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A *ROSAT* observation of the powerful distant radio galaxy 3C 356

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ABSTRACT
We present results obtained with the Position Sensitive Proportional Counter on *ROSAT* of the first X-ray detection of a powerful distant radio galaxy, 3C 356. The X-ray source has a luminosity of $\sim 2.5 \times 10^{44}$ erg s^{-1}, mostly from the region spanned by the radio lobes. The spectrum shows no evidence of strong intrinsic absorption. Such absorption is observed in the nuclei of nearby powerful radio galaxies, implying that the X-rays from 3C 356 are probably from a dense halo of hot gas, cooling at a rate of 500–1500 $M_{\odot}$ yr^{-1}.

Key words: galaxies: active – cooling flows – galaxies: individual: 3C 356 – radio continuum: galaxies – X-rays: galaxies.

1 INTRODUCTION

Studies of the evolution of clusters of galaxies and of intracluster gas have relevance to many areas of extragalactic astronomy. The work requires observations of both nearby and distant objects. The latter, being faint, are the most difficult to discover and examine. In this paper we present the results of an X-ray observation of a distant radio galaxy, 3C 356 at a redshift $z = 1.079$, which, if its environment resembles that of similarly powerful but nearer radio galaxies, should lie in a cluster. We argue that the detected X-ray flux originates in the hot intracluster medium of this cluster and not in the nucleus itself, which is probably absorbed at soft X-ray wavelengths. On this interpretation, our results have interesting implications for cooling flows and the alignment effect observed in powerful distant radio galaxies.

The intracluster medium surrounding a powerful radio galaxy provides the working surface on which the jets from the nucleus make the radio lobes. X-ray observations of two of the nearest powerful radio galaxies, Cygnus A (Arnaud et al. 1984, 1987) and 3C 295 (Henry & Henriksen 1986), show them both to lie at the centre of dense, rapidly cooling, intracluster gas. Optical counts of galaxies around luminous radio galaxies at $0.4 < z < 1$ by Yates, Miller & Peacock (1989) and Hill & Lilly (1991) demonstrate that they inhabit the centres of rich clusters, although the intracluster medium itself is not immediately detectable at optical wavelengths. Direct X-ray detection of the intracluster gas in clusters more distant than 3C 295 ($z = 0.46$) is now possible with the high X-ray sensitivity of *ROSAT*; the difficulty in making such studies lies in selecting very distant clusters. We chose to observe the Fanaroff–Riley II radio galaxy 3C 356. It is five times more powerful a radio source than Cygnus A, which we use as a comparison object throughout this paper.

Distant radio-loud quasars also appear to lie in clusters rich in gas (for surrounding galaxy counts, see Yee & Green 1984, 1987; Ellingson, Yee & Green 1991; Hintzen, Romanishin & Valdes 1991; for evidence of high gas pressure see Crawford & Fabian 1989; Heckman et al. 1991; Bremer et al. 1991). Further evidence for the association of powerful radio-loud objects with dense intracluster gas comes from observations of a systematic depolarization asymmetry (Pedelty et al. 1989; Garrington, Conway & Leahy 1991) similar to that seen in Cygnus A (Dreher et al. 1987), and from the distorted and compressed structures of many powerful distant radio sources (Hintzen, Ulvestad & Owen 1983; Barthel & Miley 1988).

The results are consistent with the idea that radio-loud quasars and radio galaxies are the same population of objects, with quasars being viewed within about 45° of the radio axis and radio galaxies at larger angles (Barthel 1989). The active nucleus in a distant radio galaxy is then of similar luminosity to a quasar, but is not readily observed at optical or UV wavelengths due to beaming of the radiation, probably caused by a wide equatorial zone of obscuration close to the nucleus. For example, the X-ray emission from the nuclei of the powerful radio galaxies Cygnus A (Arnaud et al. 1987) and 3C 109 (Allen & Fabian 1992) is heavily absorbed by column densities of 8×10^{22} and 5×10^{21} cm^{-2}, respectively. The beam may become apparent, however, if the surrounding medium scatters some of it into our line of sight. This could be due to electrons or dust (embedded in cold clouds) in the intracluster medium. If the Thomson depth in the dense cooling gas around the radio galaxy exceeds about 1 per cent, as observed for nearby massive cooling flows

(White et al., in preparation), then electron scattering alone can provide the explanation (Fabian 1989) for the optical continuum emission that is commonly found along the radio axis in many high-redshift radio galaxies (Chambers, Miley & van Breugel 1987; McCarthy et al. 1987). The intrinsic optical polarization of this continuum (di Serego Alighieri et al. 1989; Tadhunter, Scarrott & Rolph 1990; Tadhunter et al. 1992) demonstrates that scattering is responsible for a significant part, if not all, of the aligned continuum. The clearest example of this phenomenon at low redshift is the polarized optical nebulosity associated with Cygnus A (Tadhunter et al. 1990), which can also be accounted for by electron scattering in the surrounding cooling gas.

The radio source 3C 356 is a large asymmetric double (760-kpc separation; $H_0=50$ km s^{-1} Mpc^{-1}, $q_0=0$ used throughout) with a position angle of 170°. The radio source has weak depolarization to the south-east, the side of the lobe closer to the centre (Pedelty et al. 1989). (The depolarization is probably weak because the source is so large that its lobes are projected beyond the core of the surrounding intracluster medium.) The galaxy counterpart has been imaged in both the optical and the infrared by several authors (le Fèvre, Hammer & Jones 1988; Eales & Rawlings 1990; Eisenhardt & Choksi 1990; Rigler et al. 1992). It is unusual in that it comprises two components separated by 54 kpc along the radio axis. The northern object has the higher ionization emission-line spectrum (Spinrad 1982; McCarthy 1988) and for this reason had been commonly associated with the origin of the radio source. Eales (1992) cites recent results by Ferrini which suggest that both components are radio nuclei. [If they are both active nuclei then the criticisms by Eales & Rawlings (1990) of the electron scattering model for the alignment effect no longer hold.] The northern component is compact in the optical on scales of 5 kpc, but with an extension stretching 3 arcsec (~ 35 kpc) directly to the south. This extension is also apparent in redshifted [O II]λ3727 images, although the whole of the northern object appears unresolved in the *K* band. The second component to the south is more diffuse in both optical and infrared, appearing slightly elongated perpendicular to the radio axis. Whilst its integrated luminosity is similar to the northern component in both continuum and [O II], it is redder and has a low-ionization emission-line spectrum. The extent of any optical continuum aligned with the radio axis in this object is at present unclear.

2 OBSERVATIONS AND ANALYSIS

3C 356 was observed by the Position Sensitive Proportional Counter on *ROSAT* over the period 1992 June 23 to 29, with a total exposure time of 18 565 s. The central 15.8-arcmin square region of the total PSPC field surrounding 3C 356 is shown in Fig. 1, for (observed) energies ~ 0.5–2.4 keV. 3C 356 is the source at the centre of the field. A contour map of the X-ray emission on an expanded scale is shown in Fig. 2, where it is clear that the bulk of the X-ray emission comes from the region inside the radio lobes. The possibility of an extension along the radio axis is intriguing but unquantifiable, given the low count rate.

Analysis of the *ROSAT* image was performed using the Starlink ASTERIX package. Extracting data from PHA channels 17–250 (~ 0.17–2.5 keV), we find there are 25–32 counts above an expected background rate of 5.5–6.5 counts, where the variation is due to taking a range of radii to encompass the source, and different neighbouring background regions. 3C 356 is detected at a significance level corresponding to $\sim 6\sigma$. The source is present in both soft (channels 17–50) and hard (channels 50–240) bands. We extracted an X-ray spectrum of 3C 356 in four bins over the energy range of 0.19–2.15 keV. A background spectrum was extracted from a large annulus around 3C 356 that was free from obvious contaminating sources, and subtracted from the source spectrum.

We have modelled the X-ray spectrum using the XSPEC spectral fitting package (Shafer et al. 1991). With only four data points, we cannot carry out a rigorous statistical comparison of models, but we can conclude that the source is soft, without intrinsic absorption comparable to that of the nucleus of Cygnus A, and that it is consistent with the emission from a dense intracluster medium. Although XSPEC gives us goodness-of-fit parameters such as χ^2, we do not tabulate these as the data are only marginally Gaussian at about 6 counts per spectral bin; the results are best assessed by inspection of Fig. 3.

In detail, we consider two classes of model for the emission: an absorbed power-law continuum and a hot thermal plasma (using updated Raymond & Smith 1977 spectra). Galactic absorption was fixed at the equivalent hydrogen column density for our Galaxy of 2.75×10^{20} atom cm^{-2} (Stark et al. 1992). The photon index of the power-law continuum was fixed at 1.8 (the same as that of the nucleus of Cygnus A – Arnaud et al. 1987) and gives an adequate representation of the data if no intrinsic absorption is included (upper dotted line in Fig. 3). The goodness of fit reduces sharply if this power law is absorbed (this model is formally excluded by the increase in χ^2 or maximum likelihood, but note that the statistics are of small numbers). This is illustrated in Fig. 3 (lower dotted line) with the power law absorbed by an equivalent column density (1×10^{22} cm^{-2} when the redshift is taken into account) to that detected in X-rays for the nucleus of Cygnus A (Arnaud et al. 1987). Alternatively, a fit of an isothermal bremsstrahlung spectrum at a temperature of 4 keV (matching that of the Cygnus A cluster) with abundance of 0.4 times solar is an adequate fit to the data (dash–dot line in Fig. 3). If we now model the cluster as gas cooling from 4 keV (for details of the spectrum, see Johnstone et al. 1992), we obtain what is the best fit to the data (dashed line in Fig, 3). The inferred mass deposition rate is $\dot{M}\sim 500$ M$_\odot$ yr^{-1}. $\dot{M}$ increases if the gas is cooling from lower temperatures, reaching values of 1300 M$_\odot$ yr^{-1} for gas cooling from 2 keV (solid line in Fig. 3). If there is intrinsic absorption associated with cold clouds embedded in the cooling flow, as found for low-redshift cooling flows (White et al. 1991), then $\dot{M}$ can rise to 2500 M$_\odot$ yr^{-1} or greater.

After correction for absorption by our Galaxy, all models give intrinsic luminosities in the range $1.96\text{–}2.4\times10^{-14}$ erg cm^{-2} s^{-1} for the observed 0.2–2 keV band: the lower value is obtained from the isothermal bremsstrahlung spectrum at 4 keV, and the upper value from the gas cooling from a temperature of 4 keV. The instrinsic 0.42–4.2 keV luminosity from 3C 356 is thus in the range $2.3\text{–}2.9\times10^{44}$ erg s^{-1}.

Finally, we have examined the spatial extent of the source by making a radial profile of the emission about its centroid.

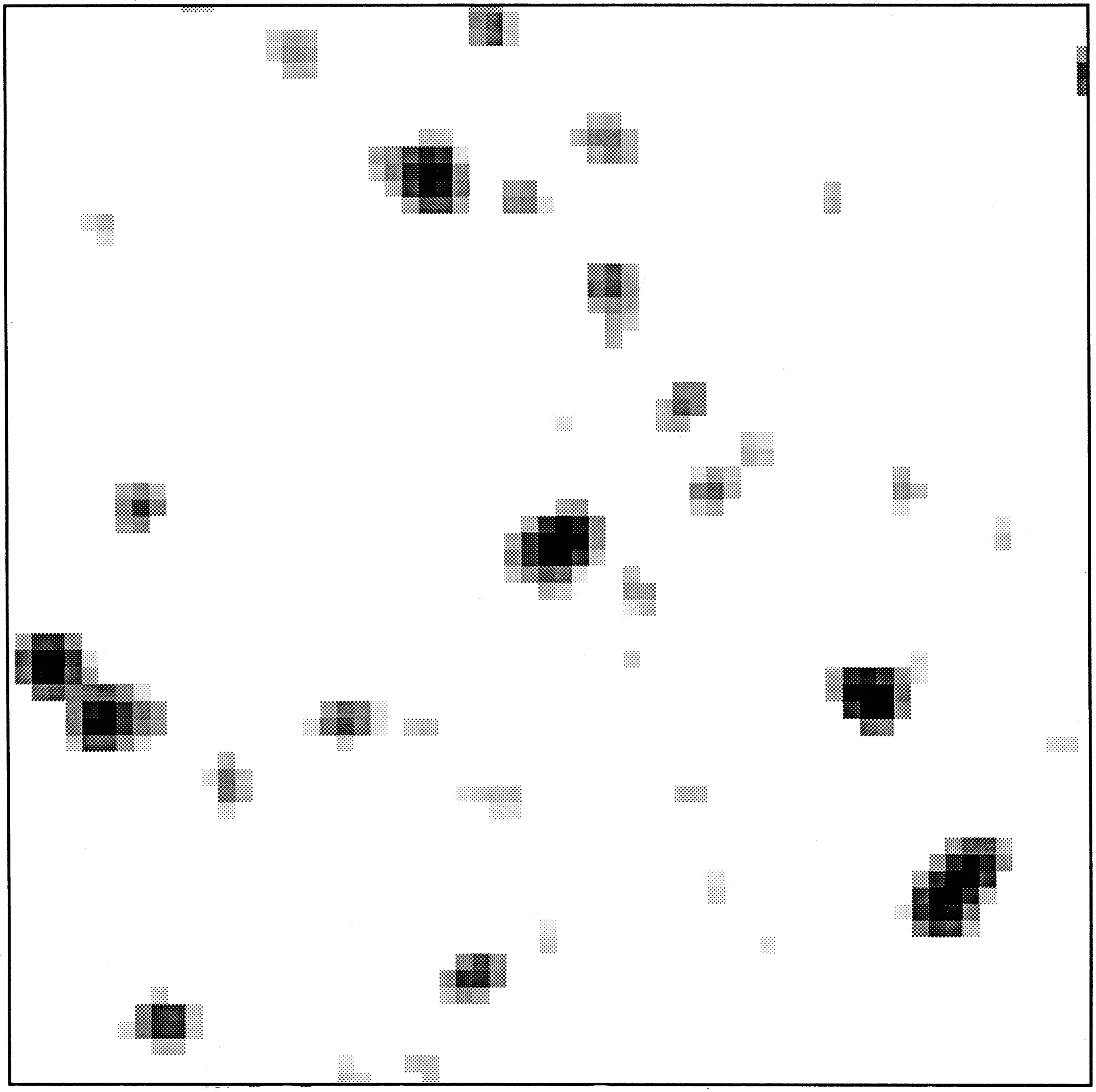

Figure 1. The central 15.8-arcmin square region of the total PSPC field including 3C 356 for (observed) energies ~0.5–2.4 keV. Pixels are 15 arcsec square, and the data have been smoothed twice.

Approximating the point spread function of the PSPC as a Gaussian with a dispersion (σ) of 12 arcsec, we find that acceptable fits are obtained both for a point source alone and for a combination of a point source containing 20 per cent of the flux with a Gaussian of 30 arcsec containing the remaining flux (the total flux in this combined case is then slightly higher than for a single point source). We cannot be more specific with so few counts, except to note that the source cannot be much more extended than in this last model; a much deeper image is needed to resolve the source more clearly.

3 DISCUSSION

The X-ray data on 3C 356 show a source centred on the radio galaxy which has a spectrum inconsistent with a heavily absorbed nucleus, such as that observed in a similar powerful, low-redshift radio galaxy such as Cygnus A. We cannot discriminate further between the different acceptable fits to the X-ray spectrum of 3C 356, but find that a hot gaseous halo, required by most theories of the formation of radio lobes, gives an acceptable spectrum. The X-ray luminosity is several orders of magnitude greater than that seen for

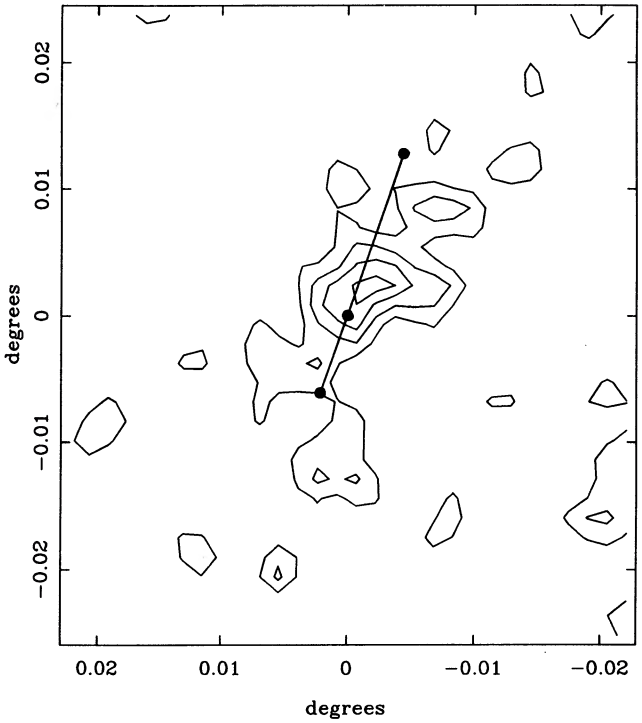

Figure 2. Contours of X-ray emission from 3C 356. The radio axis with the positions of the radio lobes from the 1490-MHz map of Leahy, Muxlow & Stephens (1989), and that of the central source (Spinrad et al. 1985), have been superposed to show that most of the X-ray emission originates from a region well within the lobes.

isolated elliptical galaxies and one order greater than that of the Virgo cluster. It is about half the luminosity of the cluster surrounding Cygnus A and has a mass cooling rate 5–15 times higher. The X-ray luminosity is similar to those of the most X-ray luminous FRII radio galaxies reported by Fabbiano et al. (1984) in their study of low-redshift radio galaxies (mostly much less radio-powerful than 3C 356). Only 3C 109 is more X-ray luminous. The origin of the X-rays from the nearby FRII galaxies is not clear (see also Miller et al. 1985), but, until X-ray spectra are available, absorbed emission from active nuclei as in 3C 109 (Allen & Fabian 1992) cannot be ruled out as a major contributor.

The cooling flow interpretation for the hot gaseous halo is further supported by consideration of the emissivity of the source if we assume that a significant fraction of the flux is emitted from a region which is less than 30 arcsec in diameter (330 kpc). This is in good agreement with the results obtained on the spatial extent of the source in the previous section. If we model the source as a uniform sphere of hot gas at temperature $10^7 T_7$ K, emitting via bremsstrahlung, then the density is $9 \times 10^{-3} T_7^{-1/4}$ cm^{-3}, the cooling time is 2×10^9 yr and the cooling rate is approximately 1500 M$_\odot$ yr^{-1}. We suppose that the emission is more extended than we detect (at least to beyond the radio lobes), but that the surface brightness there is too low to be detected. The Thomson depth of the gas in the spherical core is at least 0.25 per cent and exceeds 1 per cent if the density profile varies inversely with radius as in nearby cooling flows. Electron scattering can then produce an aligned continuum if the radio galaxy houses a powerful quasar beamed out of our

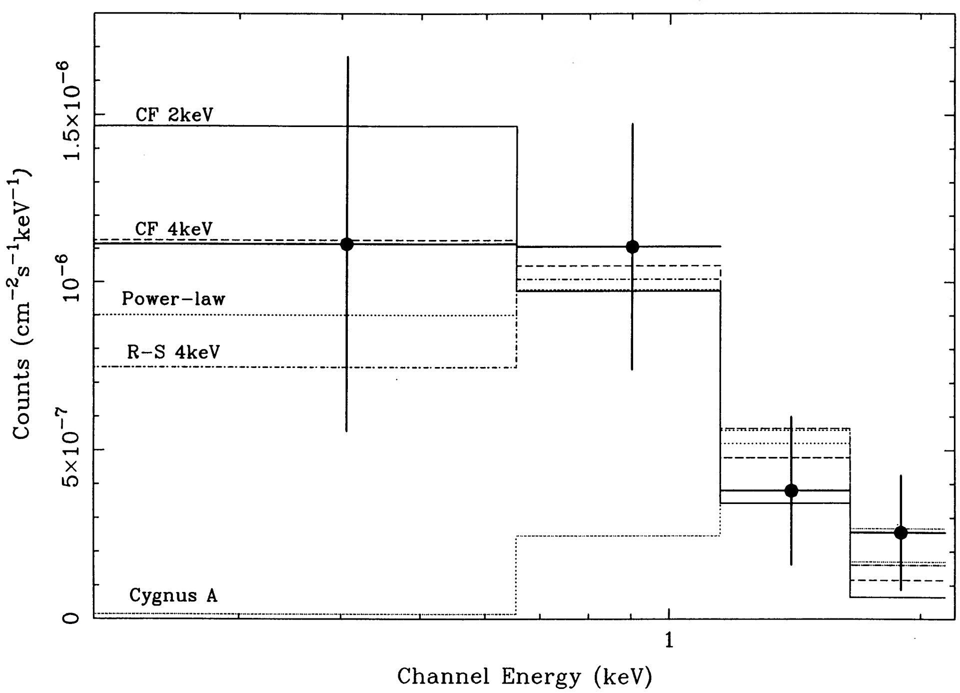

Figure 3. The spectrum of 3C 356 over the observed energy range 0.19–2.15 keV. The error bars represent $\pm 1\sigma$ uncertainties on the flux (count cm^{-2} s^{-1} keV^{-1}) and the width of the energy bin. Models plotted are: (i) Cygnus A-type absorbed power law (lower dotted line); (ii) a power law (without intrinsic absorption) with photon index slope fixed at 1.8 (upper dotted line); (iii) a Raymond–Smith isothermal bremsstrahlung spectrum from gas at 4 keV (dash-dot line); (iv) gas cooling from 4 keV (dashes); and (v) gas cooling from 2 keV (solid line).

line of sight. If similar X-ray results are obtained for distant radio galaxies in which a clear alignment effect is observed, then hot electrons must provide much of the aligned, polarized optical continuum.

Our results are consistent with the hypothesis that powerful radio galaxies act as beacons marking distant clusters which are rich in dense, cooling gas. 3C 356 then marks the most distant cluster yet detected in X-rays. Further X-ray observations of 3C 356 and similar objects, with greater exposure times and at higher angular resolution, are required to confirm and extend this interpretation.

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