The X-ray spectrum of the broad-line radio galaxy 3C445

K. A. Pounds
X-ray Astronomy Group, Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH

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SUMMARY
The first X-ray spectrum of the giant radio galaxy 3C445 is reported. The spectrum is well fitted by a power law of slope close to the 'canonical' value for emission-line galaxies. This suggests that the X-ray emission of 3C445 is dominated by its Seyfert nucleus and is not directly related to the radio flux, a conclusion supported by the large low-energy absorption evident from the X-ray spectrum. The implied intrinsic absorbing column of $\sim 1.7 \times 10^{23}$ cm$^{-2}$ is the largest ever seen for such a high-luminosity source as 3C445 ($L_{2-10} \sim 3.3 \times 10^{44}$ erg s$^{-1}$).

1 INTRODUCTION
One of the emission-line galaxies chosen for study in the early UK programme of observations with the Large Area Counter (LAC) on GINGA was the broad line radio galaxy 3C445. A short observation with EXOSAT in 1984 provided an interesting but poorly constrained X-ray spectrum (Turner & Pounds 1989). This showed a MEDA spectrum ($\sim 2-10$ keV) with a power law much flatter (photon index $\Gamma \sim 1.34$) than the canonical value of $\Gamma \sim 1.7$. Even with this flat power law, the EXOSAT spectrum showed evidence for intrinsic absorption, with $N_H \sim 53$ (+61, −37) $\times 10^{21}$ cm$^{-2}$. A second fit, assuming the canonical $\Gamma \sim 1.7$, was also statistically acceptable (3C445, with $F_{2-10} \sim 1.2 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, was too faint for a well-constrained EXOSAT spectral observation), with $N_H \sim 74$ (+24, −19) $\times 10^{21}$ cm$^{-2}$. Either way, this EXOSAT result made 3C445 a prime object for GINGA, being a rare, high-luminosity AGN with a substantial intrinsic absorbing column, or a radio bright emission-line galaxy with an unusually flat X-ray power-law spectrum.

3C445 is a relatively nearby ($z \sim 0.057$) BLRG with $m_c \sim 15.8$. No previous X-ray spectrum existed prior to EXOSAT, where a possible confusion with the richness 2, distance class 4 cluster, A2440, lying $\sim 0.5^\circ$ from 3C445 was noted (Turner & Pounds 1989). Similar confusion appears in earlier X-ray data from this region, with the source 3A2221-018 being identified in the 3A catalogue (McHardy et al. 1981) with A2440 (at a 2–10 keV flux of $F_{2-10} \sim 3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$), but H2216-027B identified with 3C445 (also with $F_{2-10} \sim 3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$) from the HEAO-1/A2 survey (Marshall et al. 1979). The HEAO/A1 survey also detected a source in this region, with $F_{2-10} \sim 1.6 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (Wood et al. 1984). In the softer X-ray band, Abramopoulos & Ku (1984) reported a 0.5–4 keV luminosity for A2440 of $(6 \pm 2.4) \times 10^{43}$ erg s$^{-1}$, based on an Einstein IPC detection (and an incorrect redshift of 0.057). At the correct cluster redshift of 0.094 (Struble & Rood 1987), the IPC measurement corresponds to $L_{0.5-4} \sim (11 \pm 8) \times 10^{44}$ erg s$^{-1}$. The measured IPC flux from A2440 was $F_{0.5-4} \sim 6 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. Reference to the IPC database shows this emission to be clumpy, but clearly located on A2440. The IPC quasar survey (Wilkes & Tananbaum, private communication) shows a faint source coincident with 3C445 with 6 ± 1.5 counts from a 535 s exposure (0.16–3.5 keV). From this we deduce an incident broad band IPC flux $\sim 3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (for an unattenuated power-law spectrum, $\Gamma \sim 1.3$), and $\sim 7 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (for the spectrum reported in Section 2.1, $\Gamma \sim 1.7$, $N_H \sim 1.7 \times 10^{23}$ cm$^{-2}$).

GINGA observed 3C445 (and A2440) from 1988 November 2, 0600 UT to 1988 November 3, 0600 UT. An attitude correction about one-third through the observation moved the axis of the LAC by $\sim 0.17^\circ$. The initial and final positions of 3C445 and A2440 are shown in Fig. 1, related

![Figure 1](https://academic.oup.com/mnras/article-abstract/242/1/20P/979202/2)

Figure 1. The initial and final positions of 3C445 ($C_1, C_2$) and of A2440 ($A_1, A_2$) in the LAC field of view.
to the short ($X$) and long ($Z$) coordinates of the LAC field-of-view. This manoeuvre turned out to be valuable in helping resolve the X-ray emission of the cluster from that of 3C445.

## 2 SPECTRAL ANALYSIS

After subtraction of the X-ray and particle background by the procedure described in Hayashida et al. (1989), using data from an adjacent source-free field (RA 336°3, Dec. -7°1, observed from 1988 October 31, 0900 UT to 1988 November 1, 0800 UT), the source pulse height spectrum was found to have significant counts in channels 3–18 (~1.5–10 keV) in the LAC front layer and channels 12–30 (~6–16 keV) in the LAC mid-layer. All subsequent spectral fits were carried out on the summed front- and mid-layer data.

The first trial fit, of a power law plus cold absorption (characterized by a column density, $N_H$, of neutral, solar abundance material, with cross-sections from Morrison & McCammon 1983), gave a flat spectrum (similar to the EXOSAT best fit), but an unacceptably high reduced chi-squared ($\chi^2/r$) of 3.92 for 25 degrees of freedom (Table 1, line 1). Examination of the source-minus-model residuals showed a substantial excess count near 6 keV; hence, a second fit was tried, with an Fe K-emission line at 6.4 keV added. Table 1, line 2, details this fit, which gave a significantly improved $\chi^2/r$ of 2.05 (24 degrees of freedom). When allowed as a free parameter, the line energy moved to 6.3 keV (with 90 per cent confidence limits of 5.9 and 6.6 keV), but an unchanged $\chi^2/r$.

### 2.1 Confusion with A2440

A soft excess in the residuals of the above fit suggested a possible contribution from the nearby cluster A2440. As a first check on this, the power-law spectral fit (plus Fe K-line) was re-run with the addition of a thermal bremsstrahlung component of assumed temperature 3.0 keV. The effect was a dramatic steepening of the power-law component, to a canonical slope of $\Gamma$ = 1.68, with a counterbalancing high-absorption column (Fig. 2). The details of this revised spectral fit are given in Table 2, line 1, and gave an excellent $\chi^2/r$ of 0.85 (23 degrees of freedom). The relative insensitivity of the 3C445 spectral parameters to the bremsstrahlung

![Figure 2. The composite GINGA spectrum corresponding to the fit detailed in Table 2, line 1. The dashed lines show the separate components attributed to 3C445 and A2440.](https://academic.oup.com/mnras/article-abstract/242/1/20P/979202)

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**Table 1.** Power-law spectral fits to 3C445.

<table>
<thead>
<tr>
<th>Norm(**)</th>
<th>Power Law Index</th>
<th>$N_H$ (b)</th>
<th>Fe K-line(c)</th>
<th>$r^2$ / d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>2.3 (1.8–2.8)</td>
<td>1.28 (1.20–1.40)</td>
<td>9.7 (3.1–16.4)</td>
<td>3.92 / 25</td>
</tr>
<tr>
<td></td>
<td>(2.0–2.6)</td>
<td>(1.23–1.36)</td>
<td>(5.1–13.8)</td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td>1.8 (1.5–2.4)</td>
<td>1.22 (1.13–1.35)</td>
<td>3.0 (0–10.6)</td>
<td>2.05 / 24</td>
</tr>
<tr>
<td></td>
<td>(1.6–2.1)</td>
<td>(1.16–1.30)</td>
<td>(0–7.4)</td>
<td></td>
</tr>
</tbody>
</table>

(a) The normalization represents the absorption-corrected flux in $10^{-3}$ ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV; (b) solar abundance equivalent hydrogen column in units of $10^{18}$ cm$^{-2}$; (c) Fe K-line flux in units of $10^{-6}$ ph cm$^{-2}$ s$^{-1}$; (d) 90 per cent confidence limits with all parameters of interest; (e) 90 per cent confidence limits with only one parameter of interest.

**Table 2.** Power-law plus bremsstrahlung spectral fits.

<table>
<thead>
<tr>
<th>Norm</th>
<th>Power Law Index</th>
<th>$N_H$</th>
<th>Fe-K</th>
<th>Norm.</th>
<th>$kT$ (keV)</th>
<th>$N_H$</th>
<th>$r^2$ / d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>6.4</td>
<td>1.68</td>
<td>175</td>
<td>3.1</td>
<td>3.4</td>
<td>3</td>
<td>0.5 / 0.85 / 23</td>
</tr>
<tr>
<td></td>
<td>(2.6–15.1)</td>
<td>(1.34–2.06)</td>
<td>(96–266)</td>
<td>(0–9.0)</td>
<td>(2.8–3.8)</td>
<td>(2.8)</td>
<td>(F)</td>
</tr>
<tr>
<td></td>
<td>(3.5–9.8)</td>
<td>(1.50–1.88)</td>
<td>(131–221)</td>
<td>(0–6.4)</td>
<td>(3.1–3.6)</td>
<td>(F)</td>
<td>(F)</td>
</tr>
<tr>
<td>(2)</td>
<td>5.3</td>
<td>1.64</td>
<td>192</td>
<td>3.1</td>
<td>2.5</td>
<td>4</td>
<td>0.5 / 0.86 / 23</td>
</tr>
<tr>
<td></td>
<td>(2.8–14.8)</td>
<td>(1.26–2.07)</td>
<td>(105–304)</td>
<td>(0–9.1)</td>
<td>(2.1–2.8)</td>
<td>(2.1)</td>
<td>(F)</td>
</tr>
<tr>
<td></td>
<td>(3.5–9.6)</td>
<td>(1.43–1.88)</td>
<td>(142–248)</td>
<td>(0–6.4)</td>
<td>(2.3–2.7)</td>
<td>(2.3)</td>
<td>(F)</td>
</tr>
</tbody>
</table>

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temperature is indicated in Table 2, line 2, where $kT \sim 4$ keV is assumed. In this temperature range the flux attributable to the bremsstrahlung component is compatible with a cluster of the richness class and distance of A2440. For example, adjusting either bremsstrahlung component in the GINGA fits of Table 2 for the 0.5° offset from A2440, yields a flux $F_{0.5,3.5} \sim 1 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. The corresponding luminosity, $L_{0.5,3.5} \sim 2 \times 10^{44}$ erg s$^{-1}$, is well matched to a redshift-corrected temperature in the range 3.1–4.2 keV (Mushtozky 1984a; Edge 1989). With either spectral fit of Table 2, the cluster emission dominates the GINGA spectrum below ~7 channel 7 and contributes a soft flux of $F_{0.3,1.0} \sim 7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. Although this flux, when corrected for the GINGA offset angle is $\sim 1.8 \times$ larger than the IPC flux reported by Abramopoulos & Ku (1984), it lies close to their upper limit. Furthermore, the residual soft flux attributable to the strongly cut-off power law of 3C445, $F_{0.2,3.3} \sim 4 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, is consistent with the IPC detection reported in the Introduction.

A direct check on the essential correctness of this spectral de-convolution was obtained by examining the GINGA X-ray light curve, particularly over the interval where the attitude was altered (see Fig. 1). These time-series data showed a ~90 per cent flux increase in the low-energy channels 3–6 (~1–3 keV), but a simultaneous decrease of ~15 per cent in the higher energy channels 24–25 (~4–12 keV). These variations are consistent with >85 per cent of the low-energy flux coming from A2440 and the major part of the higher energy flux from 3C445. The deconvolution of the GINGA spectrum (Fig. 2) into the two components described in Table 2, line 1, show, respectively, ~90 per cent of the measured 1–3 keV flux being due to the 3 keV bremsstrahlung component and ~80 per cent of the flux at 4–12 keV to the power law.

3 DISCUSSION

Although the presence of two similarly bright X-ray sources within the GINGA field of view complicated our observation, the substantially different nature of the spectra of 3C445 and A2440 (aided by their 0.5° separation and the fortuitous attitude manoeuvre) has allowed the individual spectra to be resolved. Our main new result is that 3C445 has a canonical power-law slope, but with a large intrinsic absorbing column. (This is entirely compatible with the faint IPC detection of 3C445 and with the absence of any LE flux from 3C445 in our earlier EXOSAT observation; Turner & Pounds 1989.) As a bonus, we have obtained a revised X-ray flux and luminosity for the distant cluster A2440.

Our finding, that 3C445 has a power-law spectral slope close to the canonical value of $\Gamma \sim 1.7$ (Mushtozky 1984b; Turner & Pounds 1989), offers no direct support to the conclusion, based essentially on IPC observations, that radio-loud emission-line galaxies have unusually flat spectra (Wilkes & Elvis 1987). We note, however, from a study of a large sample of fainter IPC detections, Canzianes & White (1989) found that the flattest spectra ($\Gamma \sim 1.4$) occur for the radio-loud objects with flat radio spectra (defined as having an energy index $\alpha$ less than 0.5 at a few GHz). If this is essentially equivalent to a sub-class of core-dominated radio galaxies, then we may not expect 3C445 to comply, since its GHz spectra is dominated by the emission of the giant double radio galaxy (Kronberg, Wiebelink & Graham 1986; Bridle 1984) and $\alpha_{1.5} \sim 0.7$ (Wall & Peacock 1985). In the context of the ‘unified scheme’ discussed by Browne & Murphy (1987), we would then conclude that any Doppler-boosted core component of the X-ray emission is weak and we are seeing the normal X-ray spectrum of a Seyfert-type galaxy. Presumably this is also the case for the second bright BLRG, 3C120, for which EXOSAT found a canonical power-law slope, $\Gamma \sim 1.79$ (Turner & Pounds 1989); the evidence for super-luminal radio features (Walker, Benson & Unwin 1987) makes this a tighter constraint in the case of 3C120. It remains a possibility that substantial absorption is, in fact, common in BLRG, a hypothesis supported by the EXOSAT spectrum of Cygnus A (Arnaud et al. 1987). If true, this could yield a deceptively flat power law in the IPC band.

The confirmation of a large intrinsic absorption in 3C445 is our most important result. In the most comprehensive such study to date, 18 of 35 emission-line AGN in the EXOSAT survey were found to have significant intrinsic absorption, with $N_{HI}$ in the range $10^{21} - 10^{23}$ H atoms cm$^{-2}$ (Turner & Pounds 1989). However, of these AGN, only the QSO MR2251 + 63 and 3C445 were in a higher luminosity group, with $L_{X10} > 10^{44}$ erg s$^{-1}$. The EXOSAT column for MR2251 + 63 was $~10^{22}$ cm$^{-2}$, making our new GINGA result, $N_{HI} \sim 1.7 \times 10^{23}$ cm$^{-2}$ for 3C445, particularly extreme. The absorption-corrected (at source) luminosity from our GINGA observation of 3C445 is $L_{X10} > 3.3 \times 10^{44}$ erg s$^{-1}$. (Here, as elsewhere in this paper, we assume $H_0 = 50$.)

BLRG’s typically have steeper (redder) optical continua and steeper Balmer decrements than normal Seyfert’s 1’s. Rudy & Tokunaga (1982) report the detection of an unusually strong $P - \alpha$ line in 3C445 and deduce a reddening $E(B-V) ~ 1$ mag. For a normal (ISM) dust-to-gas ratios this corresponds to a column density, $N_{HI} \sim 7 \times 10^{22}$ cm$^{-2}$, which is significantly greater than the galactic column of $5 \times 10^{20}$ cm$^{-2}$ in the line-of-sight to 3C445. However, again as pointed out by Turner & Pounds (1989), it is common to find X-ray columns substantially larger than those indicated by reddening and BLR line ratios. For about half of the high-column AGN in the EXOSAT sample, the X-ray values were considerably larger than the optical values, implying a location of most of the (cold) absorbing gas closer to the central nucleus than the BLR clouds. The absence of a large Fe K-absorption edge (beyond that corresponding to the measured $N_{HI}$ value for solar abundance material) suggests that the absorbing material is not strongly photo-ionized. Without more detailed spectral data or evidence of column variability, this question cannot be well defined. However, it appears that 3C445 joins the ever-larger group of emission-line galaxies containing high-density matter close to the nucleus. Whether this is seen primarily as a soft excess, or in absorption – as in the present case of 3C445, probably depends on our angle of view. One further constraint to this central geometry is provided by the iron line detection. The measured line flux, at a rest energy close to 6.4 keV for 3C445, corresponds to an equivalent width of ~150 eV. We note that the differential redshift of A2440 will result in the 6.7 keV thermal emission line of the cluster being indistinguishable from a fluorescent 6.4 keV line in our analysis and have, therefore, allowed for a line of 500 eV equivalent.
width from A2440 (Edge 1989). This leaves a residual 6.4 keV line flux of $1.8 \times 10^{-2}$ ph cm$^{-2}$ s$^{-1}$ from 3C445, corresponding to an equivalent width of $\sim 100$ eV. Such a line is consistent with a near-spherical covering of the central source by a shell of the measured column of $1.7 \times 10^{23}$ cm$^{-2}$ and normal iron abundance. If any strongly beamed X-ray component is present in 3C445 it is neither directed towards us nor apparently towards a substantial fraction of the surrounding cold matter.

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REFERENCES