THE X-RAY INTRACLUSTER MEDIUM

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1. Introduction

Clusters of galaxies are the largest aggregates of matter that have decoupled from the universal expansion and have approximately evolved to a proper dynamical equilibrium configuration. While in the optical they are just observed as dense concentrations of galaxies, they are seen in X-rays as continuously connected entities through the emission of the X-ray luminous intracluster plasma (e.g. Sarazin 1986). Relativistic particles and magnetic fields are observed in clusters in radio halos, in regions around radio galaxies and through Faraday rotation of the radiation from background radio sources (see contribution by L. Feretti and e.g. Kronberg, 1994). Thus Clusters of galaxies are the largest, well characterized astrophysical laboratories in which plasma physical processes of diffuse media can be studied. In this brief summary the bulk properties of the intracluster medium (ICM) are discussed and two studies of the interaction of galactic radio lobes with the intracluster plasma are presented (related topics are discussed by F. Owen and L. Feretti in this volume).

X-ray observations of galaxy clusters show, that the space between the galaxies in clusters is filled with a hot, tenuous ICM with temperatures between 10 and 100 Million degrees. The X-ray surface brightness distribution reflects the plasma density distribution in the cluster. X-ray spectroscopy provides the means to determine the temperature of the hot intracluster plasma. Assuming that the plasma is approximately in hydrostatic equilibrium in the cluster one can use the density and temperature profile in connection with the hydrostatic equation to derive the mass of the X-ray luminous gas and the total cluster mass. Such studies have been carried out in detail for tens of clusters in particular with the ROSAT Observatory (Trümper 1992). A good general picture of the mass, composition and the

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structure of galaxy clusters has emerged from these studies and the major results are summarized in the following table.

Components of massive galaxy clusters and their ICM

- **gravitational mass :** $3 \cdot 10^{14} - 3 \cdot 10^{15} M_{\odot}$
- **galaxies :** $\sim 2 - 7\%$ of the total mass
- **hot intracluster plasma:** $\sim 10 - 30\%$ of the total mass
  X-ray luminosity : $\sim 10^{44} - 5 \cdot 10^{45}$ erg s^{-1}
  energy content : $\sim 10^{62} - 10^{63}$ erg
  energy density (at the core radius) : $\sim 10^{-11} - 10^{-10}$ erg cm^{-3}
- **radio halo:** luminosity $\sim 10^{41} - 10^{42}$ erg s^{-1}
  energy density in relativistic particles: $\sim 10^{-12} - 10^{-11}$ erg cm^{-3}
  energy density in the magnetic field: $\sim 10^{-12}$ erg cm^{-3}
  energy content of the relativistic plasma: $\sim 10^{59} - 10^{60}$ erg
  necessary energy input to power the radio halo: $\sim 10^{42}$ erg s^{-1}

These results imply that the gas mass is much larger than the mass in galaxies and that most of the gravitationally inferred matter is "dark". The energy in the magnetic field and in relativistic particles is generally less than the energy in the thermal ICM and they are therefore unimportant for the gas dynamics and pressure (this conclusion is still under discussion, however).

2. Pressure interaction of radio lobes with the ICM in NGC 1275

The central dominant galaxies of galaxy clusters are found very often to be radio sources displaying radio lobes. The lobes are often bend for which interactions with the cluster ICM are made responsible. A good example is NGC 1275 in the Perseus cluster. Two radio lobes are seen which extend to a radius of almost 1 arcmin from the center (e.g. Pedlar *et al.*, 1990) and are on larger scales embedded in a "mini-radio-halo" (e.g. Noordham and de Bruyn, 1985). In a recent high resolution ROSAT observation a displacement of the hot ICM by the inner radio lobes has clearly been observed now for the first time (Böhringer *et al.*, 1993).

Fig. 1 shows the ROSAT HRI image of NGC 1275. Superposed as contour plot is the radio emission observed by Pedlar *et al.* (1990) with the VLA at 332 MHz. One notes the deficiency of the X-ray emission in the regions of the radio lobes out to a radius of 30 - 40 arcsec (15 - 21 kpc). The pressure in the surrounding ICM and in the lobes is almost equal (within a factor of 3; for a k-value of 100) which supports the picture that the minima in the X-ray surface brightness are due to a displacement by the lobe pressure.

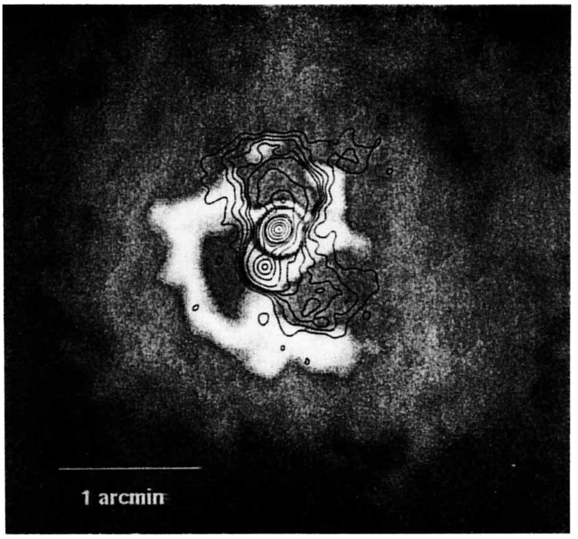

Figure 1. ROSAT HRI image of the central part of the Perseus cluster showing the halo region of the dominant galaxy NGC 1275. A contour map of the radio lobes of this galaxy observed by Pedlar *et al.* (1990) at the VLA at 332 MHz is superimposed onto the X-ray image.

3. The radio and X-ray halo of M87

The opposite effect of radio–X-ray correlation is observed in the halo of M87, the central galaxy of the Virgo cluster (Böhringer *et al.*, 1995). Fig. 2 shows the X-ray halo of the central region of the Virgo cluster from a deep ROSAT PSPC observation, where a spherically symmetric X-ray halo model has been subtracted from the image, and the radio map of Feigelson *et al.* (1987). The positive correlation out to a radius of $\sim$4 arcmin is clearly visible. A spectroscopic analysis of the X-ray data from the ROSAT observation shows that the excess emission in the radio lobes clearly originates from thermal plasma (Böhringer *et al.* 1995). Thus the emission is not due to the inverse Compton effect caused by the relativistic electrons in the radio lobes as it was speculated earlier (e.g. Andernach *et al.* 1987; Feigelson *et al.* 1987). Why the gas is more luminous, denser and also cooler in the radio lobes is not obvious; it has been speculated (Böhringer *et al.* 1995) that there may be cold gas and magnetic bubbles intermixed with the hot gas causing the observed effects.

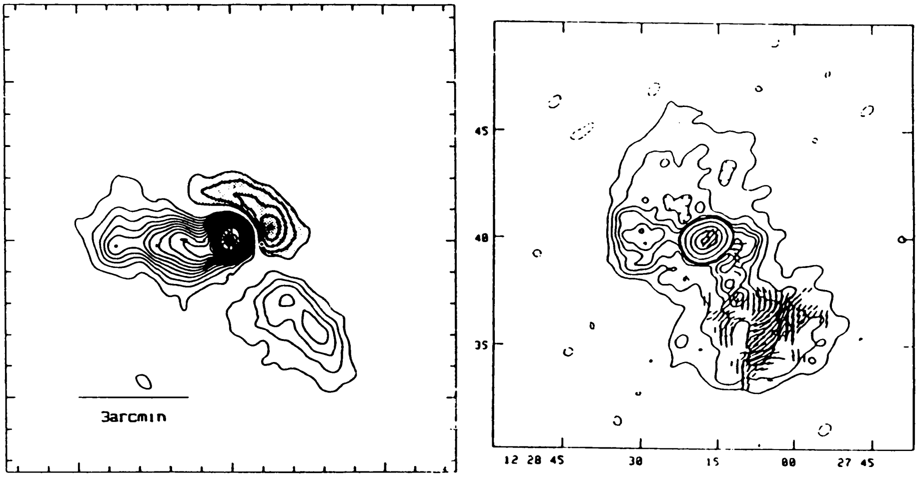

Figure 2. Contour plot (left panel) of the residual image of the X-ray halo of M87. The image was obtained from the cluster image by subtracting a spherically symmetric model halo. The Radio map (right panel) of this region was obtained by Feigelson *et al.* (1978) with the VLA at 1.4 GHz. The nearly perfect correlation of the excess X-ray emission with the radio lobes is well visible.

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