Coded mask X-ray images of the Virgo cluster – I. Hard X-rays from the Seyfert galaxy NGC 4388

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SUMMARY
Spectrally resolved hard X-ray (2–32 keV) images of the Virgo cluster of galaxies were obtained with the University of Birmingham coded mask X-ray telescope on the Spacelab–2 mission. The images demonstrate that much of the hard X-ray emission previously reported from the cluster originates in NGC 4388 which has been described on the basis of optical observations as a type 2 Seyfert galaxy. Flux was detected from NGC 4388 in the energy range $\sim 2$–$18 \text{keV}$ and has a spectrum consistent with that expected from a type 1 Seyfert, but with a very high hydrogen column density. Its luminosity in the 2–10 keV energy-band is $\sim 10^{45} \text{erg s}^{-1}$ (assuming a distance of 20 Mpc). When combined with recent optical detections of faint broad wings to the $\text{H}_\alpha$ line, our results suggest that NGC 4388 should be reclassified as a narrow emission-line galaxy (NELG), a class of objects widely held to contain heavily obscured, low-luminosity type 1 Seyfert nuclei.

1 INTRODUCTION
The Virgo cluster was the first extragalactic X-ray source to be identified (Byram, Chubb & Friedman 1966; Bradt et al. 1967). At energies of a few keV the emission is mostly from an extended region $\sim 3^\circ$ in diameter, centred on the giant elliptical galaxy M87 (Fabricant & Gorenstein 1983) rather than the dynamical centre of the cluster (which lies $1^\circ$ to the north-west of M87). In addition there is emission from the nucleus of M87 itself (Lea, Mushotzky & Holt 1982) and from its jet (Schreier, Gorenstein & Feigelson 1982) and some evidence for a much more extended component (Forman et al. 1978; Lawrence 1978; Nulsen et al. 1979; Ulmer et al. 1980). Many individual galaxies within the Virgo cluster were detected by the Einstein Observatory but had luminosities $\sim 10^{-2}$ of that of M87 (Forman et al. 1979; Forman, Jones & DeFazio 1985).

Spectral observations using non-imaging instruments with comparatively wide fields of view have on several occasions indicated the presence of a hard tail to the cluster spectrum (Laros, Matheson & Pelling 1973, and references therein; Serlemitsos et al. 1977; Davison 1978; Lea et al. 1981). The nature and location of the hard component has, however, remained very uncertain.

Davison (1978) reported Ariel V observations which showed that, whereas at low energies (1–5 keV) the centroid of emission is consistent with the position of M87, it moves progressively west–north-west with increasing energy, being $\sim 1^\circ$ away from M87 in the 8–14 keV energy-band. Lawrence (1978) suggested from an analysis of Ariel V SSI data that there was a source of emission more extended than that surrounding M87, somewhat offset from it and having a harder spectrum. Based on observations which indicated that the hard power-law component seen in the total cluster emission was variable, and on the detection of a power-law component in the Einstein SSS observations of M87, it has been suggested that the hard tail comes from the nucleus of M87 (Lea et al. 1981; Lea, Mushotzky & Holt 1982; Fabricant & Gorenstein 1983). Observations with the comparatively narrow field of view (0.75' x 0.75') EXOSAT ME detector (Smith & Stewart 1985) did not resolve the question but detected some excess flux from a position offset in the same general direction as implied by other measurements.

We report here hard X-ray imaging observations of the Virgo cluster and show that the dominant source of hard X-rays is NGC 4388, a Seyfert galaxy whose flux in the Einstein 0.5–3.0 keV band is only $\sim 0.5$ per cent of that of M87 and its immediate surroundings.

2 OBSERVATIONS AND DATA ANALYSIS
The observations reported here were made with the University of Birmingham X-ray telescope (SL2 XRT) which was flown as part of the Spacelab-2 mission on the Space Shuttle Challenger between 1985 July 29 and August 6. The SL2 XRT, which is described by Skinner et al. (1987a), comprises two co-aligned coded mask telescopes imaging the same $6^\circ \times 6^\circ$ region of sky. Both telescopes have an effective energy range of $\sim 2$–$32 \text{keV}$. The first of these instruments,
termed the coarse telescope, is optimized for the study of extended emission and has an angular resolution of 12 arcmin FWHM. The second, the fine telescope, is optimized for studying point sources having a resolution of 3 arcmin FWHM. For both telescopes the attitude can be determined to \( \pm 1 \) arcmin.

The targets of the SL2 XRT observations included clusters of galaxies, the Galactic Centre and the Vela supernova remnant (Skinner et al. 1987b, 1988). One of the prime objectives was to obtain hard X-ray images of clusters of galaxies to study the temperature distribution of the intracluster gas. Results on the emission from the Virgo cluster and from M87 will be reported elsewhere; we consider here only the source of the emission at high energies.

Because the angular size of the Virgo cluster \(( \sim 12^\circ \) is larger than the field of view of the SL2 XRT the observations were centred on four positions surrounding M87. In this way we were able to measure most of the central \( 8^\circ \times 8^\circ \) region of Virgo, although the sensitivity was lower at the edges of the field than at the centre. Excluding periods of high background, the total exposure time was \( \approx 10^4 \) s. This was comprised of many separate pointings \(( = 50 \) of widely varying duration \(( 10^{-2} \times 10^2 \text{ s} \) covering the period 1985 July 31 to August 4.

The analysis of data from the SL2 XRT is complex and involves division of the data into time intervals within which the pointing direction varies by no more than a prescribed amount. Corrections for small pointing drifts within these intervals are then applied to the recorded photon positions, followed by inversion using Hadamard transform techniques, correction for the collimator response and the formation of a final image from a weighted combination of data from the separate pointing directions with appropriate coordinate transformations. At each stage, data from different energy channels are handled separately. Weights and errors are calculated separately for each pixel. Some of the processes involved are described by Skinner et al. (1987c).

### 3 RESULTS

Fig. 1 shows a 2−20 keV SL2 XRT coarse telescope image of a \( 8^\circ \times 8^\circ \) region of the Virgo cluster centred on M87. In addition to the bright extended source associated with M87, a point-like source is seen \( \sim 1^\circ \) to the west. The position of this source from the fine telescope is \( \alpha = 12^h23^m15.4^s, \delta = +12^\circ55'39.7" \) (1950.0). We identify this with the galaxy NGC 4388, the optical nucleus of which lies within the 1.5 arcmin radius SL2 XRT error circle at \( \alpha = 12^h23^m14.56^s, \delta = +12^\circ56'17.35" \) (Argyle 1987, private communication, quoted by Stone, Wilson & Ward 1988).

NGC 4388 was identified as a Seyfert galaxy by Phillips & Malin (1982) and classified as a relatively low-luminosity type 2. Despite an unusually high radial velocity, it is thought to be a Virgo cluster member (Helou, Salpeter & Krumm 1979; Phillips & Malin 1982). It is seen almost edge on (see photographs by Phillips & Malin 1982; Hummel, van Gorkom & Kotanyi 1983 estimate an inclination of 75\(^\circ\)). NGC 4388 was detected in the Einstein IPC observations of Forman et al. (1979), but only as the fourth brightest galaxy in the cluster, with a 0.5−3.0 keV luminosity of \( 1.7 \times 10^{40} \text{ erg s}^{-1} \).

![Figure 1](https://academic.oup.com/mnras/article-abstract/242/2/262/999761)

**Figure 1.** A 2.0−19.6 keV SL2 XRT image of an \( 8^\circ \times 8^\circ \) region of the Virgo cluster centred on the optical position of M87. North is to the top, east to the left. Axes are marked with offsets from the nucleus of M87 in degrees. The image has been smoothed with a 12' FWHM Gaussian. Contours indicate intensity relative to the local noise level and are logarithmically spaced with a ratio of 1.65 between adjacent contours. For a point source they represent a significance of detection of approximately 3.7\( \sigma, 6.1 \sigma, \ldots \). The corresponding fluxes vary over the field of view due to the effect of the collimation and the different pointing directions.

The results of fitting an absorbed power law to the SL2 XRT spectrum of NGC 4388 are shown in Fig. 2. The best-fitting spectrum requires a photon index, \( \alpha = 1.5^{+0.9}_{-0.7} \) and an absorbing column of \( (2.1^{+0.2}_{-0.9}) \times 10^{23} \text{ cm}^{-2} \).\( \chi^2/\nu = 26.2/27 \). Thus the data are clearly consistent with the canonical 2−10 keV photon index for Seyfert 1 galaxies of \( \alpha = 1.65 \pm 0.10 \) ( Mushotzky et al. 1980). Fixing \( \alpha \) at 1.65 implies a column density of \( N_H = 2.7 \times 10^{23} \text{ cm}^{-2} \). For comparison, the galactic column density in this direction is \( 2 \times 10^{20} \text{ cm}^{-2} \) (Burstein & Heiles 1982). The observed 2−10 keV flux is \( 2.1 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \), corresponding at a distance of 20 Mpc to a luminosity of \( 1.0 \times 10^{42} \text{ erg s}^{-1} \). Allowing for the absorption implied by an \( \alpha = 1.65 \) spectrum, the corresponding intrinsic luminosity must be \( \sim 3.5 \times 10^{42} \text{ erg s}^{-1} \).

### 4 DISCUSSION

Fig. 3 shows SL2 XRT images of the Virgo cluster in the energy ranges 2.0−4.9, 4.9−8.6, 8.6−13.2 and 13.2−19.6 keV. Superposed on Fig. 3(a)−(c) (shaded regions) are the 1.4−4.8, 4.8−8.1 and 8.1−13.6 keV centroid locations found by Davison (1978) from Ariel V proportional counter spectrometer observations. Given the 3.5\( \sigma \) resolution of this instrument it is clear that the relative change in the fluxes...
Figure 2. (a) The 2–18 keV spectrum of NGC 4388 as determined with the SL2 XRT. The solid line shows a best-fit absorbed power-law spectrum, which has a photon index $\alpha = 1.5 \ (dN/dE \propto E^{-\alpha})$ and an absorbing column $N_H = 2.1 \times 10^{23}$ cm$^{-2}$. (b) Contours of constant $\chi^2$ for power-law fits to the SL2 XRT NGC 4388 data. Contours are $\chi^2_{\text{min}} + 2.3$ and $\chi^2_{\text{min}} + 4.6$ corresponding to 68 and 90 per cent confidence levels for two parameters of interest.

Figure 3. (a)–(d) 2.0–4.9, 4.9–8.6, 8.6–13.2 and 13.2–19.6 keV SL2 XRT images of a 4'×4' region of sky centred on the position of M87. Contours as in Fig. 1, except that levels correspond to a significance of detection for a point source of 2.4$\sigma$, 3.9$\sigma$, etc. The shaded regions in 3(a)–(c) are the 1.4–4.8, 4.8–8.1 and 8.1–13.6 keV 90 per cent confidence centroid locations for the Virgo cluster determined by Davison (1978).
from the M87 region and NGC 4388 could account for the energy dependence of the centroid position found by Davison (1978).

Although NGC 4388 is a powerful source of hard X-rays, the observed flux is less than some reports of hard X-ray emission from the region. Lea et al. (1981) report a variable hard tail, consistent at its lowest level with the NGC 4388 flux reported here but rising to four times this value. Earlier less detailed measurements (Laros et al. 1973, and references therein) imply even higher levels. An extended source of high-energy emission much larger in size than even the 12′ resolution element of the coarse SL2 XRT telescope and containing several times the flux from NGC 4388 could have been missed, but such a component could not vary on a time-scale of years. Since all the detections of a high-energy tail were made with non-imaging instruments having fields of view sufficiently wide to include emission from most of the cluster, including NGC 4388, the simplest explanation for the variations in the reported high-energy flux is that NGC 4388 is variable, as might be expected for a Seyfert galaxy.

Lea et al. (1982) report observations of the nucleus of M87 made with the narrow-aperture (6 arcmin diameter) Einstein SSS instrument that also apparently require the presence of a hard power-law component. Our higher-energy SL2 XRT observations of M87 do not show any evidence for such a component. Fitting a thermal bremsstrahlung plus power-law model, and fixing the column densities and photon index at the values used by Lea et al. (1982), we obtain a 90 per cent confidence upper limit for the power-law component which corresponds to a $2 \times 10^{-1}$ keV luminosity of $4 \times 10^{40}$ erg s$^{-1}$, five times lower than implied by their results. This would suggest that any non-thermal emission from M87 is also variable, although it should be noted that the spectral modelling of Lea et al. is confined to data in the 0.5-4.5 keV band and so an alternative explanation for the differences between the SL2 XRT and SSS results is that any hard power-law component does not extend to high energies.

The Einstein IPC spectrum for NGC 4388 is best fitted by a relatively soft spectrum ($\alpha = 3$) with a modest column density of only $N_H = 1.6 \times 10^{22}$ cm$^{-2}$ (Seward, private communication). The SL2 XRT flux is 200 times greater than would have been expected based on this spectrum so, unless variability is invoked, the flux seen with Einstein must represent a separate, soft component. One possibility is that the absorbing material is clumpy (cf. NGC 4151, see Holt et al. 1980 and Perola et al. 1986) although the low-energy emission could be from a physically distinct region, presumably farther from the nucleus.

The classification of NGC 4388 as a type 2 Seyfert galaxy by Phillips & Malin (1982) was based on an optical emission line spectrum that showed the strong narrow emission lines of high excitation that are characteristic of Seyfert galaxies but lacked the broad components to the Balmer lines that are present in type 1 Seyferts. Their conclusion was apparently supported by the low soft X-ray luminosity $L_{\text{X}}(0.5-3.5 \text{ keV}) = 2 \times 10^{40}$ erg s$^{-1}$ reported for this source by Forman et al. (1979), which is consistent with that observed in other Seyfert 2 galaxies (Kriss, Canzianes & Ricker 1980). However, unlike Seyfert 1 galaxies and narrow emission line galaxies (NELGs), no Seyfert 2 has previously been detected as a hard X-ray source.

NELGs have been the subject of considerable interest because they seem to possess characteristics of both type 1 and type 2 Seyferts. As their name suggests, their optical spectra show strong narrow emission lines that are similar to those of type 2 Seyferts (Véron et al. 1980). In contrast to this, however, their X-ray spectra are typical of low-luminosity type 1 Seyferts (Maccacaro, Perola & Elvis 1982; Mushotzky 1982). Many NELGs have also been shown to have faint broad wings on their Hα line and from the strength and shape of their optical spectra appear to be dusty (Véron et al. 1980; Maccacaro, Perola & Elvis 1982). NGC 4388 fits very well into this picture since Filippenko & Sargent (1985) have discovered a very faint broad (7600 km s$^{-1}$) component to the Hα emission (see also Shields & Filippenko 1988) and from optical spectroscopy Phillips & Malin (1982) find $A_V = 1.0-1.5$, implying considerable intrinsic absorption. Lawrence & Elvis (1982) have also noted that NELGs are selectively edge-on, as is the case with NGC 4388. Based on the combination of broad Hα wings and the hard X-ray emission we propose that NGC 4388 should be re-classified as a NELG.

5 CONCLUSIONS

The identification of NGC 4388 as a bright source of hard X-rays suggests the explanation of the longstanding puzzle concerning the Virgo cluster high-energy X-ray emission. At energies above ~ 8 keV NGC 4388 is the brightest source in the Virgo cluster. Thus the shift of the emission centroid westwards from M87 with increasing energy reported by Davison (1978) is explained, as may also be the tendency for estimates of the size of the cluster emission to increase with the effective energy of the instrument concerned (Lawrence 1978). When combined with recent optical studies that provide strong evidence NGC 4388 contains a heavily obscured type 1 Seyfert nucleus, our X-ray spectrum suggests that this source should be re-classified as a narrow emission-line galaxy.

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REFERENCES


