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A *ROSAT* HRI study of the interaction of the X-ray-emitting gas and radio lobes of NGC 1275

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ABSTRACT

A high spatial resolution *ROSAT* image of NGC 1275 in the centre of the Perseus cluster of galaxies shows for the first time clear evidence for the interaction of the relativistic particles in the radio lobes with the X-ray-emitting intracluster plasma. The thermal plasma is displaced by the inner parts of the radio lobes, causing a significant decrease of the X-ray surface brightness in those regions. The equipartition pressure in the radio lobes is somewhat less than the pressure in the surrounding intracluster medium unless a high ratio of relativistic protons to electrons is assumed.

Key words: galaxies: active – galaxies: clusters: individual: Perseus – cooling flows – galaxies: individual: NGC 1275 – radio continuum: galaxies – X-rays: galaxies.

1 INTRODUCTION

The idealized picture of a cluster of galaxies with a cooling flow consists of a well-relaxed system of dark matter and galaxies in which the hot gas in the central region has had enough time to cool and to develop a gentle, pressure-driven inflow. The Perseus cluster was the first system for which the cooling flow properties were modelled in some detail (Fabian & Nulsen 1977; Fabian et al. 1981). A closer look at Perseus, however, shows that it is far from being a quiescent cluster. The central galaxy, NGC 1275, has an active nucleus and is the bright radio source 3C 84. With its spectral and radio properties, NGC 1275 is intermediate between a Seyfert galaxy and a BL Lac object (e.g. Seyfert 1943; Véron 1978). A radio jet emerges from the the nucleus of NGC 1275 and ends in radio lobes embedded in an extended radio halo which has been traced out to a diameter of 300 kpc (Pedlar et al. 1990; Jaffe 1992; Burns et al. 1992); where $H_0 = 50$ km s^{-1} Mpc^{-1} was used here as well as throughout the paper.

It has been estimated by Pedlar et al. (1990) that the radio halo is powered by an energy output in relativistic particles of at least 10^{43} erg s^{-1}. This corresponds to roughly 10 per cent of the energy radiated in X-rays by the thermal plasma in the cooling flow region. Since the existence and structure of the cooling flow have been deduced on the assumption that there is no balancing heat source for the thermal intracluster plasma, the presence of this significant source of power has caused some criticism of cooling flow models (e.g. Pedlar et al. 1988; Rosner & Tucker 1989). Moreover, the pressure of the relativistic particles and the magnetic field in the inner parts of the bipolar radio lobes is deduced to be $\sim 10^{-9} - 10^{-10}$ erg cm^{-3}, which is larger than the pressure of the thermal gas of $\sim 2 \times 10^{-10}$ erg cm^{-3} (Pedlar et al. 1990). It is therefore expected that the cooling flow is disturbed in the inner region of about 10 – 20 kpc extent, a small fraction of the total cooling region which extends out to about 200-kpc radius. Some evidence that the central region is very complex is also provided by observations of optical emission-line nebulosity over a region of 30-kpc radius around the nucleus of NGC 1275 (e.g. Minkowski 1957; Lynds 1970; Cowie et al. 1983; Unger et al. 1990). The emission-line complex has two distinct systems with different radial velocities, one extensive component at the velocity of NGC 1275 and a second component centred to the north-west with a relative recession velocity of about 3000 km s^{-1} with respect to NGC 1275. It has been attributed to a spiral galaxy falling into NGC 1275.

Nevertheless, there is strong evidence for the existence of a cooling flow in the cluster, apart from the highly peaked X-ray surface brightness, in terms of the decrease in the temperature profile towards the centre in the NGC 1275 halo region (Schwarz et al. 1992) and from the detection of soft X-ray emission lines in the intermediate temperature range from 10^6 to 10^7 K (Mushotzky et al. 1981; Canizares, Markert & Donahue 1988). It is therefore important to incorporate all these observational phenomena into a unified model of the halo region of NGC 1275. One reason for the lack of a better understanding of this region is the fact that no correlation of the structures observed in the different wavelength regions has been seen so far. In particular, no disturbance has been observed in the X-ray surface brightness distribution due to the radio lobes.

We have therefore studied NGC 1275 in X-rays at high spatial resolution using the High Resolution Imager (HRI) on *ROSAT*, and have discovered the signature of the interaction of the thermal cooling flow plasma with the radio lobes of the galaxy. The manner in which the radio halo and the cooling flow interact can now be seen in some detail for the first time. In the following sections we describe the high-resolution X-ray observation, compare the X-ray structure with the appearance of the NGC 1275 halo at radio and optical wavelengths, and then discuss the interaction of the radio halo with the thermal gas.

2 *ROSAT* OBSERVATION

NGC 1275 was observed with the *ROSAT* HRI on 1991 February 10 for 10.78 ks. The instrument covers the energy range from 0.1 to 2.4 keV. Detailed results of the whole X-ray image and from a complementary *ROSAT* PSPC observation are described by Voges et al. (in preparation) and Edge et al. (in preparation). Here we concentrate on the region covering the innermost 30 kpc about NGC 1275. Fig. 1 (opposite p. L26) shows the central part of the HRI image of the Perseus cluster within a diameter of $\sim$ 5 arcmin. The bright central peak in the X-ray surface brightness originates from the active nucleus of NGC 1275. This peak is flanked by two X-ray brightness minima to the north and south and a bright extended patch to the east. The brightness difference between the minima and the adjacent rim at about 1-arcmin radius is about a factor of 1.6 to 2, while the eastern excess is brighter by about a factor of 2 compared to the surroundings outside the minima. Another minimum in the X-ray surface brightness can be seen further out in the north-east. This feature was already seen in the *Einstein Observatory* HRI image of the Perseus cluster (Fabian et al. 1981).

The central peak in the X-ray surface brightness at the nucleus of NGC 1275 shows a slight elongation in the north–south direction on a scale of 2 arcsec at the same position angle as the radio jet (not visible with the smoothing scale of the image in Fig. 1; but see Voges et al., in preparation). This could be due to self-Comptonized synchrotron radiation from the relativistic jet itself.

3 COMPARISON WITH RADIO AND OPTICAL OBSERVATIONS

The clue for understanding the interaction of the relativistic particles in the radio lobes with the thermal intracluster medium comes from the comparison of the X-ray structure with the radio image of the NGC 1275 halo region by Pedlar et al., which is shown in superposition in Fig. 1. The radio image has been obtained by combining radio data from VLA observations with the A and B configuration at 90 cm (332 MHz) at a resolution of 4.9 to 5.5 arcsec. The outer radio lobes coincide with the minima in the X-ray surface brightness, suggesting that the pressure of the relativistic gas has displaced the thermal gas. There are also indications of a breakthrough of the radio lobes through a rim of higher X-ray surface brightness in the north-western and south-western corners of the radio lobes.

Inspection of the surface brightness distribution at a radius of $\sim$ 1 arcmin around NGC 1275 shows that the brightest regions are located just outside the radio lobes. Thus it seems that some gas from the inner regions was pushed outwards by the pressure of the radio lobes. This interpretation is not certain, however. The nucleus of NGC 1275 is displaced by about 25 arcsec from the centre of symmetry with respect to the X-ray structure of the inner part of the Perseus cluster (that is, with respect to the spherical symmetry at radii of 1.5 to 3 arcmin). If one now studies the X-ray surface brightness distribution in concentric circles around this cluster centre instead of in circles around the galactic nucleus, no excess brightness is found near the radio lobes. Thus, if the gravitational potential is also spherically symmetric with respect to the cluster centre at radii of $\sim$ 1 arcmin, the surface brightness distribution is consistent with gas in hydrostatic equilibrium. Only if the potential in this region still follows spherical symmetry around the galaxy is an additional dynamical pressure effect of the radio lobes causing a gas outflow implied. Since no detailed and independent information on the gravitational potential in this region is available, one cannot decide between the two interpretations.

The inner radio lobes in Fig. 1 follow the position angle of the jet-like features at PA $\sim$ 160°. At a radius of about 25 arcsec a strange bend occurs in the southern radio lobe, changing to PA $\sim$ 235°. This bend has been discussed as an unsolved puzzle by Pedlar et al. The explanation is obvious from Fig. 1. The bend occurs where the inner radio lobe collides with the dense blob of gas in the east. The knee of the bend is marked by a sharp gradient in the radio surface brightness, which is probably accompanied by strong magnetic fields.

No direct coincidences are detected on comparing the X-ray features with the optical emission-line system (e.g. Unger et al. 1990; Caulet et al. 1992; Nørgaard-Nielsen et al. 1993). The low-velocity system (at $\sim$ 5000 km s^{-1}) has a maximum to the east of the NGC 1275 nucleus, just north of the X-ray maximum. The high-velocity system ($\sim$ 8000 km s^{-1}) has an emission region to the north-west of the active nucleus and has also no direct correspondence with the X-ray structure. The latter emission-line system is probably associated with an infalling spiral. It is located approximately between the nucleus and the X-ray minimum to the north-west. It is too far away from this surface brightness minimum to be directly responsible for it.

It is noteworthy that the emission-line system is mainly oriented in the east-west direction while the radio jet emerges perpendicular to this axis. The orientation could be explained by a process in which the pressure of the relativistic plasma in the radio jet has squeezed the warm emission-line gas into a disc perpendicular to the radio lobes, similar to the effect seen in the X-ray-emitting gas.

4 DISCUSSION AND CONCLUSION

If the radio lobes were indeed able to push the thermal gas out of those regions where the surface brightness minima are now observed, the pressure in the lobes has to be comparable to the thermal pressure of the gas. Pedlar et al. (1990) have calculated the pressure for the radio halo designated *a* in their paper, which is just slightly larger than the lobes bounded by the cavities in the X-ray-emitting gas. Correcting for the different Hubble constant of H_0 = 75 km s^{-1} Mpc^{-1} used

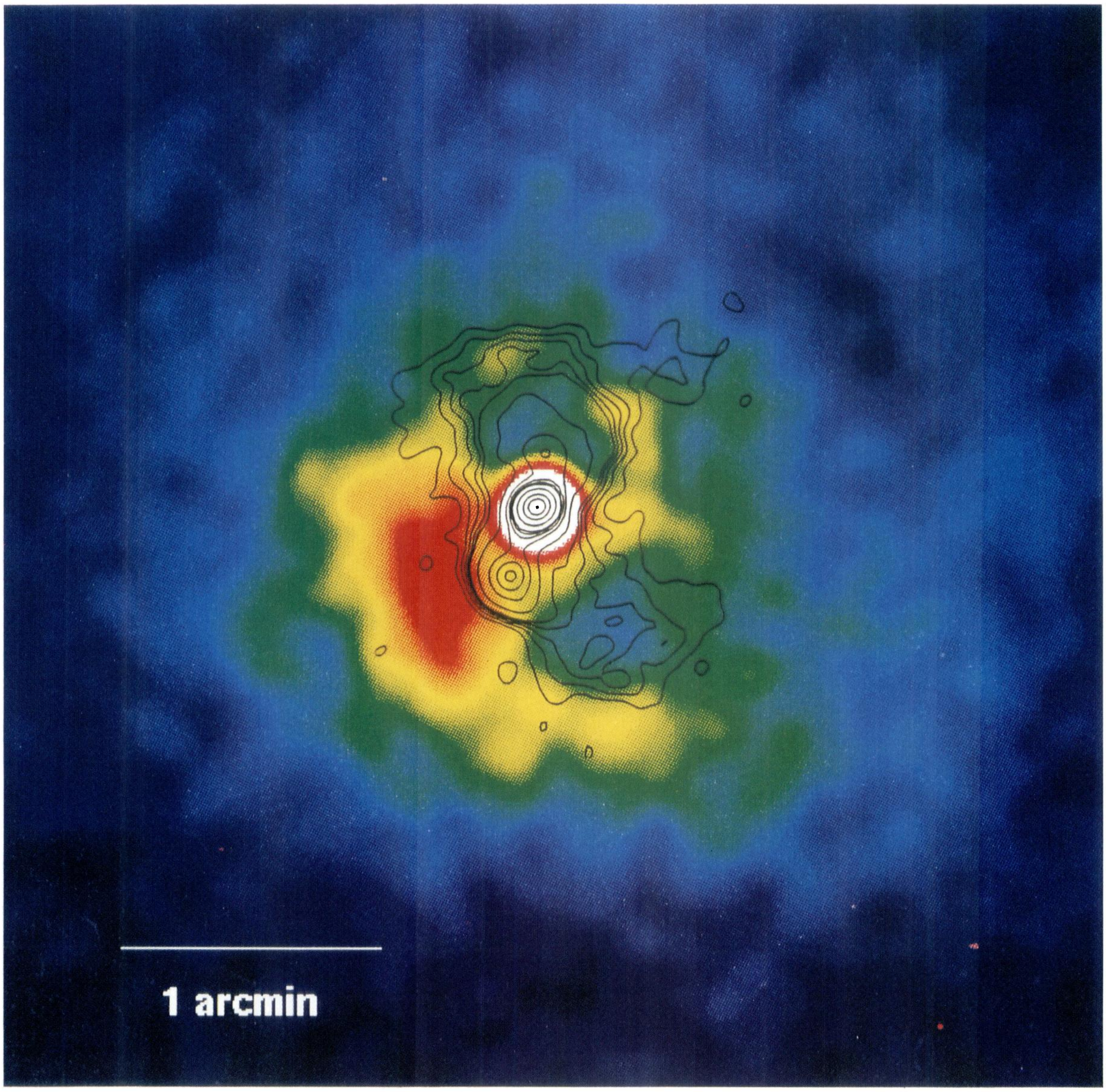

Figure 1. Central part of the *ROSAT* HRI image of the Perseus cluster of galaxies, showing a region of about 5-arcmin diameter around NGC 1275. A contour map of the radio lobes from Pedlar et al. (1990) is superimposed on this image. The radio data were obtained by Pedlar et al. with the VLA at 332 MHz, at a resolution of about 5 arcsec.

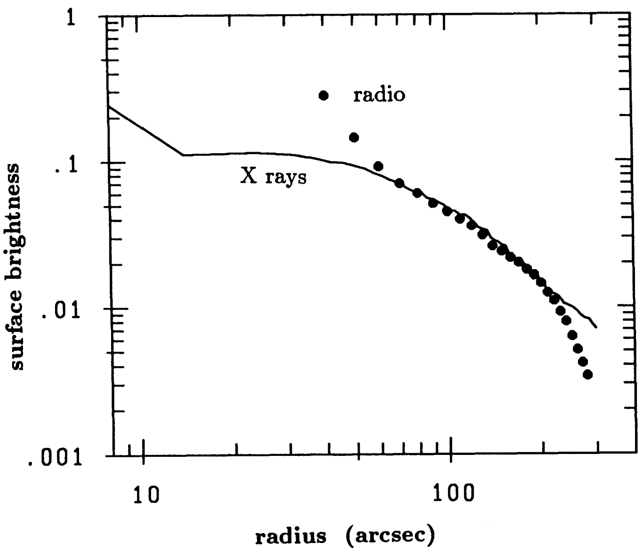

Figure 2. Averaged radial surface brightness of the radio and X-ray emission in the halo of NGC 1275. The radio data (dots) are taken from Pedlar et al. (1990) and are plotted in Jy beam^{-1} (resolution 41×42 arcsec^2). The X-ray surface brightness (line) is normalized to the radio profile at 100 kpc.

in their paper, the pressure is about 5.7×10^{-11} erg cm^{-3}. The gas pressure in the central region is determined from the gas density and temperature of the X-ray-emitting gas (see Edge et al., in preparation) as $2(\pm\ 0.25) \times 10^{-10}$ erg cm^{-3}. Thus the inferred radio lobe pressure is within a factor of 4 of the gas pressure, which is close considering the crude approximations made in the geometry and the uniformity of the radio spectrum over the area. The large difference in the X-ray surface brightness between the minima in the lobes and the surrounding area, by almost a factor of 2, leads to the conclusion that the lobes must be almost empty of thermal plasma, taking into account the fact that most of the observed X-ray emission in these areas is already contributed by the outer shells in the line of sight. The pressure of the thermal plasma inside the lobes is therefore probably unimportant compared to the pressure of the relativistic gas. One should note that the radio lobe pressure calculated by Pedlar et al. was obtained on the assumption of energy equipartition of the magnetic field and the relativistic particles, taking a ratio for the energy density in unseen protons to that in synchrotron radiation emitting electrons ('k-value') of 100. A decrease of the k-value decreases the radio lobe pressure further, much below the value for the gas pressure. Therefore it seems that, for pressure balance at the outside of the lobes, one should find either a large proton component in the relativistic plasma or alternatively a deviation from the equipartition condition.

The X-ray-determined pressure is a lower limit, since the gas density is well-determined from the X-ray surface brightness and the temperature could be higher than the adopted King-law gravitational potential allows. High central gas pressures are also obtained from the optical [S II] lines. Heckman et al. (1989) find $P \approx 5 \times 10^{-10}$ erg cm^{-3} at a radius of about 8 kpc. They too have stressed that the gas pressure is much higher than the equipartition radio pressure. Our observations rule out the possibility they suggest, namely that the radio plasma is in equipartition but has a low filling factor.

The observations indicate that the pressure in the radio lobes has been sufficient to push the gas away out to radii of $\sim 30-40$ arcsec (15 – 21 kpc). Synchrotron emission of relativistic electrons is also observed at larger radii. In Fig. 2 the azimuthally averaged radial surface brightness profiles of the radio and X-ray emission are compared. The edge of the radio lobes is at a radius of about 30 to 40 arcsec, characterized by the sharp increase of the radio brightness towards the centre. What is the connection between the relativistic plasma inside and outside the radio lobes?

Gull & Northover (1973) have pointed out that the relativistic particles inside the radio lobes are buoyant because the relativistic plasma is not as dense as the thermal gas at the same pressure. The boundary region is Rayleigh–Taylor-unstable (as also discussed by Böhringer & Morfill 1988 and Schwarz et al., in preparation) and they estimate that the lifetime of the lobes close to the nucleus is only of the order of $10^6 - 10^7$ yr. Outside the radio lobes on a somewhat larger scale the radio emission region is fairly spherically symmetric around NGC 1275. Therefore, either rising bubbles of relativistic plasma should spread and mix with the thermal gas or the relativistic particles have to diffuse into the thermal plasma. Either way, the transport times for the particles out to the radii of ~ 300 kpc over which radio emission is observed are large, and the lifetimes of the electrons are short, $\sim 10^8$ yr at the high-frequency end of the synchrotron emission; reacceleration in the turbulent cooling flow region appears necessary in order to account for the large-scale radio halo (Böhringer & Morfill 1988; Tribble 1993; Schwarz et al., in preparation).

Turning now to the prominent X-ray surface brightness maximum to the east of the nucleus of NGC 1275, we note that the brightness contrast between the blob and the regions outside the radio lobes at the same radii is about a factor of 2. The most obvious explanation for this feature is that the gas there has a temperature lower by about a factor of 1.4 than the rest of the gas at that radius, and a correspondingly higher gas density. The gas mass in the blob amounts to a few $\times 10^9$ M$_\odot$, with a mass deposition rate of 10 – 20 M$_\odot$ yr^{-1} due to the rapid cooling of the gas. It is interesting that this maximum is close to, but just within, a loop of blue continuum emission with several bright knots seen in the optical (Sandage 1971), which may indicate some recent star formation activity. Other signatures of star formation in NGC 1275 are the A-type spectrum (Rubin et al. 1977) and the young ages of the central globular clusters inferred by Richer et al. (1993; see also Holtzmann et al. 1992 and Nørgaard-Nielsen et al. 1993).

Combining all the above features, we arrive at the following conclusion. Since NGC 1275 seems to be off-set from the gravitational centre of the cluster, it may be oscillating in the cluster potential. The radio lobes on the scale of Fig. 1 do not show the common Z-shape usually explained by a precessing of the jet, but rather a C-shape that could be induced by the motion of NGC 1275. The same motion – currently to the east – may be responsible for sweeping up the gas that now forms the bright eastern blob.

Finally, we have found that the cooling flow is disturbed by the radio lobes in the innermost 18-kpc region, while most of the cooling flow zone out to ~ 100 kpc appears to be unaffected. Even in the inner, disturbed area, mass deposition of cooling gas is presumably still occurring but in a more inhomogeneous way, defined by the positions of the radio lobes.

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