistical comparisons with core radio and optical emission will be made once more B2 objects are observed. However, it is already apparent that the unresolved core emission typically suffers only modest absorption ($N_H \sim 10^{21}$ cm^{-2}), similar to that suggested by reddening in the dusty disks often detected with HST. This, together with a spectrum consistent with the optically-thin radio spectral index, suggests that the detected core emission is predominantly radio related. An exceptional case is NGC 4261 (Zezas et al., in preparation). This source, lying close to the plane of the sky, with two-sided X-ray jet emission, has a core X-ray spectrum that includes a flat, heavily absorbed ($N_H > 10^{22}$ cm^{-2}) component. Here we are likely seeing true nuclear X-ray emission.

kpc-scale Jets: The synchrotron lifetimes of electrons emitting the X-radiation are of the order of tens of years. Since the detected X-ray jets are thousands of light years in length, *in situ* particle acceleration is required. Although the jet X-ray emission is strongest in the inner regions where the speed is likely still to be moderately fast, before the deceleration which accompanies the larger jet opening angles, more diffuse X-ray emission can be traced further out in several sources. The phenomenon seen in 3C 66B (Hardcastle, Birkinshaw, & Worrall 2001), of X-ray bright regions offset upstream of radio-bright regions, is now seen in other sources. Together with the flat spectra in the X-ray bright regions, this suggests that the acceleration of electrons to the TeV energies needed for X-ray synchrotron emission is most efficient in strong shocks at the upstream ends of the radio-bright regions. However, diffuse jet X-ray emission shows that electron acceleration is more widespread. The 'universal' integrated spectral distribution which is emerging for radio galaxies and BL Lac objects, of a broken power law with $\Delta\alpha \sim 0.6$ to 0.9, must arise from a combination of electron acceleration and loss processes that are similarly balanced in the jets, perhaps because the populations of shocks capable of accelerating particles are similar. That this process is granular is clear from the highest spatial resolution data, such as we see in our radio/X-ray monitoring of the knotty X-ray jet of the closest radio galaxy, Cen A (Kraft et al. 2002).

Thermal X-ray Atmospheres: Low-power radio galaxies were known from ROSAT to live in group or cluster X-ray-emitting atmospheres (Worrall & Birkinshaw 2000). *Chandra* generally detects the galaxy atmosphere. The deceleration of the radio jets from bulk relativistic speeds to less than about 0.1c is thought to be due to entrainment of external material. A steep pressure gradient in the external X-ray emitting gas is required to prevent jet disruption. Galaxy atmospheres are thus expected, and are now routinely being detected.

References

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