Proceedings of *The Riddle of Cooling Flows in Galaxies and Clusters of Galaxies*: E27
May 31 – June 4, 2003, Charlottesville, Virginia, USA
Ed. T. H. Reiprich, J. C. Kempner, & N. Soker

The ASCA View on Cooling Flows and its Implications

K. Max Makishima[1,2]

[1] *Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyoku, Tokyo, Japan (maxima@phys.s.u-tokyo.ac.jp)*
[2] *Cosmic Radiation Laboratory, Institute of Physical and Chemical Research, Hirosawa, Wako, Saitama, Japan*

ASCA observations of central regions of cD clusters have yielded three important pieces of evidence against the cooling flow hypothesis. Firstly, the excess X-ray surface brightness around cD galaxies has been found to result from a hierarchical structure in the gravitational potential, rather than from radiative cooling of the X-ray emitting gas. Secondly, the cool emission from core regions of cD clusters has been measured to be significantly less luminous than was estimated in the past. Finally, an increase in the overall gas metallicity and changes in the chemical composition have been detected in the central regions of several cD clusters; neither of these can be explained by the cooling flow scenario. When combined with several additional *ASCA* results, these findings suggest that the origin of the cool X-ray component is tightly related to cD galaxies, rather than to putative cooling flows. These discoveries have well preceded the recent achievements with *XMM-Newton* and *Chandra*. A semi-quantitative idea is presented to explain the lack of massive cooling flows, based on the assumption that kinetic energies of member galaxies (including their dark halos) is dissipated on the plasma heating through magnetohydrodynamic effects.

1. Prologue

ASCA (Advanced Satellite for Cosmology and Astrophysics; Tanaka et al. 1994), the 4th Japanese cosmic X-ray satellite following *Hakucho* (1979), *Tenma* (1983), and *Ginga* (1987), was launched on 1993 February 20 and reentered on 2001 March 2. Toward the new century, it has initiated two novel trends in the X-ray astrophysics. One is the reflective imaging of moderately hard X-rays (up to ~ 10 keV), achieved by the four X-Ray Telescopes developed under an extensive Japan-US collaboration. The other is the much improved energy resolution of the focal plane imagers, the Solid-state Imaging Spectrometer (SIS) developed under another Japan-US collaboration, and the Gas Imaging Spectrometer (GIS; Ohashi et al. 1996; Makishima et al. 1996) which we developed ourselves. These two capabilities have made *ASCA* highly successful, and fully complementary to the high angular resolution in soft X-rays (< 2 keV) achieved over the same era with *ROSAT*.

As the first space-use X-ray CCD camera operated in single-photon mode, the SIS has produced a number of novel scientific outputs. The valuable experience accumulated with the SIS is carried over to the *Chandra* ACIS and *XMM-Newton* EPIC.

The GIS has also played an crucial role particularly in the study of clusters of galaxies, with its high quantum efficiency for hard X-rays, a large field of view ($\sim 45'$ diameter), and an extremely low background needed in broad-band imaging spectroscopic observations of extended sources. Indeed, the GIS background per unit detector area (typically $\sim 5 \times 10^{-4}$ c s^{-1} cm^{-2} over 1–10 keV) is several times lower than those of the ACIS and EPIC. Moreover, in the actual analysis of extended sources, we must consider the background *per unit sky area*; then, the GIS background becomes even 1.5–2 orders of magnitude lower. Accordingly, the *ASCA* GIS archive still provides the best available X-ray data as to outer regions of relatively nearby and hence largely extended clusters, or in energy regions above ~ 4 keV where the data from the newer generation satellites suffer from poor signal statistics.

After operating *ASCA* for about a year, we became aware that the data of nearby clusters of galaxies imply, in several respects, subtle but fundamental contradictions to the cooling flow (CF) scenario. We have described our doubts on the CF hypothesis in a series of conference proceedings (Makishima 1994ab, 1995, 1996, 1997b, 1998, 1999), as well as refereed publications (Fukazawa et al. 1994; Ikebe et al 1996, 1997; Makishima 1997a; Xu et al. 1998; Matsushita et al. 1998; Ikebe et al. 1999; Tamura et al. 2000; Fukazawa et al. 2000). These results are summarized in Makishima et al. (2001; hereafter MEA01). Here, we wish to describe the entire story from a somewhat different angle. The bibliography is rather incomplete, and is heavily weighted on the *ASCA* results.

2. The Hierarchical Gravitational Potential and the Central Excess Emission (CEE)

2.1. *Central Excess Brightness in Hard X-Rays*

From the era of the *Einstein Observatory*, the centrally-peaked brightness profile, or “central excess emission” (CEE), had been widely seen in soft X-rays around cD galaxies. This was long thought to result from a density increase in the intra-cluster medium (ICM), which in turn occurs in response to the radiative cooling.

Using the *ASCA* GIS data, however, Xu et al. (1998) have discovered that the prominent CEE of A1795, a pro-

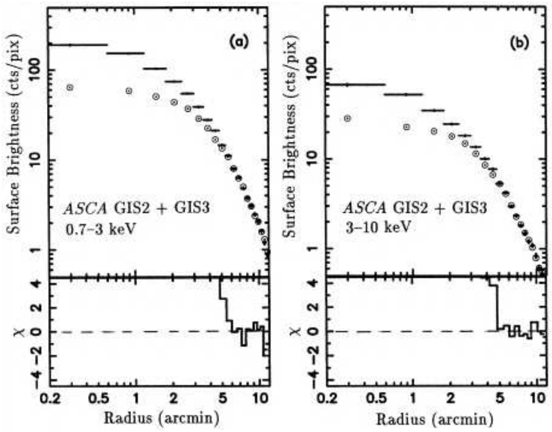

FIG. 1.— The 0.7–3 keV (left) and 3–10 keV (right) radial X-ray count-rate profiles of A1795, obtained with the *ASCA* GIS (Xu et al. 1998). Crosses represent the data, while circles show the best-fit model which is convolved with the instrumental point-spread function. The model is fitted to the data outside 5′ of the center, in order to highlight the CEE. The degree of central excess is not much different in the *ROSAT* PSPC data (Xu et al. 1998).

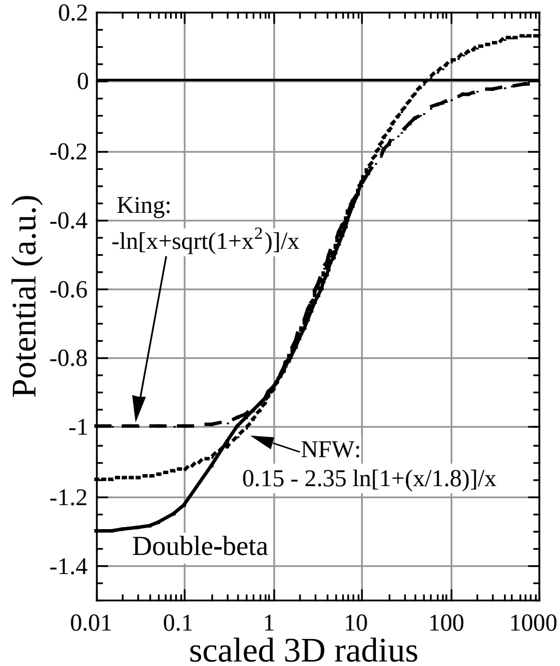

FIG. 2.— A comparison of three typical gravitational potential shapes, shown as a function of rescaled three-dimensional radius x (MEA01). The King-type model assumes a core radius of $x = 1$. The hierarchical double-β profile has core radii of $x = 0.12$ and $x = 1$, and the narrower component has a normalization 40 times higher than that of the wider component. The Navarro-Frenk-White potential has a scale parameter corresponding to $x = 1.8$.

totypical "CF cluster," is present not only in softer X-rays but also in harder X-rays above 3 keV. Figure 1 is a reproduction from this important publication that made a full use of the hard X-ray imaging capability of *ASCA*. Therefore, the CEE in this case is implied to originate from a central increase in the ICM *pressure*, rather than from the hypothesized *density* increase. Evidently, the pressure enhancement must in turn result from a central deepening in the gravitational potential, with no intrinsic relation to the CF. This result, we believe, has ruled out one of the observational facts supporting the CF hypothesis.

2.2. *Potential Shapes Near the Cluster Center*

Today, it is becoming a consensus that a flat "core," such as is implied by the King model, is absent in the actual cluster potential profile. Instead, an increasing number of works report that the radial X-ray surface brightness of clusters can be described as emission from an isothermal gas sphere trapped hydrostatically in an Navarro-Frenk-White (NFW) type potential.

The *ASCA* results are somewhat different from this consensus. While the radial brightness profile of the non-cD cluster A1060 was described adequately by the NFW model (Tamura et al. 2000), those of cD clusters generally exhibit an even stronger CEE (and hence a deeper central potential drop), requiring a "double-β" modeling (Ikebe et al. 1997, 1999; Xu et al. 1998). In Fig. 2, we compare such a potential shape with the NFW profile. The double-β feature is particularly prominent in groups of galaxies, including the Fornax group (Ikebe et al. 1996), NGC 4636 (Matsushita et al. 1998), and several others (Mulchaey & Zabludoff 1998).

2.3. *The Prevalence of Double-β Profiles*

Using the *ROSAT* radial profiles and *ASCA* temperatures, Ota et al. (2002) have discovered that some clusters (9 out of 79; often hosting cD galaxies but not always) exhibit the double-β radial profiles, of which the two core radii are concentrated at $\sim$ 60 and $\sim$ 220 kpc. Even among the remaining clusters for which the single-β model is acceptable, the core radii are preferentially found at either of the above two values.

As discussed in MEA01, the double-β structure in the X-ray brightness profile, thus found ubiquitously, is considered to reflect a hierarchical structure in the gravitational potential profile, and hence in the total mass distribution. The larger of the two core radii can be ascribed naturally to the entire cluster. Although we are tempted to associate the smaller core radius to the cD galaxy, recent *Chandra* data often reveal a third and smallest β-component on a length scale of $\sim$ 10 kpc. If this smallest spatial component is associated with the cD galaxy, the intermediate one ($\sim$ 60 kpc) may correspond to the halo of the cD galaxy. The formation of such hierarchical potential structure may not be explained by collision-less cold dark matter alone; we suspect that baryons are playing a certain role.

As a future work, we may simultaneously utilize the *Chandra*/*XMM-Newton* data and those from *ASCA*, and tightly constrain the radial profiles in the central and outer regions, respectively. Another approach may be to focus on distant clusters with *XMM-Newton* and *Chandra*, because in this case the X-ray surface brightness can be measured over a wider spatial scale than for nearby ones. Actually, a double-β profile is reported, e.g., on A1835 (with a redshift of $z = 0.23$), based on the *XMM-Newton* data (Jia et al. 2003, private communication).

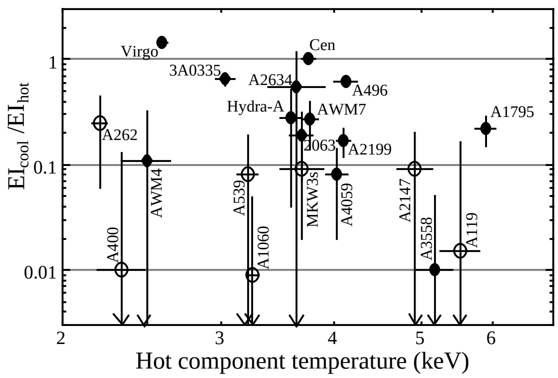

Fig. 3.— Ratio of the emission integrals between the cool and hot ICM components, calculated within $\sim$ 70 kpc of the cluster center based on the 2T modeling, and plotted as a function of the hot-component temperature. The filled symbols refer to clusters with Bautz-Morgan types I, I-II, or II; the open symbols those with II-III or III (MEA01).

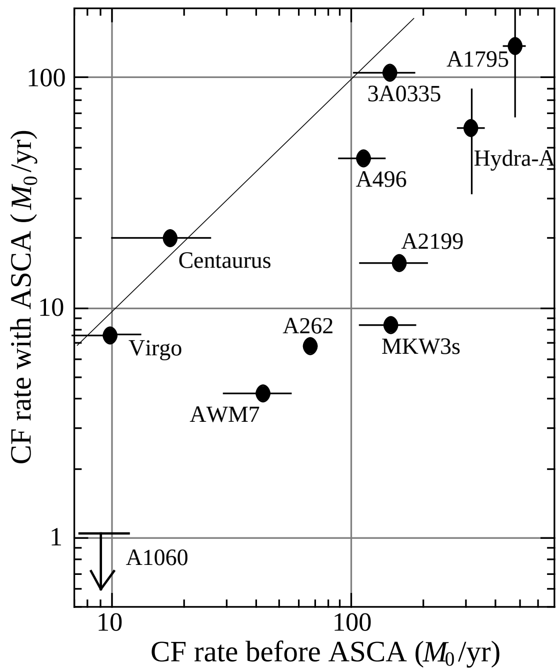

Fig. 4.— Comparison of the cooling flow rates measured with *ASCA*, against those reported previously (mainly from Edge et al. 1992). Details are given in MEA01.

3. Thermal Structure of the ICM and the Central Cool Component (CCC)

The imaging spectroscopy with *ASCA* has drastically improved the accuracy of measuring the ICM thermal structure (e.g., distributed emission measure and spatial gradients of the representative temperature). The SIS/GIS combination turned out to be ideal, because the SIS can diagnose the cooler component utilizing various low-energy emission lines, while the GIS can accurately fix the hot component (even better than the *XMM-Newton* EPIC). The complex angular response of the telescope has been overcome using a sophisticated simulator employing extensive Monte-Carlo simulations (e.g., Ikebe et al. 1999).

3.1. *The Two-Temperature (2T) Modeling*

From an early *ASCA* observation of the Centaurus cluster, we have obtained two important clues as to the ICM thermal structure of this nearby well-studied cluster. One is that the "central cool emission" (CCC) has been resolved clearly via spectroscopy, in the form of cool emission accompanied by many low-energy lines (Fabian et al. 1994). The other is that the hot (uncooled) ICM permeates the entire cluster volume right to the center, in spite of the clear presence of CCC. These results have later been reinforced by Ikebe et al. (1999), based on a much sophisticated analysis.

The above discoveries have prompted us to construct a "two-temperature" (2T) picture of the ICM (Ikebe et al 1999; MEA01); that is, an approximately isothermal "hot phase" with a temperature $T_{\rm h}$ fills the entire cluster, while a small amount of "cool phase" with a lower temperature $T_{\rm c}$ is admixed in the central region. This cool phase can be identified with the CCC, and is considered to be in a pressure equilibrium with the hot phase.

In the particular case of the Centaurus cluster, we have $T_{\rm h} \sim 3.8$ keV and $T_{\rm c} \sim 1.6$ keV (Fukazawa et al. 1994; Ikebe et al. 1999). Although the volume filling factor of the cool phase increases toward the center, the hot phase is inferred to remain still dominant there (Ikebe et al. 1999). As described by I. Takahashi et al. (these proceedings), the *XMM-Newton* data reconfirm these *ASCA* results.

Figure 3 summarizes the ratio of the cool-phase emission integral to that in the hot phase, as a function of $T_{\rm h}$. As explained in the caption, the sample is sub-divided into cD and non-cD clusters, based purely on the optical morphology. Considering this result and those from the previous section, the CCC may be regarded as a phenomenon local to cD galaxies.

3.2. *The Overestimated Cooling-Flow Rates*

Through *ASCA* observations of several prototypical CF clusters with reported CF rates reaching several hundred $M_\odot$ yr^{-1}, we have obtained yet another important result (MEA01). That is, their CCC luminosities determined through the *ASCA* spectroscopy fall far below those claimed previously mainly on the morphological basis. Representative examples include the Hydra-A cluster (Ikebe et al. 1997) and A1795 (Xu et al. 1998), and an extensive compilation is given in Fig. 4. Thus, we have concluded in MEA01 that *the CF rate was previously overestimated significantly.* It is then quite instructive to examine what caused these overestimates. Below, we attempt to answer this question from two different aspects.

In terms of radial profile measurements, the pre-*ASCA* observers did not know that the CEE is present even in hard X-rays above $\sim$ 3 keV (Fig. 1). They hence mistook the entire CEE for cooling signals, even though the CCC is only a minor fraction of CEE. In order to make this point clear, we compare in Fig. 5 the CEE and CCC luminosities of representative objects, concluding that the former much exceeds the latter.

In terms of spectroscopy, the pre-*ASCA* investigators

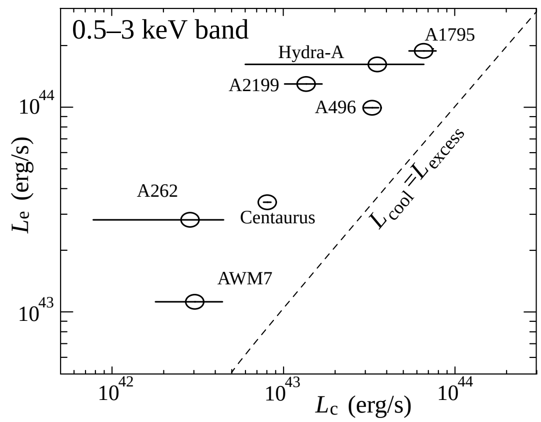

FIG. 5.— The 0.3–5 keV CCC luminosity measured with *ASCA* from a sample of cD clusters, compared with their CEE luminosity in the same band. Details are given in MEA01.

had neither the hard X-ray sensitivity nor the sufficient energy resolution. As a result, they mistook the entire emission from the core region again for cooling signals, although in reality it originates predominantly from the hot phase (§ 3.1).

It is thus quite natural that *ASCA*, with its two novel capabilities (§ 1), has cast for the first time the serious observational doubt on the CF hypothesis. These insights, we believe, are something more than simply saying that massive cooling flows do not exist.

3.3. *Remaining Issues*

Even invoking the newest *XMM-Newton* and *Chandra* data, the exact thermal structure of the ICM around cD galaxies is still unclear. Specifically, the following three possibilities are yet to be distinguished.

1. The ICM has only one temperature at each radius (i.e., single-phased), which decreases monotonically towards the center.

2. The ICM consists mainly of hot and cool phases (i.e., 2T or two-phase picture developed by *ASCA*), with the cool-phase contribution increasing to the center.

3. The ICM at each radius contains a number of components with different temperatures (i.e., multi-phased), and this "distributed (or differential) emission measure" (DEM) shifts toward lower temperatures as we approach the cluster center.

Although the *XMM-Newton* and *Chandra* data can often be described adequately with the single-phase view (e.g., Matsushita et al. 2003), this does not necessarily rule out the other possibilities. Indeed, some of the papers in these proceedings (e.g., by J. Kaastra) present impressive results from their successful DEM analyses.

In spite of these ambiguities, one thing rather robust is the universal relation of $T_{\rm c} = T_{\rm h}/2 \sim T_{\rm h}/3$, found by Ikebe (2001) and Allen et al. (2001). This must be answered by any model alternative to the CF hypothesis.

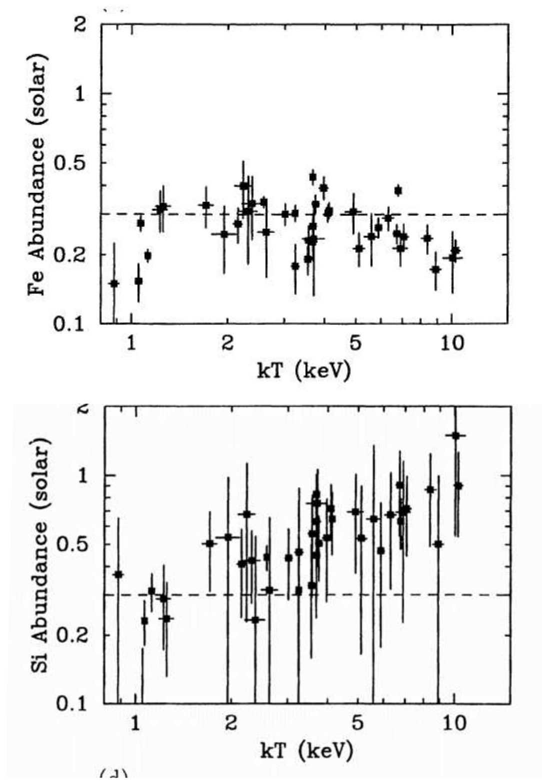

FIG. 6.— Iron (top) and silicon (bottom) abundances of the ICM of clusters observed with *ASCA*, plotted as a function of the ICM temperature. Central regions are excluded. Taken from Fukazawa et al. (1998).

4. **The ICM Metallicity**

The spatially-resolved metallicity measurements are yet another research area where *ASCA* has produced a quantum jump.

4.1. *Fe and Si Abundances*

Mushotzky et al. (1996), and later Fukazawa et al. (1998), discovered that the Fe abundance in outer cluster regions is ~ 0.3 solar regardless of the cluster richness, whereas that of Si is higher in richer clusters. We reproduce this result in Fig. 6.

Given these results, the cluster-wide ICM abundances may be understood as a varying mixture of the following two components. One is Si-rich materials, presumably supplied via Type II supernovae (SNeII) in the form of energetic winds in an early stage of cluster formation. The other is prolonged products from member galaxies, which are more Fe-enriched because of a larger contribution of Type Ia supernovae (SNeIa). Then, the decreasing Si/Fe ratios toward poorer systems suggest that their gravitational potential is too shallow to trap the energetic SNeII winds responsible for the former component (Fukazawa et al. 1996,1998).

The interpretation of the former (Si-rich) component is much reinforced by the *XMM-Newton* results on some clusters (e.g., Matsushita et al. 2003); the abundance profile of oxygen, which is a more pure-SNeII element, is quite flat at ~ 0.15 solar, even though Fe and Si show prominent central increase. Similarly, the interpretation of the latter (Fe-rich) component is supported by the findings that the large-scale iron mass in the ICM (outside ∼ 100 kpc) follows a similar radial slope as the optical light: this was confirmed in AWM7, A4059, and the Perseus cluster (Ezawa et al. 1997; Kikuchi et al. 1999), utilizing the extremely low background and the large field of view of the *ASCA* GIS.

4.2. *The Central Metallicity Increase*

Following a pioneering work by *Ginga* on the Virgo cluster (Koyama et al. 1991), a steep increase in the ICM abundance (mainly of iron), localized near the center (within ∼ 100 kpc), has been found with *ASCA* from a fair number of cD clusters (Fukazawa et al. 1994; Matsumoto et al. 1996; David et al. 1996; Xu et al. 1997; Hatsukade et al. 1998; Kikuchi et al. 1999). In contrast, the ICM abundances of the prototypical non-cD cluster A1060 show little radial gradient (Tamura et al. 2000). These results are now much reinforced by the *XMM-Newton* and *Chandra* observations. Although the abundances measured with *Chandra* are reported to sometimes drop at the very center (∼ 10 kpc; Fabian et al. 2002), the effect could be artificial (see J. S. Sanders, these proceedings).

The *excess* metals in the ICM, found around each cD galaxy, exhibit approximately SNeIa-like chemical composition, as revealed by Fukazawa et al. (2000) based on *ASCA* measurements. This makes a contrast to the outer-region abundances of rich clusters which are more SNeII-like (Fig. 6). It is therefore of little doubt that these excess metals ware produced by SNeIa in the cD galaxy.

Quantitatively, the mass of *excess* iron around cD galaxies (of order 10^9 $M_\odot$) can be supplied by a single giant elliptical over the Hubble time, as first pointed out by Fukazawa et al. (1994) and recently refined by Kawashima et al. (2003, private communication) employing the *XMM-Newton* results. Since the excess metals are found over roughly the same regions where the CCC is found, we may regard that the cool phase is generally metal-enriched, although it remains a future work to determine the abundances of the central cool and hot phases (or of multiple phases) separately.

4.3. *Contradictions to the Cooling Flow Scenario*

The overall metallicity measurements by *ASCA*, as reviewed above, contain several important lines of argument against the CF hypothesis.

If, for example, the CF were actually taking place, the excess metals ejected from the cD galaxy would be swept back, and would drop out more quickly than metal-poor portions, due to an enhanced cooling function. Then, the CCC strength would be anti-correlated with the central abundance increase (e.g., Reisenegger et al. 1996). However, what we have found with *ASCA* is quite opposite; as shown in Fig. 7 (again taken from MEA01), the actually measured relative CCC strength is *positively* correlated with the central abundance increase.

In addition to the above argument, the distinct chemical composition seen around cD galaxies cannot be explained readily with cooling flows. We have thus concluded in MEA01 that the CCC can be interpreted as significantly contributed by hot inter-stellar medium of the cD galaxy, rather than resulting from CFs.

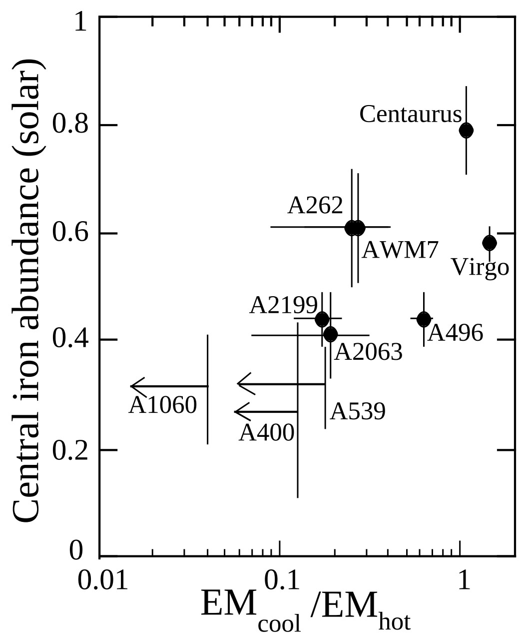

FIG. 7.— The ICM iron abundance in the cluster core region, plotted against the cool-to-hot emission integral ratio measured with *ASCA*. Originally presented by Tamura et al. (1997), and updated in MEA91.

4.4. *Iron-Mass to Light Ratio (IMLR)*

Although we have so far considered the ICM *abundances*, a more physically meaningful argument must employ the concept of "iron-mass to light ratio" (IMLR; Renzini 1997), namely the mass of iron in the ICM (in the unit of $M_\odot$) to the optical light (in the unit of $L_\odot$). We can thus eliminate ambiguities introduced by varying gas-to-light ratios.

Figure 8 summarizes the IMLR of systems with various richness, as a function of the plasma temperature. Thus, the IMLR takes a value of ∼ 0.01 in the solar unit, when spatially averaged over individual clusters. Clearly, even the Fe-rich SNe Ia material is seen to escape significantly from poor systems. This implies that a large fraction of heavy elements produced in member galaxies were actually ejected into the ICM, rather than confined to their vicinities, and explains why the inter-stellar medium of each elliptical galaxy has a much lower metallicity (at most ∼ 1 solar; Awaki et al. 1994; Matsumoto et al. 1997; Matsushita et al. 1997, 2000) than had been expected before *ASCA*.

With regard to the CF problem, a key concept is the radial profile of IMLR, or "IMLR profile" (MEA01). As shown in Fig. 9, the IMLR profile of the non-cD cluster A1060 decreases significantly toward the center; this is an immediate consequence of its nearly flat ICM abundance profile, and the generally stronger concentration of the stellar component than the ICM. A similar decrease is observed even in the Centaurus cluster that

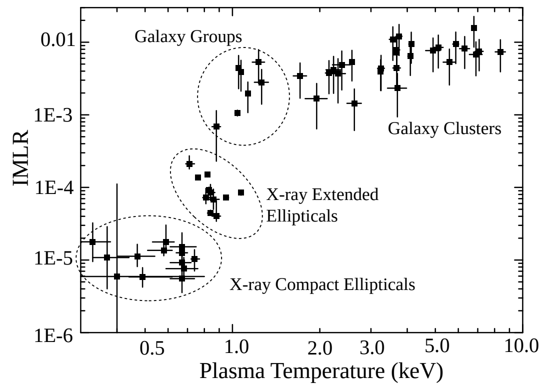

FIG. 8.— Spatially-resolved iron-mass to light ratio of various systems, shown as a function of the plasma temperature that serves as the system mass indicator. Initially presented by Fukazawa (1996), and then updated by Fukazawa (1997).

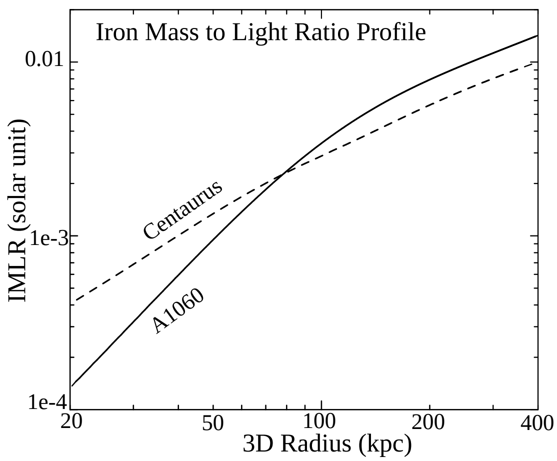

FIG. 9.— Radial profiles of the IMLR for the Centaurus cluster (dashed curve; Ikebe et al. 1999) and Abell 1060 (solid curve, from Tamura et al. 2000).

hosts the prominent central excess metals. Since the outward metal diffusion is considered inefficient (Ezawa et al. 1997), these results have been interpreted by MEA01 as possible evidence of gradual infall of the stellar component. The central decrease in the IMLR profile is not due to the insufficient angular resolution of *ASCA*, since the calculation of Fig. 9 properly takes into account the XRT point spread function.

5. Excess Hard X-Rays from Groups of Galaxies

Currently, there appears to be a consensus that some heating mechanism prevents the ICM from the predicted radiative cooling. Such a mechanism may well involve particle acceleration too. One good evidence is the extended radio synchrotron halos found in some clusters. Another evidence is the excess hard X-ray emission reported for a few clusters based on the *BeppoSAX* PDS data, although its significance and reality appears still controversial.

Using *ASCA*, Fukazawa et al. (2001), and then Nakazawa (2001), detected clear excess hard X-rays from

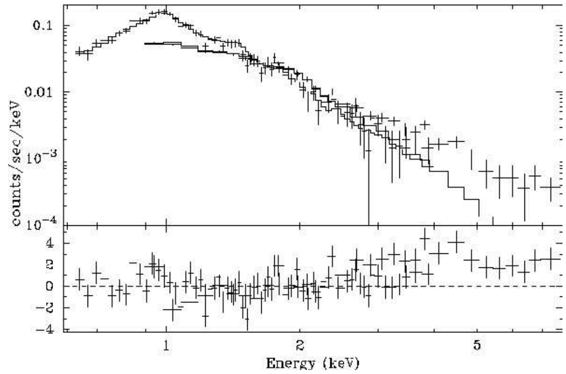

FIG. 10.— The *ASCA* SIS and GIS spectra of the compact group of galaxies HCG62, fitted jointly with a single-temperature plasma emission model in energies below 4 keV. Taken from Fukazawa et al. (2001).

several groups of galaxies. The excess is detectable even in the *ASCA* energy band, because the thermal emission of groups of galaxies has a sufficiently low temperature. Figure 10 shows the best example, namely the compact group HCG62, where the SIS data tightly constrain the ordinary thermal emission, while the GIS data reveal prominent excess hard X-rays. In this particular case, the excess emission is roughly co-spatial with its thermal emission, and has a luminosity comparable to that of the thermal emission.

Although the hard X-ray emission has been detected from a fair number of groups (Nakazawa 2001), and considered to be of non-thermal nature, its emission mechanism is still unclear. Non-thermal Bremsstrahlung by mildly relativistic electrons would require too much energy input, because they would lose 3–4 orders of magnitude larger energies in the Coulomb scattering off thermal electrons. Inverse-Compton scattering by relativistic (typically 1–100 GeV) electrons off the cosmic microwave photons is another possibility, but in this case the relatively tight upper limits on the radio synchrotron emission implies too low a magnetic field ($\sim 0.1\ \mu$G).

One possible way out of this problem with the inverse-Compton scenario is to assume that the magnetic field is highly inhomogeneous, and the electrons avoid high-field regions. Alternatively, the electron spectrum may turn over above $\sim$ 10 GeV, thus suppressing the radio synchrotron emission.

6. A Possible Scenario of the ICM Heating

6.1. *General Consideration*

Since the radiative cooling of a hot plasma is a simple and well established physical process, there is little doubt that the ICM cooling time is rather short. Nevertheless, all the available broad band X-ray data, beginning with *ASCA*, indicate the absence of massive CFs. As a result, we may consider that some heating mechanism is acting on the ICM. Such a mechanism must satisfy the following conditions.

1. It should supply the ICM with the needed radiative energy, typically $10^{43.5-44.5}$ erg s^{-1}.

2. It should balance against the cooling in a stable

manner, keeping T_c at $1/2 \sim 1/3$ of T_h.

3. It should also explain that the CCC region is metal enriched, and very likely to be two- or multi-phased.

As was discussed extensively in the present conference, two major candidates for the heating mechanism are proposed. One is heating by jets from the cD galaxy, while the other is heat conduction from outer parts. However, the former may have a difficulty in satisfying the 3rd condition, while the latter suffers from a fine tuning problem (2nd condition) as already pointed out long ago by Takahara & Takahara (1979).

We instead consider that the motion of member galaxies is playing an important role, through dynamical friction, or "ICM drag." Specifically, the galaxies swimming in the ICM will transfer their kinetic energies gradually to the ICM; then, the ICM will be heated, while the galaxies will fall to the center. Actually, many authors considered this issue repeatedly, and concluded that the associated heating effect is small because the galaxy motion is trans-sonic (e.g., Bregman & David 1989). However, these previous works all treated the ICM as a *neutral* fluid, and considered only hydrodynamical effects. In reality, we must fully consider magnetohydrodynamic (MHD) effects, particularly MHD turbulence and magnetic reconnection (Makishima 1994b, 1997ab, 1999; MEA01), because the ICM is such an ideal classical plasma. To our knowledge, there have been few such attempts except ours.

6.2. *Magnetohydrodynamic Effects*

The ICM is ubiquitously magnetized, since an extremely small difference (of order 10^{-4} of the ion sound speed) between the bulk ion velocity and that of electrons is sufficient to produce large-scale magnetic fields of significant strength (Makishima 1997ab). It is hence extremely difficult to prevent the ICM from being magnetized, whatever the seed magnetic field be. Furthermore, each galaxy has its own magnetized plasma (inter-stellar medium; ISM) and its own magnetosphere. Therefore, each galaxy can be approximated as an electrical conductor, with a typical radius of $R \sim 10$ kpc.

While moving through the ICM, each galaxy that is an electrical conductor will pick up intra-cluster magnetic fields, push them, and stretch them. This will cause significant MHD turbulence in the ICM because of the extremely low magnetic Reynolds number, and the galaxies will in turn receive friction. Under such a turbulent condition, many MHD simulations suggest that the average magnetic pressure reaches $\sim 10\%$ of the gas pressure, regardless of the initial field intensity. This yields a field strength of several micro Gauss, in good agreement with the Faraday rotation and other measurements.

In fact, *Chandra* data are revealing such a strong interaction between galaxies and the ICM, involving significant stripping of the galaxy plasmas. For example, Iizuka et al. (2003, private communication) have detected cool ($kT \sim 1$ keV) plasma plumes on one side of the spiral galaxy NGC 4388 in the Virgo cluster.

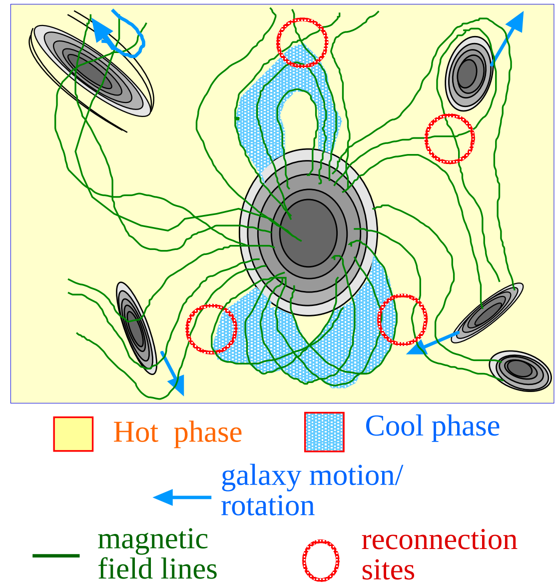

Fig. 11.— A possible magnetic configuration of the region around a cD galaxy, taken from Makishima (1997b).

Once a significant MHD turbulence is excited in the ICM, frequent magnetic reconnection will dissipate the turbulent energy in the plasma heating. In § 6.3, we describe a semi-quantitative scenario based on the above consideration. It fully utilizes the ICM properties as an ideal plasma.

6.3. *The "cD-Corona" Model*

In the cluster core region where the ICM is dense, the MHD interaction is expected to strip galaxies of their plasmas, disrupt their magnetospheres, and mix their ISM efficiently into ICM.

The only exception is cD galaxies, which are at rest with respect to the ICM. As a result, a cD galaxy may develop its own ordered magnetosphere, consisting of closed loops and open-field regions via analogy to the solar corona. The open-field regions must be permeated by the uncooled ICM, while the closed magnetic loops are occupied mainly by the cD's ISM that has a temperature of ~ 1 keV. Figure 11 gives a schematic illustration of this idea, first proposed explicitly in the 3rd *ASCA* workshop (Makishima 1997b).

The above scenario, to be called "cD-corona" model, has a number of advantages as an alternative idea explaining the ICM thermal structure near the cluster center. First of all, it can easily explain the 2T picture (§ 3.1), including the co-existence of the hot and cool plasmas, the increasing cool-phase filling factor toward the center, the dominance of the hot phase even near the center, and the exclusive association of the CCC with cD clusters (Fig. 3). The DEM properties can also be explained by assuming that, like in the solar corona, magnetic loops have a range of temperature.

A second advantage is related to heat conduction. It is almost meaningless to ask how much the thermal (and electrical) conductivity is suppressed relative to the Spitzer value. From a plasma physics viewpoint, the answer is simple and straightforward: the conductivity is close to the Spitzer value if measured along the field lines, while it can be neglected across them. As a result, the two phases can be kept thermally insulated. Furthermore, we can efficiently utilize the heat conduction in the open-field regions, to transport the much needed heat without making the cool phase to evaporate.

As a third merit of the model, we can utilize the MHD turbulence and magnetic reconnection for further heating. As mentioned in § 6.2, the open-field region must be quite turbulent. The turbulent magnetic fields will reconnect with one another, and with the closed-loop fields, thus depositing the energy onto the cool-phase plasma.

Yet another important and immediate ingredient of the model is that the metallicity increase and the SNeIa-like chemical composition can be explained easily. The metal-rich material (cool phase) inside the loops will be slowly ejected into the outer world via magnetic reconnection, and the ejected heavy ions will remain near the center because of their very low diffusion coefficients (Ezawa et al. 1997) in contrast to the very rapid electron transport along the filed lines.

Finally, a very important merit of the model is a built-in thermal stability of the cool phase (i.e., closed loops), thanks to a mechanism discovered by Rosner, Tucker & Vaiana (1978). It assumes that each loop is in a pressure equilibrium with the surrounding ICM. The loop interior is assumed to be heated by some unspecified mechanism, while it is cooled via heat conduction along the loop as well as via radiation. If the cooling becomes too enhanced, the consequent pressure reduction makes the loop thinner, and reduces the conductive flux thus realizing a stable feedback.

6.4. *Numerical Estimates*

In closing this section, we conduct several order-of-magnitude estimates as to the proposed model. The galaxy-to-ICM energy transfer luminosity, $L_{\rm heat}$, is already given by Sarazin (1988) as

$$L_{\rm heat} \sim N\pi R^2 n m_{\rm p} v^3 \quad . \qquad (1)$$

Here N is the galaxy number, R is the interaction radius of each galaxy, n is the ICM density, v is the representative galaxy velocity, and $m_{\rm p}$ is the proton mass. Substituting typical values of $N = 300$, $n = 1 \times 10^{-3}$ cm^{-3}, $R = 10$ kpc, and $v = 500$ km s^{-1}, we obtain $L_{\rm heat} \sim 2 \times 10^{44}$ erg s^{-1}, which is sufficient in view of the 1st condition of § 6.1. This calculation does not explicitly consider the MHD effects, but the assumption of $R = 10$ kpc is based on the MHD view presented in § 6.2.

From a plasma physics viewpoint, we may cross-check the efficiency of thermalization of the MHD turbulence via magnetic reconnection. Assuming that the magnetic pressure is 10% of the ICM pressure, we obtain the Alfvén speed as $v_{\rm A} \sim 3 \times 10^7$ cm s^{-1}. By dividing the typical cluster core diameter of ~ 10 kpc by $v_{\rm A}$, the Alfvénic time scale is estimated as ~ 0.3 Gyr. Empirically, the reconnection time scale is expected to be an order of magnitude longer (slower) than the Alfvénic one. We hence obtain a reconnection time scale of 3 Gyr, which is not too long.

Now that the galaxy to ICM energy transfer has been shown to be efficient enough, we must calculate the available total dynamical energy $E_{\rm gal}$ in the galaxy motion. Usually, the stellar mass $M_{\rm gal}$ in a rich cluster is estimated to be a few percent of the total cluster mass, or $10^{13}\ M_\odot$. However, we expect dark halos of individual galaxies to be moving together with the visible galaxies. As a result, we may take $M_{\rm gal} = 10^{13.8}\ M_\odot$ as the total moving mass, and obtain

$$E_{\rm gal} \sim 3 \times 10^{62} \left(\frac{M_{\rm gal}}{10^{13.8}\ M_\odot}\right) \left(\frac{v}{700\ {\rm km/s}}\right)^2 \ \ {\rm ergs}\ . \qquad (2)$$

Therefore, even if 10% of $E_{\rm gal}$ is consumed, it can sustain the luminosity for $0.1E/L_{\rm heat} \sim 5$ Gyr

Finally, we may quantitatively utilize the Rosner-Tucker-Vaiana (1978) scaling law; it predicts the maximum temperature inside a loop of length L to be

$$T_{\rm max} = 1.4 \times 10^3 (pL)^{1/3} \ \ {\rm K}\,, \qquad (3)$$

regardless of the heating power, where p is the external pressure acting on the loop. This scaling has been verified quantitatively in the solar corona using the *Yohkoh* observatory (Kano & Tsuneta 1995). For clusters of galaxies, we may substitute $L = 50$ kpc, and $p = 2 \times 10^{-11}$ dyne cm^{-2} ($n = 3 \times 10^{-3}$ cm^{-3} and $T_{\rm h} = 5$ keV). This gives $T_{\rm max} \sim 1.8$ keV, which is very close to $T_{\rm c}$ observed from many clusters. The proportionality between $T_{\rm c}$ and $T_{\rm h}$ might be explained by further considering this scaling.

7. **Epilogue**

As reviewed so far, the *ASCA* results have lead us to construct a novel view as to central regions of clusters of galaxies. At present, it can explain many of the essential observational results. As written in MEA01, "this view describes the region around a cD galaxy as a site of significant and active evolution, where a large amount of heavy elements are produced, a self-gravitating core develops, and presumably certain ICM heating processes are operating. This scenario is in contrast to the previous view, which emphasized the role of radiative plasma cooling."

We hoped to much reinforce this new paradigm using *ASTRO-E*, the 5th Japanese X-ray mission developed under a Japan-US collaboration. It carried onboard the non-dispersive X-ray Spectrometer (XRS) with a superb energy resolution, the improved CCD camera called X-ray Imaging Spectrometer (XIS), and the Hard X-ray Detector (HXD; Nakazawa et al. 1999) which is sensitive in the 10–600 keV range. The former two are coupled to the X-Ray Telescope (XRT), which updates those of *ASCA*.

On 2000 February 10, however, the launch of *ASTRO-E* using the 3-stage all-solid Mu-5 rocket has ended in a failure to our great regret. Toward the later epoch (55–75 sec after the lift off) of the first-stage burning, the rocket nozzle got a heat damage. This in turn disabled the active feedback of the movable nozzle, and the rocket attitude was disturbed significantly. Although the 2nd stage (ignited at 75 sec) and the 3rd stage (at 218 sec) both functioned normally, and attempted to bring the rocket back to the correct locus, the loss of kinetic energy due to the attitude disturbance could not be recovered. The satellite made $\sim 1/3$ revolution around the earth, but reentered the atmosphere and was lost.

Thanks to the encouragement by many colleagues worldwide, the recovery mission *ASTRO-E2* has been approved. Carrying the same instruments onboard, it is scheduled for launch in January or February 2005. We have nearly completed the fabrication of the instruments, including the HXD (now called HXD-II) of our own, and the satellite integration has started. Employing the combination of the XRS, HXD, and XIS, we hope to construct a new scenario, in place of the CF hypothesis, as to the thermal evolution of clusters of galaxies. The XRS data will clarify the thermal structure of the ICM including the hot component emitting Fe-K and Ni-K lines, and allow us to search for line broadening due to the suggested ICM turbulence. In addition, the HXD will perform the highest-sensitivity search for excess hard X-rays from clusters.

Optical observations of distant clusters are also important in order to examine our scenario. If galaxies are really heating the ICM and receiving the drag, we expect them to gradually fall to the cluster center as they evolve. Then, more distant clusters are expected to have more extended galaxy distributions relative to their X-ray extent. At present, X-ray images of distant clusters are extensively available, but optical determination of their light distribution is a bottle neck because of the obvious membership problem. The Suprime Cam of the *Subaru* telescope may be best suited to such a study.

The author would like to express his deepest thanks to Takaya Ohashi, Yasushi Fukazawa, Yasushi Ikebe, Kyoko Matsushita, Haiguang Xu, Takayuki Tamura, Ken-ichi Kikuchi, Kazuhiro Nakazawa, Isao Takahashi, Madoka Kawaharada, and Tadayuki Takahashi.

References

Allen, S. et al. 2001, MNRAS 328, L37
Awaki, H., Mushotzky, R. F. et al. 1994, PASJ 46, L65
Bregman, J. N. & David, L. P. 1989, ApJ 341, 49
David, L., Jones, C. & Forman, W. 1996, ApJ 473, 692
Edge, A., Stewart, G., & Fabian, A. 1992, MNRAS 258, 177
Ezawa, H., Fukazawa, Y. et al. 1997, ApJL 490, L33
Fabian, A. C., Arnaud, K. A., Bautz, M. W. & Tawara, Y. 1994, ApJL 436, L63
Fabian, A. C. & Sanders, J. S. 2002, MNRAS 331, 273
Fukazawa, Y. 1997, PhD Thesis, the University of Tokyo
Fukazawa, Y., Ohashi, T. et al. 1994, PASJ 46, L55
Fukazawa, Y., Makishima, K. et al. 1996, PASJ .48, 395
Fukazawa, Y., Makishima, K. et al. 1998, PASJ 50, 187
Fukazawa, Y., Makishima, K. et al. 2000, MNRAS 313, 21
Fukazawa, Y., Nakazawa, K. et al. 2001, ApJL 546
Hatsukade, I. et al. 1998, in The Hot Universe (Proc. IAU Symposium 188), ed K. Koyama, S. Kitamoto, M. Itoh (Kluwer Academic, Dordrecht) p134
Ikebe, Y., Ezawa, H. et al. 1996, Naure 379, 427
Ikebe, Y., Makishima, K. et al. 1997, ApJ 481, 660
Ikebe, Y., Makishima, K. et al. 1999, ApJ 525, 58
Ikebe, Y. 2001, astro-ph/0112132
Kano, R. & Tsuneta, S. 1995, ApJ 454, 934
Kikuchi, K., Furusho, T. et al. 1999, PASJ 51, 301
Koyama, K., Takano, S. & Tawara, Y. 1991, Nature 350, 135
Makishima, K. 1994a, in New Horizon of X-Ray Astronomy, ed F. Makino, T. Ohashi (Universal Academy Press, Tokyo) p.171
Makishima, K. 1994b, in Elementary Processes in Dense Plasmas, ed. S. Ichimaru, S. Ogata (Addison-Wesley, New York) p.47
Makishima, K. 1995, in Dark Matter (AIP Proceedings No.336), ed S. S. Holt, C. Bennet (AIP, New York) p.172
Makishima, K. 1996, in UV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas, ed K. Yamashita, T. Watanabe (Universal Academy Press, Tokyo) p.167
Makishima, K. 1997a, Plasma Phys. Control. Fusion 39, A15
Makishima, K. 1997b, in Imaging and Spectroscopy of Cosmic Hot Plasmas, ed. F. Makino, K. Mitsuda (Universal Academy Press, Tokyo) p.137
Makishima, K. 1998, in The Hot Universe (Proc. IAU Symposium No.188), ed K. Koyama, S. Kitamoto, M. Itoh (Kluwer Academic, Dordrecht) p.181
Makishima, K. 1999, in Observational Plasma Astrophysics: Five years of Yohkoh and beyond, ed T. Watanabe, T. Kosugi, A. Sterling (Kluwer Academic, Dordrecht) p.51
Makishima, K. et al. 1996, PASJ 48, 171
Matsumoto, H., Koyama, K. et al. 1996, PASJ 48, 201
Matsumoto, H., Koyama, K. et al. 1997, ApJ 482, 133
Matsushita, K., Makishima, K. et al. 1997, ApJL 488, L125
Matsushita, K., Makishima, K. et al. 1998, ApJL 499, L13
Matsushita, K., Ohashi, T., & Makishima, K. 2000, PASJ 52, 685
Matsushita, K., Finoguenov, A., Böhringer, H. 2003, A&A 401, 443
Mulchaey, J. S. & Zabludoff, A. I. 1998, ApJ 496, 73
Mushotzky R., Loewenstein M.et al. 1996, ApJ 466, 686
Nakazawa, K. 2001, PhD Thesis, the University of Tokyo
Nakazawa, K. et al. 1999, SPIE 376, 148
Ohashi, T. et al. 1996, PASJ 48, 157
Ota, N. & Mitsuda, K. 2002, ApJ 567, L23
Reisenegger, A., Miralda-Escude, J. & Waxman, E. 1996, ApJ 457, L11
Renzini, A. 1997, ApJ 488, 35
Rosner, R., Tucker, W. & Vaiana, G. 1978, ApJ 220, 643
Sarazin, C. L. 1988, X-ray Emissions from Clusters of Galaxies (Cambridge: Cambridge Univ. Press), p.152
Takahara, M. & Takahara, F. 1979, Prog. Theor. Phys. 62, 125
Tamura, T. et al. 1997, in X-ray Imaging and Spectroscopy of Cosmic Hot Plasmas, ed. F. Makino, K. Mitsuda (Universal Academy Press, Tokyo) p.127
Tamura, T., Makishima K. et al. 2000, ApJ 535, 602
Tanaka, Y., Inoue, H. & Holt, S. S. 1994, PASJ 46, L37
Xu, H., Ezawa, H., Fukazawa, Y. et al. 1997, PASJ 49, 9
Xu, H., Makishima, K. et al. 1998, ApJ 500, 738