EXTENDED X-RAY EMISSION AROUND RADIO-LOUD QUASARS

Martin J. Hardcastle
Department of Physics, University of Bristol
Tyndall Avenue, Bristol BS8 1TL, UK
m.hardcastle@bristol.ac.uk

Abstract It has only recently become possible to separate extended from nuclear X-ray emission in intermediate-redshift radio-loud quasars. I discuss the observations that exist so far and their implications for the quasars' cluster environments; several quasars at $0.3 < z < 0.7$ have been found to lie in reasonably rich cluster environments. I briefly comment on the improvements to be expected from the new generation of X-ray satellites, and show, as an illustration, a new *Chandra* detection of extended emission around a $z = 0.66$ quasar.

1. Introduction

There are several reasons why we should expect to be able to see luminous extended thermal X-ray emission around radio-loud, steep-spectrum quasars at intermediate redshifts ($0.3 < z < 1.0$). Firstly, there is optical evidence for overdensities of galaxies around such objects (see for example Bremer, this volume; Wold et al., this volume). Secondly, all models of extragalactic double radio sources require that the pressure in the external medium should be comparable to the pressure inside the radio lobes, which implies the presence of a reasonably luminous distribution of hot, X-ray-emitting gas around them. Thirdly, hot gas around the lobes is required to produce effects such as Faraday rotation and the Laing-Garrington effect. And finally, we have known for many years that some powerful radio galaxies lie in luminous X-ray clusters, and so unified models for radio galaxies and quasars require that at least some radio-loud quasars must do the same.

Detecting an X-ray-emitting cluster environment around a distant quasar, and measuring its luminosity and temperature, is valuable for several reasons. Most fundamentally, it gives us quite direct information about the mass of the host system, in contrast to the indirect approach needed to infer this information from optical observations. Detection of high-redshift X-ray clusters can be used to constrain cosmological models (e.g. Donahue et al. 1998, Fabian et al. 2001). For all quasars, we would like to understand whether there is any link between the presence of a cooling flow and the fuelling of the AGN. And for radio-loud quasars the detection of an extended X-ray environment allows us to test unified models and to constrain the dynamics of radio sources.

The problem with any attempt to detect these environments has of course historically been the same as the problem of imaging host galaxies around quasars in the optical: quasars are bright point X-ray sources with non-thermal spectra and luminosities comparable to that of a rich cluster at energies of a few keV. The quasar emission is therefore likely to dominate the measured X-ray flux. The problem is compounded by the (comparatively) low spatial and spectral resolution available with the past generation of X-ray observatories.

2. The past: *ROSAT* searches for quasar clusters

ROSAT was the best observatory for searching for host cluster emission until 2000, but the best resolution available with the *ROSAT* HRI was 5 arcsec, while the PSPC had a resolution ~ 20 arcsec. Moreover, seeing a cluster under the quasar emission depended on knowing the shape of the point-spread function, which was affected by aspect uncertainties on board the satellite and by processing errors on the ground. (Since bright point X-ray sources are rare, it was not usually possible to observe a calibration source in the same field as the quasar.) Early work with *ROSAT* was done by Hall et al. (1995, 1997); they looked at one radio-quiet and three radio-loud objects with $0.2 < z < 0.7$, selecting their targets because they were known to lie in cluster environments. They found extended X-ray emission around the radio-quiet quasar but were only able to set limits on the cluster luminosity of the radio-loud objects.

More recently two groups (Crawford et al. 1999; Hardcastle & Worrall 1999) have detected extended X-ray emission around a number of 3CR quasars. These two studies were carried out independently but the techniques used were very similar. The data were corrected for the effects of aspect error using the centroiding and restacking technique of Harris et al. (1998) — for this process, the bright quasar nucleus is an advantage, since it allows accurate centroids to be found. Once this had been done, models consisting of a point source and β model were fitted to the radial profiles of the quasars. (This involves the assumption that the quasar is at the centre of the cluster emission.) Examples of some of the fits can be seen in Fig. 1.

The 7 target sources of Crawford et al. were chosen because they were thought to lie in cluster environments, though in some cases (e.g. 3C 48) the evidence was only based on extended emission-line diagnostics. They detected all 7 objects. By contrast, in Hardcastle & Worrall (1999) we looked at all 3CRR radio sources that had been observed with *ROSAT*. We detected simi-

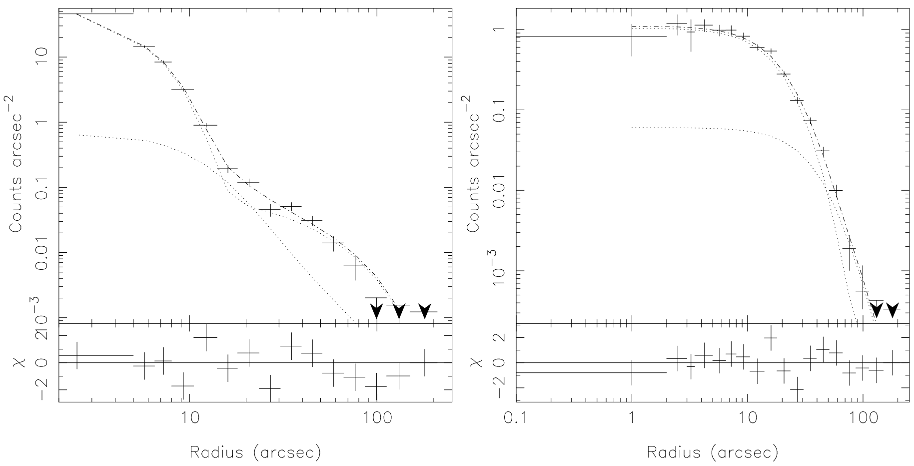

Figure 1. The ROSAT radial profiles, with best-fitting point and β models, of 3C 48 (left: HRI data) and 3C 254 (right: PSPC data).

lar environments, with similar luminosities, around the five objects we had in common with Crawford et al.; these detected objects had extended emission which made up $\sim 10 - 20\%$ of the total soft emission from the quasar. However, we also found a large number (22) of sources with *no* detected extended environment; we used the observations to determine upper limits on the cluster luminosities. In many cases these non-detections were from short *ROSAT* exposures, and the upper limits are high.

What conclusions can we draw about the environments of radio-loud quasars? In Fig. 2 I plot the inferred 2–10 keV luminosities for 3CRR objects as a function of redshift. It will be seen that most of the high-redshift objects, including all the quasars, have extended X-ray luminosities at or consistent with the level of a moderately rich cluster (Abell class 0–1). At lower redshifts (and hence lower luminosities of the radio source), the detected environments are substantially less luminous. The detected quasars occupy much the same region on this plot as radio galaxies of comparable redshift luminosity, as expected from unified models; this is consistent with the picture emerging from optical observations. Since the 3CRR objects represent at any given redshift the most radio-luminous objects in the universe, we would predict from this that more typical radio-loud objects, with lower radio luminosities (perhaps selected from radio surveys with a lower flux limit) should lie in cluster environments which are no richer than these.

We have also used these observations together with the radio data on the sources to compare the inferred internal pressure (the minimum pressure in the radio lobes) with the external pressure due to the X-ray-emitting medium

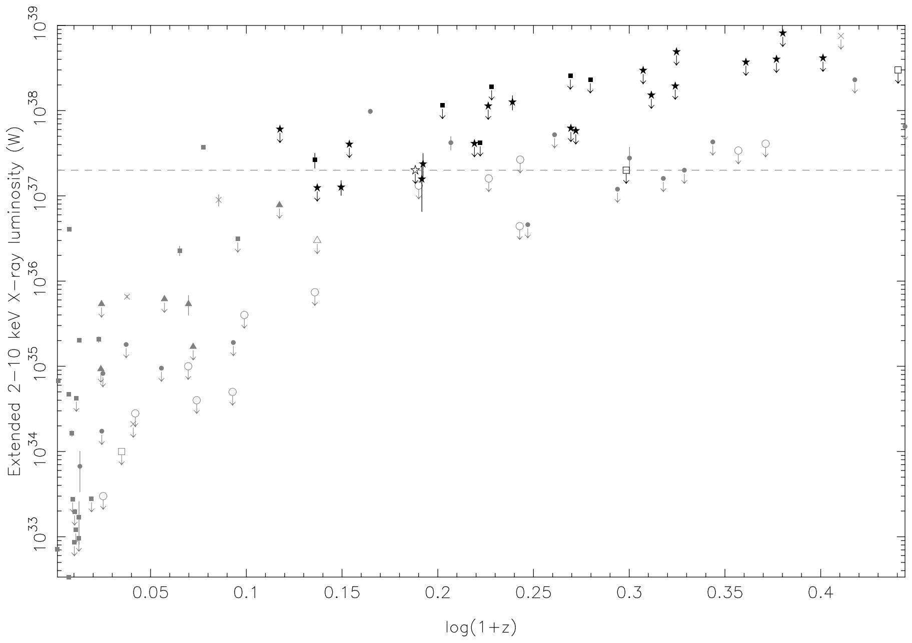

Figure 2. The extended X-ray luminosity of 3CRR radio sources as a function of redshift. Quasars are in bold; other objects are radio galaxies. The dotted line shows a representative moderately rich cluster luminosity of 2×10^{44} ergs s^{-1}.

(or an upper limit if no detection has been made). We find that the minimum pressures in both radio galaxies and quasars are systematically lower, by up to an order of magnitude, than the external thermal pressures, confirming an earlier result by Leahy & Gizani (1999) based on a smaller sample. Since radio sources cannot in fact have pressures much lower than the external pressure, the inference is that minimum pressure estimates are wrong by at least an order of magnitude. (We explore the consequences of this result in more detail elsewhere; Hardcastle & Worrall 2000). Thus, at least some progress has been made with *ROSAT* towards answering the questions posed in section 1.

3. The future: *Chandra* and *XMM-Newton*

The new imaging X-ray observatories open up new horizons for this kind of study. *Chandra* is likely to be most important, because its 0.5-arcsec resolution makes spatial decomposition of the quasar nucleus from the extended emission a comparatively trival task. We have begun a programme of *Chandra* observations of quasars and radio galaxies at intermediate redshifts, with the intention of characterising their hot gas environments much more accurately than was

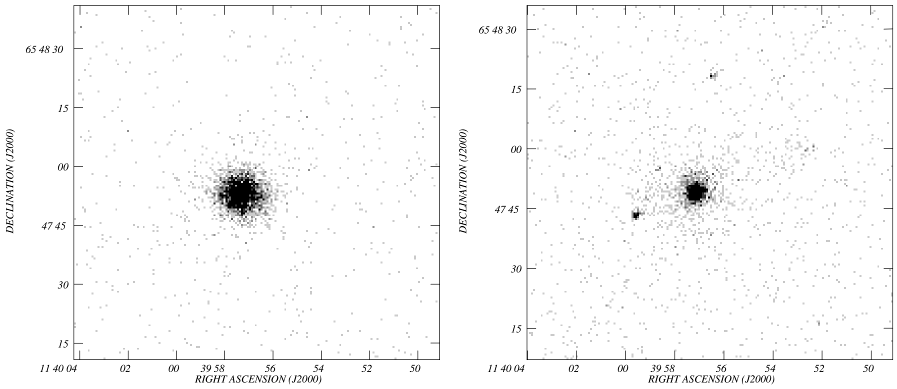

Figure 3. Observations of 3C 263 with ROSAT (left) and Chandra (right). Black is 5 counts per 0.5-arcsec pixel in both cases.

possible with *ROSAT*. The improvement provided by *Chandra* is striking. Fig. 3 shows images of the $z = 0.66$ quasar 3C 263 taken with *ROSAT* (the data analysed by Hall et al.) and *Chandra* (Hardcastle, Birkinshaw, Cameron, Harris & Worrall, in preparation). Whereas no extension was visible either to Hall et al. or to us after detailed analysis of the *ROSAT* data, extended emission (and a detection of the radio hotspot, probably inverse-Compton emission) is clearly visible by eye in the *Chandra* image; the quasar lies in a moderately luminous X-ray environment with $L \sim 10^{44}$ ergs s^{-1}, consistent with the upper limits from the *ROSAT* data. *Chandra* will also be important in comparisons between radio galaxies and radio-loud quasars, since we find that at least some radio galaxies have substantial nuclear soft X-ray emission which requires high resolution for its separation from the extended component (Worrall et al. 2001). If these early results are representative, we can expect to see substantial advances in this area in the coming years.

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