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The interaction of the radio halo of M87 with the cooling intracluster medium of the Virgo cluster

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ABSTRACT

ROSAT X-ray images and spectra of the inner parts of the Virgo cluster around M87 are presented and compared with a new deep radio map. Apart from the emission peaked on M87, a roughly linear structure, noted previously by Feigelson et al. using *Einstein Observatory* data and correlated with the outer radio halo, is seen. We have carried out the first spectral analysis of this structure.and find that it is clearly due to thermal emission from metal-rich gas at a temperature significantly lower than that of the surrounding intracluster gas. We propose several models to account for the enhanced X-ray emissivity in the radio halo.

Key words: galaxies: active – galaxies: clusters: individual: Virgo – cooling flows – galaxies: individual: M87 – radio continuum: galaxies – X-rays: galaxies.

1 INTRODUCTION

The X-ray emission from the Virgo cluster is strongly peaked and centred on the giant elliptical galaxy M87 (Schreier, Gorenstein & Feigelson 1982). The cooling time of the gas is very short within the inner few tens of kpc of the galaxy (Stewart et al. 1984) and this, with spectral evidence for a range of gas temperatures dropping below the cluster temperature of 2 keV (Canizares et al. 1979, 1982; Lea, Mushotzky & Holt 1982; Böhringer et al. 1994; Nulsen & Böhringer 1995), provides good evidence for a cooling flow taking place.

Although most of the emission is symmetrical about M87, Feigelson et al. (1987) found using *Einstein Observatory* data that a few per cent of the X-ray luminosity lies in a roughly linear structure which coincides approximately with the outer radio halo of the galaxy. These authors suggested various origins for the X-ray structure, including inverse Compton and thermal emission, but with the data available at that time were unable to draw any decisive conclusion.

In this paper we present *ROSAT* X-ray data for M87 of higher sensitivity than those from the *Einstein Observatory*. Our spectroscopic results show that the excess luminosity is due to thermal emission from gas which is cooler than the surrounding gas. We also present a new deep VLA radio map of M87 which resolves the outer radio halo much better than previous images.

2 IMAGES OF M87

2.1 The X-ray image

In Fig. 1(a) we show the X-ray image of M87 from the Position Sensitive Proportional Counter (PSPC: FWHM ~ 25 arcsec) on *ROSAT*, obtained with an exposure time of 30452 s spread over three almost equal observing intervals from 1992 June to December. Most of the emission originates from the approximately spherically symmetric plasma halo around M87. The excess emission from the regions of the outer radio lobes already noted by Feigelson et al. (1987) is clearly seen in the figure as an arc-like structure extending to the east and south-west from the centre. The brightest regions of the arc are about a factor of 1.5 to 2 brighter than the surrounding area. In the inner 0.5-arcmin radius, the major part of the emission is due to the nucleus and jet which are not individually resolved here but are seen in a *ROSAT* HRI image as two point-like sources. We have compared the HRI image with the PSPC image and found that the former does not show any new details in the excess emission regions connected to the radio lobes – except for resolving the nucleus and jet – and therefore the image is not shown in this Letter. To get a better picture of the structure of the excess emission in the radio lobe regions, a well-fitting model for the spherically symmetric gas halo away from the lobes was subtracted from the image of Fig. 1(a). The residuals are shown in Fig. 1(b). The emission regions are very localized, extend-

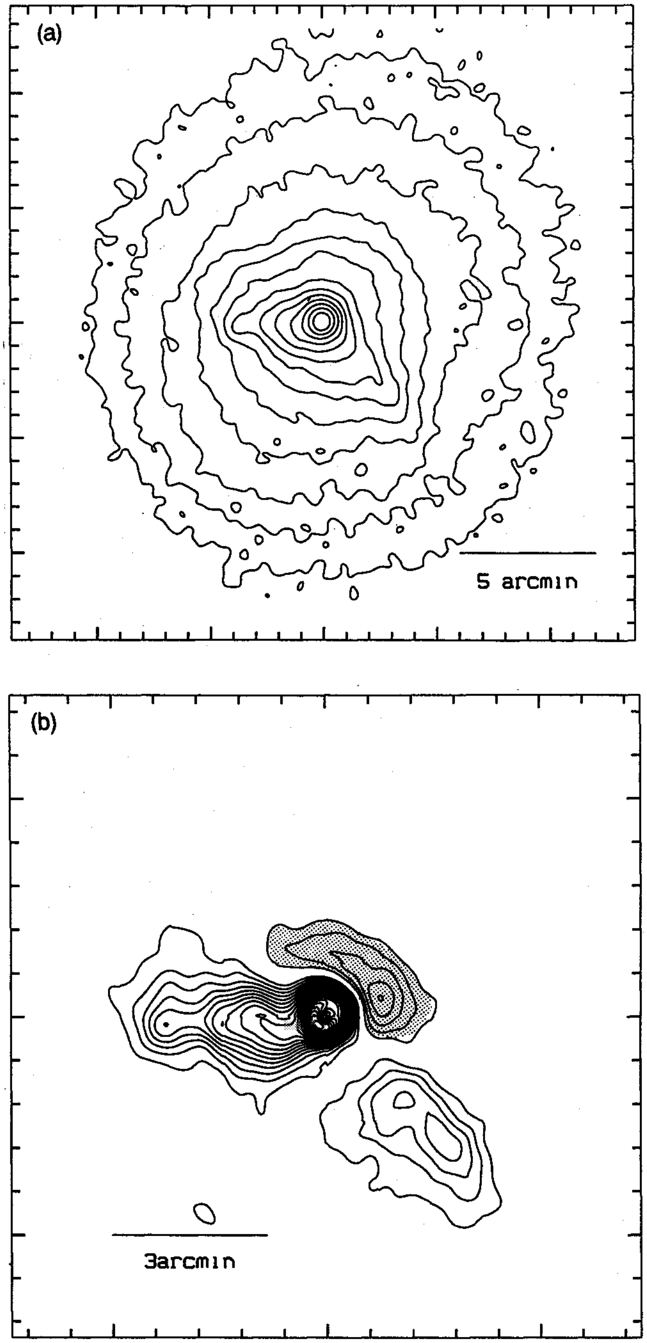

Figure 1. (a) *ROSAT* PSPC image of the X-ray halo of M87. The image was produced from the photons in the 0.5–2 keV energy band, and the contours are logarithmically spaced, increasing by a factor of 1.4. North is up. (b) Residuals of the X-ray image of the halo region of M87 after subtraction of a spherically symmetric model X-ray halo from the image shown in Fig. 1. The scale is smaller by a factor of 2 than that for Fig. 1. The contours are linearly spaced and the shaded region is negative.

ing about 4 arcmin (~ 20 kpc for a Virgo distance of 20 Mpc) to the east and about 5 arcmin to the south-west. The eastern extension has two X-ray maxima and the arc to the south-west has a sharp northern edge.

2.2 The radio image

In Fig. 2 we show the new radio map of M87. It was observed with the C configuration of the VLA in 1992 March for a total of 7 h. The observation was carried out as a spectral line experiment to search for narrow absorption features in the OH 1667-MHz transition at 12-arcsec spatial resolution. Seven overlapping bands of 3.125-MHz width were observed to obtain coverage of radial velocities between about 250 and 1250 km s^{-1}. No absorption was detected with the image noise of 5.6 mJy $beam^{-1}$ per 2.2 km s^{-1} channel. 3σ upper limits to the OH optical depth varied from about $\tau_{OH} < 0.001$ against the bright 15-arcsec-scale lobes through $\tau_{OH} < 0.003$ against the 2-arcmin-scale plateau, to $\tau_{OH} < 0.4$ over the 6-arcmin east–west oriented 'ear and tail' structure. Broad-band data from the seven 3.125-MHz bands were individually self-calibrated and deconvolved before averaging to yield the image in Fig. 2. The dynamic range (defined here as the ratio of the peak emission brightness to the peak artefact brightness) is still only about 1000:1, although the remaining image artefacts are concentrated in a negative bowl surrounding the source, consistent with the 10 per cent source flux missing in this image relative to total power measurements. Accurate radio imaging of such a complex and extended source remains a challenge, although the filamentary structures on angular scales of 5 arcmin or less have been reliably represented.

The X-ray arc to the east coincides with a radio feature in that direction which ends in a structure shaped like an 'ear'. The radio 'tail' to the other side bends down to the south-west so that the X-ray arc appears to lie along its core. At larger radii the radio emission appears to move away as plumes with a net clockwise twist. The brighter structures suggest that the jet of M87, which now points to the north-west, may precess around an axis which lies east–west in projection.

3 THE X-RAY SPECTRA

X-ray spectra have been extracted from the PSPC data in radially limited sectors corresponding to the eastern arc, the south-western arc and the regions in between. We have analysed the spectra in the arc region using three different methods of background subtraction: (i) by subtracting spectra from regions outside the radio lobes at the same radius; (ii) by subtracting the contribution from the outer shells of the gas halo by means of a deprojection technique (see Nulsen & Böhringer 1995); (iii) by subtracting a global background. We obtained similar results in all cases.

Fig. 3 shows the spectrum for the outer part of the eastern arc. A pure power law gives a very poor fit to the background-subtracted spectra. Using power law plus thermal models, either the power law must be very steep to produce a good fit (e.g. an energy index of -5) or, when the energy index is fixed at a more acceptable value, the power law causes no significant improvement to the fit. The spectral peak at about 1 keV is principally due to iron L-line emission, strongly supporting a thermal origin for the X-rays.

The bright arc is measurably cooler than the surrounding areas (~ 1.3 keV versus ~ 1.5–2 keV). Given the uncertain geometry of the cool gas, its emission measure is consistent with local pressure equilibrium, i.e. the excess luminosity

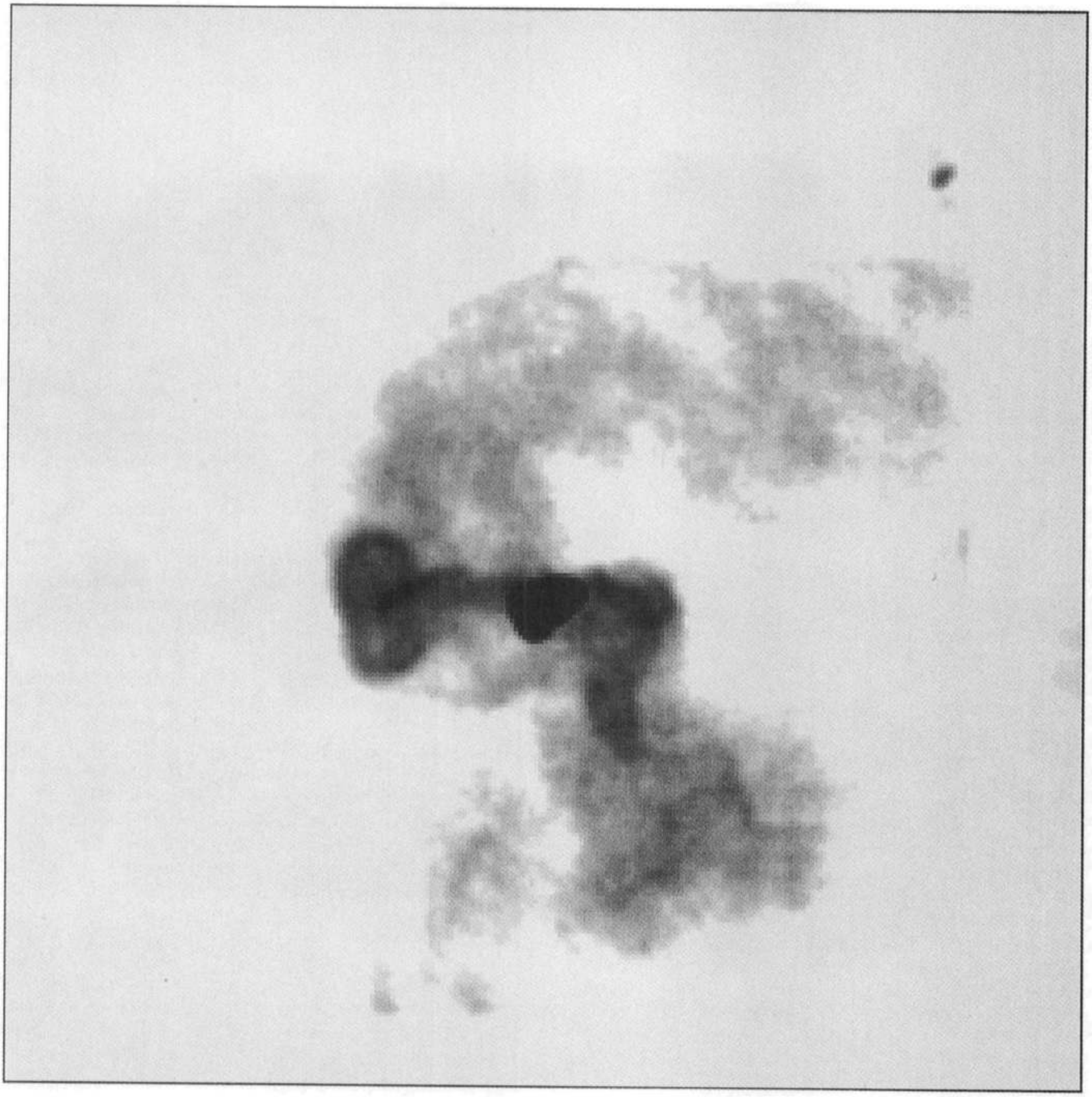

Figure 2. VLA radio image of M87 at 1667 MHz. The image is 21.33 × 21.33 arcmin square and centred at $12^{\mathrm{h}}28^{\mathrm{m}}17\overset{\mathrm{s}}{.}6$, $12^\circ 40' 60''$ (1950).

may be due to the gas in the arcs being cooler and denser than, but having the same pressure as, other gas at the same distance from the centre of M87.

4 INTERPRETATION

The thermal nature of the excess X-ray emission from the arcs shows that it is not due to inverse Compton scattering, but that the gas is simply denser there. We assume that, since the excess X-ray emission coincides with the radio emission, there is some causal connection. Higher gas density could promote brighter radio emission from a jet, but the slight misalignment between the radio jet and the X-ray arcs argues against such a mechanism. It seems more likely that the radio jets have promoted the density increase in the gas.

The most obvious processes, compression, shocks or cosmic ray heating, all work in the wrong sense, tending to raise the gas temperature. A shock may promote cooling, but only where the cooling time of the shocked gas is short compared with the time of passage of the shock, which is not the case here (the cooling time of the unshocked gas is substantially longer than the sound crossing time to the centre of M87). Other compressive disturbances, such as a magnetoacoustic wave, may promote thermal instability

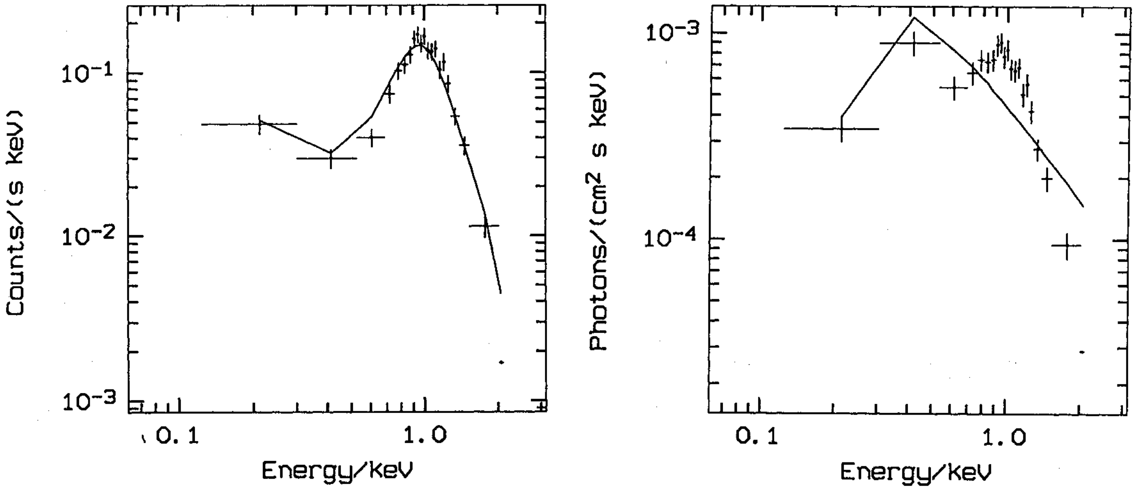

Figure 3. *ROSAT* PSPC spectra of the outer eastern arc. The left-hand panel shows the observed spectrum with the best-fitting thermal model ($kT = 1.3$ keV; metallicity $= 0.45$ solar). The right-hand panel shows the same spectrum, divided by the energy-dependent, spectral sensitivity function, and the best-fitting power-law model (of energy index -1.65), attenuated at low energies by the expected absorption in our Galaxy. The power-law spectrum clearly misses the peak produced by a blend of emission lines around 1 keV.

locally (Nulsen 1986). Their effect is weak (of second order in the pressure disturbance), however, and the time-scale for the growth of thermal instability is the cooling time of the ambient gas. Since this is equal to the inflow time of the gas (e.g. Fabian 1994), we should expect to see the effects of such a disturbance well inside the place where it first occurred. This would also require the radio source to have existed for a time approaching the cooling time of the gas where the disturbance first occurred. We note that, in the case of NGC 1275, holes are seen in the X-ray emission coincident with the radio lobes, not an excess of emission (Böhringer et al. 1993). Such exclusion of the gas seems more probable than an increase in its density.

Another possibility arises from the observed properties of cooling flows, where X-ray spectra show the presence of excess absorption (White et al. 1991; Allen et al. 1993; Fabian et al. 1994). The absorption is presumed to be due to the cooled gas which lies in a mist of very small, very cold clouds. If a radio jet passes through such a highly multiphase medium it may, through turbulent stirring and ablation, cause the clouds to disrupt and to mix in with the hot phase. This will result in cooling of the hot phase and, on a sound crossing time as the pressure equilibrates, in an increase of density. To produce the observed effect by mixing, the cold gas has to have comprised about 30 per cent of the total density (greater if the passage of the radio jet causes significant heating). We note that the non-detection of OH absorption against the radio source rules out any large column density ($N_{\rm H} \sim 10^{20}$ cm^{-2}) of accumulated cold material in a state similar to that of giant molecular clouds in our Galaxy (Dickey, Crovisier & Kazes 1981).

A further alternative is that there may be effects arising from mixing of plasma from the radio source, i.e. magnetic field and cosmic rays, into the surrounding gas, thereby making it buoyant. Provided that gas motions are subsonic, local pressure equilibrium is maintained, requiring roughly $p_B + p_{\rm gas} = p_0$, where p_B is the pressure arising from the magnetic field (and cosmic rays), $p_{\rm gas}$ is the partial pressure of the gas mixed with the field and p_0 is the ambient gas pressure. Dense gas from inner regions [the gas density around M87 rises inward as $n_{\rm e} \approx 2 \times 10^{-2} (R/10\ {\rm kpc})^{-1}$ cm^{-3} (Nulsen & Böhringer 1995)] expands when mixed with the field, so that it convects outward until the mixture has the same mean density as the surrounding gas, i.e. $\langle \rho \rangle = \rho_0$, where ρ_0 is the ambient density (the condition for buoyant stability). On large scales this occurs at speeds comparable to the free-fall velocity, so that a large bubble of mixture in M87 could reach its equilibrium position at a radius of 10 kpc comfortably in $\sim 10^8$ yr. Once there, since the gas mixed with field has a lower pressure but the same mean density as the surrounding gas, it must have a lower mean temperature. Furthermore, the magnetic field is unlikely to be uniform (note the small-scale structure in the radio emission), so that the density of the magnetized gas will vary from place to place. The variance of the gas density, $\sigma_\rho^2 = \langle \rho^2 \rangle - \langle \rho \rangle^2$, is then positive. With $\langle \rho \rangle = \rho_0$, this gives

$$\langle \rho^2 \rangle = \rho_0^2 + \sigma_\rho^2 > \rho_0^2,$$

so that the magnetized gas at convective equilibrium will have higher volume emissivity that the ambient gas. When intracluster gas first mixes with the radio plasma, its density and hence its emissivity are reduced (any cosmic ray heating will reduce them further). Unless either there is a substantial local pressure imbalance or the mixture has convected a large part of the distance to its equilibrium position, we should not expect to see excess emission from this gas.

This mechanism would have some important implications for the nature of the radio halo around M87. First, it suggests that convection may be the main driver for the outer radio plumes, as in the radio lobe model of Gull & Northover (1973). The halo radio emission may arise in a different plasma from the excess X-ray emission, but the coincidence in position and extent would be surprising if the radio plasma propagated much faster than the 'bubbles' of plasma mixture. The overall structure of the radio source then depends on the motions (possibly turbulent), density and magnetic field structures of the large-scale intracluster medium, through which it convects. Secondly, the magnetic pressure, p_B, in the mixture must be comparable to the ambient gas pressure in order to produce significant excess brightness (temperature decrease). From above, we have $n_e \approx 0.02$ cm^{-3} and $kT \approx 1.5$ keV at 10 kpc, so that, equating the gas pressure to the magnetic pressure, the magnetic field strength needs to be about 50 μG. This is comparable to the magnetic field in powerful radio sources and much stronger than the equipartition field (~ 2–5 μG: Feigelson et al. 1987) for this source. Whether or not the radio emission arises in different plasma, the gas–field mixture must be a very long way from equipartition (perhaps not surprisingly). Thirdly, the radio source must have existed for long enough (~ 10^8 yr) for the 'bubbles' of mixture to convect to their equilibrium position. Finally, the gas–field mixture could account for at least part of the Faraday rotation of the halo emission found by Owen, Eilek & Keel (1990).

5 CONCLUSIONS

The excess X-ray emission correlated with the outer radio halo of M87 is thermal and due to cooler gas along the radio jets. These observations seem to imply that, in the radio halo of M87, the presence of relativistic plasma and the associated magnetic fields has led to enhanced cooling of the gas rather than to heating by energy dissipation. Enhanced cooling may be explained either by disruption of previously condensed material in the cooling flow or by a higher cooling rate due to inhomogeneities introduced into the gas distribution by plasma waves and instabilities. Alternatively, the excess emission may come from gas that has mixed with plasma from the radio source and then convected almost to its new equilibrium position. The last mechanism has a number of implications for the nature of the radio halo of M87.

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