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X-ray structure of clusters of galaxies with ROSAT

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Abstract. X-ray emission from clusters of galaxies is due to thermal Bremsstrahlung from a hot thin gas in the intergalactic medium. The gas is generally considered to be smoothly distributed with a size of ~ 3 Mpc. X-ray imaging with the Einstein Observatory has shown that the surface brightness departs from a symmetrical distribution or has multiple peaks (sub-structure) in nearly 30% of the clusters. Recent ROSAT observations show (i) the relaxed clusters like Coma and Abell 2256 have significant sub-clustering due to on-going mergers, (ii) the existence of filamentary X-ray structure in the central regions of the cooling flow clusters, and (iii) the dominance of dark matter and the lowest metal abundance in the gas in a small group of galaxies, NGC 2300. These results from ROSAT are reviewed here.

Key words : X-ray—clusters of galaxies

1. Introduction

A typical cluster of galaxies is a gravitationally bound system extending over ~ 3 Mpc consisting of several hundred galaxies. At an average redshift of ~ 0.05, clusters of galaxies are very large objects with an angular diameter of ~15 acrmin. Pictures of some famous clusters like Virgo, Perseus and Coma can be seen in the Cambridge Atlas of Astronomy. The rich clusters have been catalogued by Abell (1958) and Abell, Corwin & Olowin (1989). Many other catalogues of poor clusters, small groups of galaxies, distant clusters exist. The galaxies in the clusters are mostly elliptical and lenticular. The large velocity dispersion observed in the clusters implies that the virial mass is far in excess of the mass visible as galaxies that contribute ~ 5-10% of the virial mass. The optical and X-ray characteristics of the clusters have been reviewed in detail by Sarazin (1986). Below (Section 2), I briefly summarize the X-ray properties, followed by a brief description of ROSAT (Section 3), and then review the most recent and exciting observations with the ROSAT in the sections that follow.

2. X-ray characteristics of clusters

The intracluster medium is dominated by hot thermal gas seen in X-rays, first detected with soft X-ray detectors flown on rockets and early X-ray astronomy satellites—Uhuru, Ariel V, OSO-8 and HEAO-1. The X-ray luminosity of the intracluster gas is in the range of 10^{43} ergs s^{-1} for poor clusters and groups to 10^{45} ergs s^{-1} for the rich clusters. Thus, clusters as a class are next only to quasars in their X-ray luminosity. A statistically complete sample of X-ray emission from Abell clusters was generated from an all sky X-ray survey by HEAO-1 (McKee *et al.* 1980). The thermal nature of X-ray emission was established with the detection of emission lines from highly ionized iron (Fe XXVI) and the temperature of the gas was found to be in the range of 6-9 keV and the density in the range from ~ 10^{-3}-10^{-2} cm^{-3} (Mushotzky 1984). The gas in poor clusters and groups of galaxies is cooler ($kT \sim 3$ keV) (Criss, Cioffi & Canizares 1983; Singh, Westergaard & Schnopper 1986). In general, there is a strong positive correlation of X-ray luminosity, L_x with temperature T_x (Edge & Stewart 1991). The intracluster medium (ICM) is normally found to be enriched with a median Fe abundance of ~ 0.3 times the solar value (Edge & Stewart 1991).

X-ray imaging with the Einstein Observatory has detected the gas out to 3 Mpc (Jones & Forman 1984). Based on imaging and spectral observations, the total mass in the gas can be calculated. The assumption of hydrostatic equilibrium and spherical symmetry of the gas have been used to fit the X-ray surface brightness distribution of the gas. Under these assumptions the total cluster mass can be estimated from the X-ray data alone and depends on the maximum extent of the gas detected (Gorenstein *et al.* 1978; Jones & Forman 1984). The mass in the X-ray gas and the total mass are uncertain at large radii with the estimates for the hot gas contribution ranging from 5% to 30% and the rest of the mass being attributed to dark matter. As the optically luminous portions contribute a similar amount of the mass, the bulk of the mass is in dark matter.

In a large fraction of clusters, the central gas densities are found to be very high leading to radiative cooling time scales much shorter than the Hubble time [see e.g. Singh, Westergaard & Schnopper (SWS) 1988a,b]. Additionally, X-ray spectroscopy of the central regions of these clusters shows that the gas in these central regions is significantly cooler than the ambient temperature of the ICM. Under these conditions a cooling flow can exist in the cores of these clusters, and these clusters are normally referred to as the "Cooling Flow" (CF) clusters. In many CF clusters even cooler gas at ~ 10^4K in H_α emission, and cold molecular gas has been seen. For more details the reader is referred to a recent review by Fabian, Nulsen & Canizares (1991).

3. ROSAT—X-ray telescope and detectors

The ROSAT (Rontgensatellit) is a joint German, US and British X-ray astronomy satellite launched on 1990 June 1. It carries an imaging X-ray telescope and an XUV telescope. The X-ray mirror assembly is in Wolter type I configuration; and it has a focal length of 2.4m and four nested grazing incidence telescopes with maximum aperture of 0.84m. The geometric reflecting area is 1141 cm^2. The effective area depends on the energy of the X-rays and the off-axis angle. The telescope can focus 0.1-2 keV X-rays with an angular resolution of 5 arcsec (Half Energy Width). The field of view (foV) is 2°. In the focal plane of the telescope two position sensitive proportional counters (PSPC) and one high resolution imager (HRI) are situated. The PSPCs cover the full 2° foV of the telescope, have a spatial resolution of ~ 25 arcsec at 1 keV, and energy resolution $\Delta E/E = 0.43\ (E/0.93)^{-0.5}$ (FWHM). The HRI covers the central 38 arcmin (square) of the focal plane and has a spatial resolution of 1.7 arcsec (FWHM). Details are given in Aschenback (1986) and Pfeffermann *et al.* (1986).

ROSAT with its improved sensitivity and high quality imaging can detect the most luminous clusters out to a redshift ~ 3, detect nearby low luminosity ICMs and extend the low luminosity end of the luminosity function to even lower values, and provide more details of the structure of ICM. The recent results obtained from ROSAT are in tune with these expectations and are reviewed below.

4. X-ray substructure

Study of substructure tells us about the dynamical state and formation processes of clusters. In the model for Cold Dark Matter Universe based on hierarchical clustering theories, the clusters are expected to build up by the merging of pre-existing smaller groups of galaxies or cluster subunits. Furthermore, violent relaxation during cluster collapse should smoothen out the central parts of the clusters. The surface brightness profile and temperature of hot gas are sensitive indicators of the depth and shape of the cluster potential. Therefore, X-ray imaging provides a sensitive probe for the study of substructure in clusters, since the gas responding to the underlying potentials (deep enough to hold the hot gas) is far more easier to detect than the study of galaxy isopleths which have comparatively poorer signal-to-noise.

The clusters with centrally condensed galaxy distribution normally show symmetrical surface brightness. Many clusters, however, show distinct departures from symmetry in terms of local enhancements in their galaxy distributions and/or the X-ray surface brightness, suggesting the presence of substructure or clumps of smaller groups of galaxies interacting or merging with the cluster. X-ray observations with the Einstein Observatory have revealed the presence of substructure in about 30% of the clusters (Forman & Jones 1990), consistent with the results from optical studies of isopleths (Geller & Beers 1982; Baier & Oleak 1983). In this context, detailed observations with the ROSAT of Coma, A2256 and Perseus are reviewed below.

Coma cluster is a nearby rich cluster and one of the brightest extragalactic X-ray sources in the sky. It is considered to be one of the most regular looking and relaxed clusters (Geller & Beers 1982; Dressler & Shectman 1988), a view that has been contested by Baier (1984) and Fitchett & Webster (1987) who have identified several groupings centered on some of the brightest galaxies. A deep image with the Einstein Observatory had revealed two point sources near the centre of the cluster, associated with the brightest cluster member (BCM) NGC 4889 and a D galaxy NGC 4874 (Davies & Mushotzky 1993). In a long pointed observation with the ROSAT PSPC, White, Briel & Henry (1993) detect X-rays from many bright galaxies over and above the cluster emission, and at least four of which lie at the centres of their associated groups or subcluster units. A contour map of the X-ray emission from White *et al.* (1993) is reproduced in figure 1. According to this map, the overall cluster emission is extended to a radius of 1° and is centered on NGC 4874, extended diffuse X-ray emission is detected in the inner regions associated with NGC 4874, a ridge between NGC 4874 and NGC 4889, a subgroup of galaxies around NGC 4911, a subcluster near NGC 4848, and another one near NGC 4839 seems to be leading the intra-group gas into cluster (White *et al.*). These observations show that a merger of small groups is taking place in Coma.

Abell 2256 is another relaxed Coma-like cluster at a redshift 0.06. Study of X-ray emission with the Einstein Observatory showed it to be of an elliptical shape (Fabricant *et al.* 1989). The X-ray image of A2256 extracted from the Einstein IPC CD-ROM dataset and

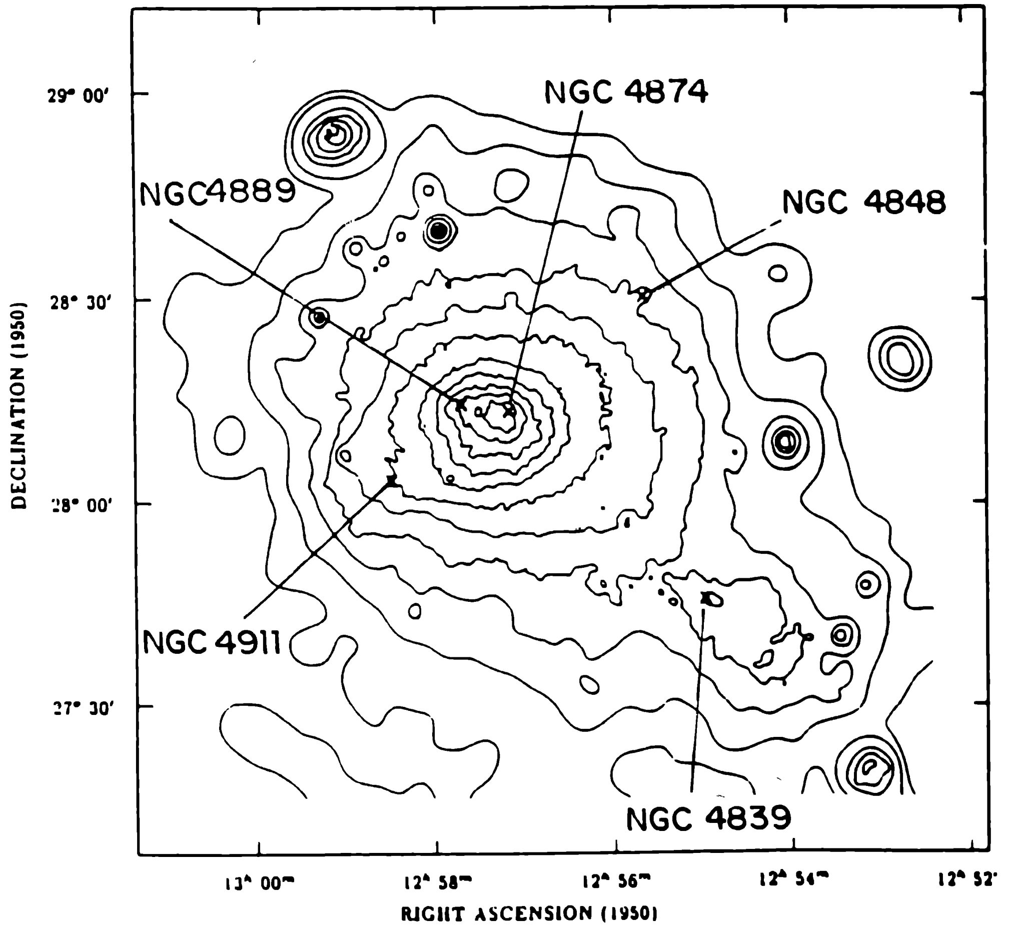

Figure 1. Contour plot of the X-ray surface brightness of Coma cluster of galaxies in the 0.5-2.4 keV energy band taken with PSPC onboard ROSAT from White *et al* (1993). The inner parts have been smoothed with a Gaussian σ of $16''$, and the outer parts with a progressively higher σ going to $128''$ in the outermost regions. The contour levels are 1.25, 2.5, 5, 10, 20, 40, 80, 120, 160, 200, 240 and 240 in units of 7×10^{-12} ergs cm^{-2} s^{-1} deg^{-2}.

deconvolved from the point spread function using the Maximum Entropy Method is shown in figure 2 (Singh & Rao 1993 (unpublished)). Significant X-ray substructure can be seen here. The ROSAT observations have revealed it to be composed of two subclusters (Briel *et al.* 1991) (a third component SE of the centre is not seen with the ROSAT). The main cluster component is centered on a cD galaxy with a mean radial velocity of 17880 ± 205 km s^{-1} and a velocity dispersion of 1270 ± 127 km s^{-1}, whereas the smaller group has a mean radial velocity of 15730 ± 158 km s^{-1} and a velocity dispersion of 350 ± 123 km s^{-1}. The velocity data, lower temperature of the gas (~ factor 5) and X-ray luminosity in the smaller component all point towards a merger in action in A2256 (Briel *el al.* 1991).

The Perseus cluster is the brightest extragalactic X-ray source with NGC 1275 as the central galaxy. The ICM is hot ($kT \sim 6$ keV) with strong iron line emission, has cooler gas ($kT \sim$ 1-2 keV) near the centre and a cooling flow of 200 M yr^{-1} is indicated (Fabian *et al.* 1981, Mushotzky *et al.* 1981). Modelling of X-ray surface brightness of Perseus has been quite problematic as it required a significantly lower gravitational potential than implied by the optically observed velocity dispersion (Fabian *et al.* 1981). ROSAT observations presented by Schwarz *et al.* (1992) show that the gas is extended to a radius of 1.3°, has an elliptic

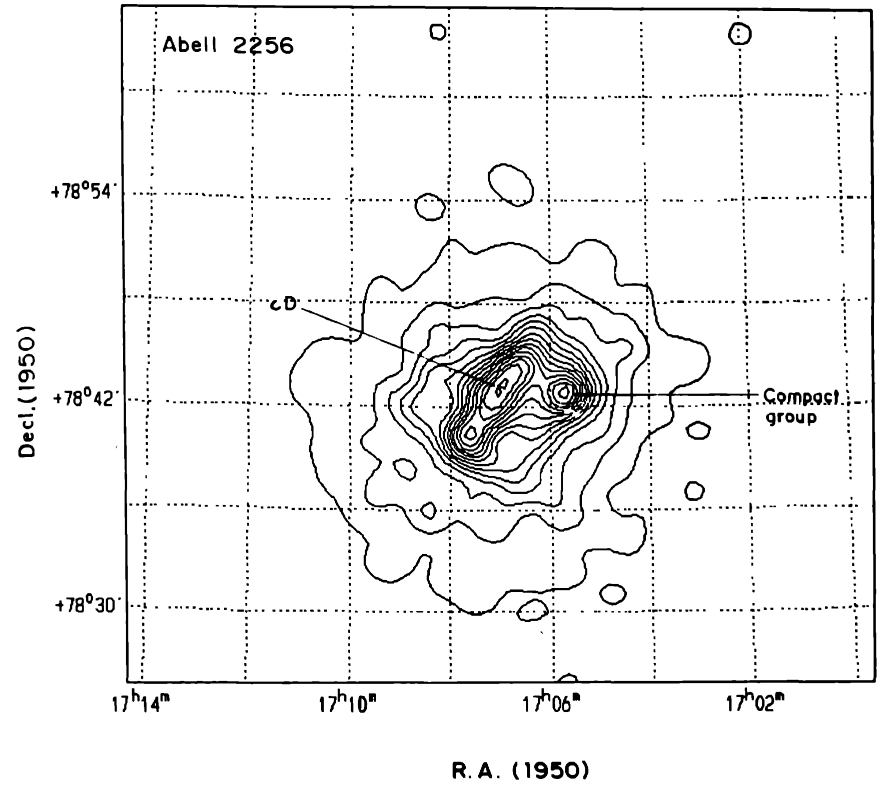

Figure 2. Contour plot of the X-ray surface brightness of A2256 cluster of galaxies in the 0.2-4.0 keV energy band taken with IPC onboard *Einstein*. The X-ray image has been processed using the Maximum Entropy Method to deconvolve the point spread function from the image. The levels are 10, 30, 50, 70, 90, 110, 130, 150, 170, 190, 210, 230, 250, 270, 290 counts arcmin^{-2}.

X-ray structure consistent with the superposition of a subcluster to the east of NGC 1275. The subcluster, however, appears unrelated to the cluster galaxies that are seen as an excess in the west along the bright chain of galaxies with an X-ray peak on IC 310 (Schwarz *et al.* 1992). The gas in the "subcluster" region is substantially cooler ($kT \sim$ 2-3 keV) and has luminosity typical of small groups. A merger has been suggested to be taking place here as well (Schwarz *et al.* 1992), indicating an unrelated cluster. This may explain the discrepancy between the virial mass estimates from the velocity and X-ray gas distributions.

The existence of significant amount of substructure, therefore, implies that the clusters are dynamically active and still evolving. Since the smaller lumps of gas engaged in merger are cooler than the intracluster gas, and since groups are generally known to have cooling flows associated with them, merger of such clumps has strong implications on the evolution of rich clusters. Merger could lead to the absence of cooling flows in rich clusters (e.g., Coma) due to disruption, heating and mixing. Mergers could even enhance the flow, lead to inhomogeneous intracluster medium, etc.

5. X-ray filamentation in cooling flows

One of the most interesting discoveries with ROSAT HRI is the detection of inhomogeneities and filamentary structure in the X-ray emission from the core of two CF clusters viz., A2029 and 2A0335 + 096 (Sarazin, O'Connell & McNamara 1992a,b). A2029 cluster is at a redshift of .0767, has a cooling radius of ~ 230 kpc and an inflow rate of ~ 370 $M_\odot$ y^{-1}, but has no associated optical line emission. Similarly, 2A0335 + 096 is a compact group at a redshift of 0.035 with total cooling rate of 100-200 $M_\odot$ y^{-1} within a radius ≤ 200 kpc (SWS 1988b) centered on a D galaxy. In figure 3 is shown an optical V-band image of the D galaxy taken with a CCD at the Vainu Bappu Telescope (Singh *et al.* 1993). A bright companion nucleus can be seen close to the nucleus of the D galaxy. 2A0335 + 096 also shows a strong optical line emission (Romanshin & Hintzen 1988). The ROSAT HRI observations show filaments, knots and blobs of X-ray emission in the cooling cores of both the clusters. In figure 4 is reproduced (from Sarazin *et al.* 1992b) the HRI image of 2A0335 + 096 with the Hα contours superposed. The X-ray structure has been attributed to excess emission rather than absorption. Not all the X-ray features correspond to features in the line emission. The surface brightness of the filaments implies very high gas densities, ~ 1 cm^{-3}. Such dense filaments cannot be supported in hydrostatic equilibrium and are expected to fall into the cluster centre on free-fall time of ~ 10^8 yr. A large supply of gas and additional forces are required to maintain the filaments. Rotation, turbulence and magnetic fields may play an important role in this regard (Sarazin *et al.* 1992b).

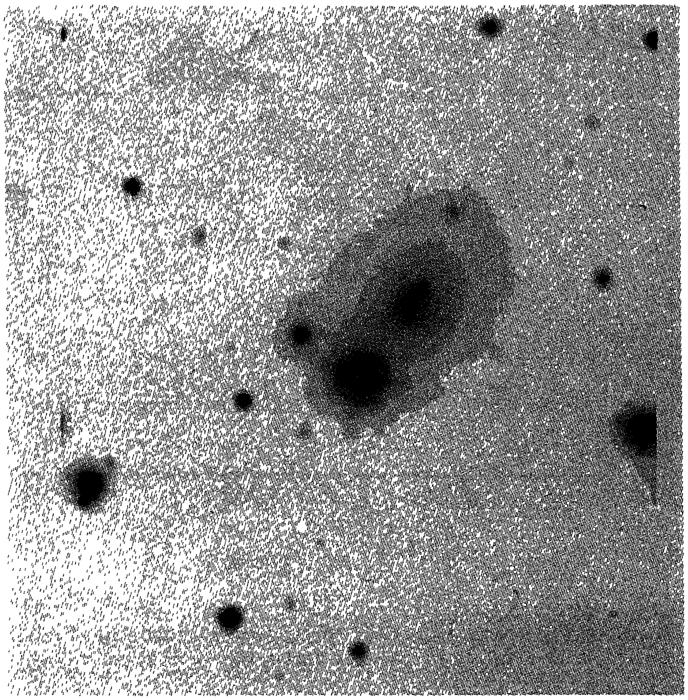

Figure 3. Optical (V-band) image of the D-galaxy in 2S0335 + 096 based on CCD observations at the prime focus of the Vainu Bappu Telescope. The companion nucleus of a merging dwarf galaxy is clearly visible. Size ~ 4 × 4 $arcmin^2$.

6. Intra-group X-ray emission from HG92 and dark matter

Diffuse intra-group X-ray emission has been discovered by Mulchaey *et al.* (1993) from a nearby group (distance = 45.7 Mpc) of galaxies known as HG92 (Group 92 in Huchra & Geller 1982) or NGC 2300 group, using the ROSAT PSPC. As described by Mulchaey *et*

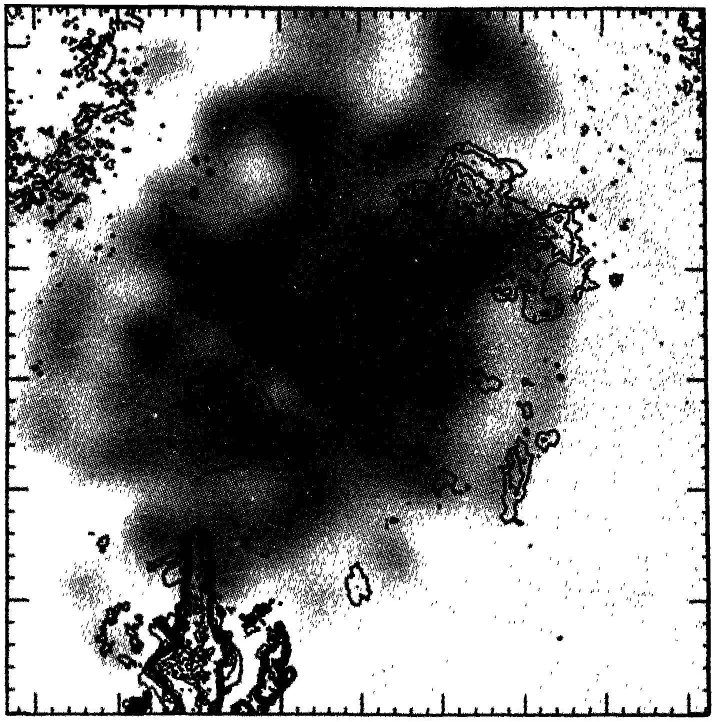

Figure 4. The grey scale X-ray image of central (64″ x 64″) cooling flow region of 2A0335 + 096 based on ROSAT HRI observations from Sarazin *et al* (1992). Superposed on the image are contours of the Hα emission-line intensity (Romanshin & Hintzen 1988). The cross on the diagram marks the position of the central D galaxy. The bright point source of Hα and X-ray emission corresponds to the companion nucleus. The structures to the lower left in the figure are artifacts produced by the bright star located near the cluster.

al. (1993), the X-ray emission extends to a radius of ~ 25 arcmin (0.3 Mpc) and completely surrounds two prominent galaxies in the group viz., NGC 2300—a bright elliptical, and NGC 2276 (Arp 25)—a peculiar late type spiral. The X-ray gas is not centred on any prominent galaxy, the centroid being ~ 3 arcmin away from NGC 2300. The temperature of the X-ray gas is ~ 0.9 ± 0.15 keV, and the elemental abundance is estimated to be in the range 0.01-0.18 solar. Under the assumption of spherical symmetry and hydrostatic equilibrium the total mass of the group has been found to be $2.0^{+0.4}_{-0.5} \times 10^{13} M_{\odot}$, whereas the baryonic mass in gas and galaxies is estimated to be only 6% (and at most 25%) of the total mass (Mulchaey *et al.*). The implication is that diffuse dark matter dominates the gravitational potential of the group which is on a megaparsec scale. So far such estimates were available only for very rich clusters. Mapping of other similar groups with ROSAT is needed before drawing more general conclusions.

7. Chemical evolution of the ICM

The intracluster gas is most probably a mixture of primordial gas trapped in the cluster potential and the processed gas that has undergone nucleosynthesis in stars and subsequently ejected or stripped, to explain the observed abundance of iron. It has been found that the ratio of gas mass to the stellar (or optically visible) mass increases with increasing depth of the cluster potential, and consequently the star (and galaxy) formation is more efficient in groups than in rich clusters in a closed system (Forman & Jones 1990). In other words, a higher fraction of the gas in rich clusters is of primordial origin, and a lower abundance of iron is predicted in rich clusters than in groups under the assumption of uniform distribution. This is in accordance with the observed correlation between Fe abundance and *kT* (see Ikebe *et al.* 1992). The Fe abundance is ~ 0.2 solar in very rich and hot clusters like Coma (Hughes *et al.* 1993), ~ 0.4 in bright but cooler compact groups (Singh *et al.* 1986), and nearly solar in small groups like Fornax with the lowest temperature (Ikebe *et al.* 1992). On the other hand, the ROSAT observations of HG92 (see Section 6 above), show almost primordial gas in the group with a temperature that is nearly the same as that of the Fornax cluster. Very low metal abundance of gas in HG92 implies the lack of ejection/stripping of the ISM of galaxies in the group. These issues are, therefore, more complex and relate to the origin of the ICM, the primordial fraction, the site of iron production and the mechanism of its dispersal into the ICM, role of cooling flows etc. Improved spatially resolved spectral measurements would help to fully investigate these issues. Studies of clusters with merging compact groups would directly trace the ongoing enrichment of the intracluster medium, in the scenario of hierarchical clustering. The recently launched (1993 February 20) US-Japanese satellite, ASCA, carrying X-ray telescopes and X-ray CCDs is an ideal instrument for an indepth study of the temperature and elemental abundances of the X-ray emitting gas in groups and clusters of galaxies.

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