Hard X-ray Emission from Groups of Galaxies
Detected with ASCA

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Clusters and groups of galaxies are one of the most energetic objects in the universe. We analyzed the ASCA data of near-by 18 groups of galaxies, and found that about half the sample show evidence for an excess hard emission, in addition to the \( \sim 1 \) keV thermal emission from the hot intra-group matter (IGM). We present the detailed analysis of HCG 62, which shows the most significant hard excess, as well as the results from the systematical analyses of other 17 groups. With these results, we for the first time study statistical properties of the hard excess X-rays in galaxy groups.

The hard component in HCG 62 is clearly extended; its radial profile is similar to or rather wider than that of the IGM. Its spectra are well fitted by a power-law with photon index \( \sim 2 \) or a thermal emission with temperature \( > 5.7 \) keV. The 2–10 keV luminosity of the hard component is derived as \( 4.2 \times 10^{41}h_{75}^{-2} \) erg s\(^{-1}\), which is \( \sim 20\% \) of the IGM luminosity in the 0.5–10 keV band. For the other groups, 9 out of 17 sample show evidence of a hard component, with the luminosity in the range \( 1 \sim 18 \times 10^{41}h_{75}^{-2} \) erg s\(^{-1}\), which is \( 10 \sim 40\% \) of that of the IGM. On the other hand, the remaining 8 groups do not exhibit statistically significant hard emission, with an upper limit of \( \sim 5\% \) of the IGM.

The hard X-rays suggest the existence of high energy particles widely distributed in the inter-galactic space. We searched many parameters for correlation with the strength of the hard X-rays, and found that most of the groups with significant hard excess emission host a few bright galaxies in their central regions, while those without hard emission predominantly host a single dominant galaxy. Using all these results, we derive constraints on the emission mechanisms proposed for the hard X-rays, and discuss possible acceleration mechanisms of the high energy particles.
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Chapter 1

INTRODUCTION

Clusters of galaxies are known as the largest gravitationally bound system in the universe. A cluster contains thousands of galaxies. It also contains thermal hot plasma (intra-cluster matter, ICM), which is observed as an extended X-ray source, as well as dark matter, which dominates the gravity source. They hold a large amount of gravitational energy, as much as $10^{64}$ erg, and are one of the most energetic objects among the universe.

Recently, non-thermal hard X-ray emission has been discovered from the Coma cluster by Beppo-SAX and RXTE satellites (Fusco-Femiano et al. 1999, Rephaeli et al. 1999). The emission is observed as a hard excess above the thermal ICM emission, appearing in energies above $\sim 30$ keV. Together with the diffuse radio halo detected in this cluster, the hard X-rays strongly suggest the existence of high energy particles widely distributed in the inter-galactic space.

The detection of the cluster hard X-rays has a great impact in two aspects. First, the acceleration mechanism itself has a potential to be the long sought origin of the "highest energy cosmic rays", the extremely energetic particles with energy $\sim 10^{20}$ eV arriving at the top of the earth's atmosphere. This is because galaxy clusters are the largest plasma source among the universe with a scale of $\sim 10^{24}$ cm, so that the high energy particles cannot escape from the region for a long time, and it has a relatively low density ($\sim 10^{-11}$ erg cm$^{-3}$), so that the energy dissipations of the particles are limited. Another issue is the non-thermal pressure associated with the high energy particles and magnetic fields. Because the cluster total mass estimates do not take these effects into account, the amount of the dark matter associated with clusters may increase if these non-thermal pressure components are properly considered. This has a great impact upon the current model of cosmology.

In clusters, the hard excess emission is detectable only above $\sim 30$ keV, below which
the strong ICM emission with a temperature of $kT = 5 \sim 10$ keV dominates the X-ray spectra. As the sensitivity of the hard X-ray detectors operating above $\sim 20$ keV is quite limited, currently the non-thermal X-rays are detected from only three clusters, including the Coma cluster (Fusco-Femiano et al. 1999, Rephaeli et al. 1999), the Abell 2256 cluster (Fusco-Femiano et al. 2000) and the Abell 2199 cluster (Kaastra et al. 1999).

Groups of galaxies have many properties similar to those of the clusters. In fact, the major difference between the two types of objects are only in their scale. A group of galaxies also contains a large amount of gravitational energy, as much as $10^{62}$ erg. On the other hand, the temperature of the hot plasma in a group is fairly low, typically $\sim 1$ keV. Thus, if a group hosts a non-thermal emission, it may be visible as a hard tail above $\sim 4$ keV. This is detectable with the current X-ray imaging instruments, such as those onboard the ASCA satellite. ASCA is equipped with X-ray mirror optics covering the energy range up to $\sim 10$ keV, and provides a high sensitivity and a good imaging capability that is currently unavailable above 10 keV. The GIS experiment onboard ASCA is characterized by its very low and stable background, and we believe that it currently provides the best tool for this study.

In this thesis, we present the observational evidence of excess hard X-ray emission from groups of galaxies obtained with ASCA. We have detected a significant hard excess emission from the HCG 62 group, as is already reported in a brief letter (Fukazawa Y., Nakazawa K. et al. 2001). Here, we perform detailed investigation of the significance and properties of the hard X-rays from HCG 62. In addition, we systematically analyze the ASCA data of other near-by 17 groups. We found about half of them host a significant hard X-rays, while the other half show little evidence for such emission. Utilizing these results, we study statistical properties of the group hard X-rays.

Throughout this thesis, we assume the Hubble constant to be $H_0 = 75h_{75} \frac{\text{Mpc}}{\text{km} \cdot \text{s}^{-1}}$. All the errors are listed in 90 % confidence level, unless otherwise noted.
Chapter 2

REVIEW

2.1 Clusters and Groups of Galaxies

2.1.1 What are clusters and groups of galaxies?

Clusters of galaxies have a scale of $L \sim 1 \text{ Mpc} (3 \times 10^{24} \text{ cm})$, each consisting of 50–1000 member galaxies (Fig.2.1a). A galaxy itself has a scale of $\sim 30 \text{ kpc}$ and contains $\sim 10^{10–11}$ stars. Clusters of galaxies are identified mainly on optical plates. They are called rich when they contain many (up to thousand) galaxies and called poor when they contain fewer (down to tens of) galaxies. Sometimes, an extremely luminous elliptical galaxy sits in the cluster center. They are called cD galaxy, and the cluster hosting it is called a cD cluster.

Abell and his colleagues cataloged about 5000 rich clusters (Abell 1958, Abell et al. 1989). These clusters are named as, e.g. Abell 1656 (A1656) and Abell S373 (AS373). Zwicke catalog (Zwicke et al. 1961-68) is also well known. For poor clusters, there are several catalogs, including the MKW catalog (Morgan et al. 1975) and AWM catalog (Albert et al. 1977).

Groups of galaxies consist of about ten galaxies, and have a scale of $L = 250 \sim 500 \text{ kpc}$ (Fig.2.1b). They are also mainly identified on optical plates. Hickson (1982) cataloged about 100 compact groups (Hickson’s Compact Groups; HCG), which form one of the best studied catalog of groups of galaxies. Another compact group catalog by Shakhbazyan and his colleges (Shakhbazyan’s Compact Groups of Galaxies; SCGG or SHK; Shakhbazyan 1973; Shakhbazyan, Petroyan 1974; Baier et al. 1974; Petroyan 1974, 1978; Baier and Tiersch 1975, 1976ab, 1978, 1979), as well as a group catalogue by Ramella and his colleges (RGH; 1995a,b), are also known. Groups are also named after its central brightest galaxy,
such as the NGC 5044 group, as well as the constellation name, such as the Pavo group. A group is called “compact” when there are several galaxies within a limited radius (see, e.g. Hickson 1982), and called “loose” when there are not.

2.1.2 Optical observations

The spatial distribution of galaxies in a cluster is empirically known to follow so called King model (King 1962),

$$N(R) = N_0 \left[1 + (R/R_{\text{core}})^2\right]^{-3/2}.$$  \hspace{1cm} (2.1)

Here, $R_{\text{core}}$ is the core radius of the cluster which is typically $\sim 250$ kpc, and $N_0$ is the central galaxy number density. Throughout this thesis, we denote the three dimensional radius $R$, and the projected radius $r$. The King model is an analytic approximation to the equation describing particle distribution in a self-gravitating hydrostatic isothermal system, although it is not valid for $R \gg R_{\text{core}}$ (see also § 2.2.1).

By measuring the redshifts of the member galaxies, we can derive the line-of-sight velocity dispersion, $\sigma_v$, of the cluster or group, which reflects the depth of the gravitational potential of the system. For rich clusters, this value ranges from 500 km s$^{-1}$ up to 1300 km s$^{-1}$. Combining $\sigma_v$ with the system size $L$, we can estimate the total gravitating mass of the cluster $M_{\text{tot}}$ as

$$M_{\text{tot}} \sim 3\sigma_v^2 \frac{L}{G},$$ \hspace{1cm} (2.2)

where $G$ is the gravitational constant. For example, the Coma cluster, a rich cluster with a velocity dispersion of $\sim 1000$ km s$^{-1}$, is shown by this method to have $M_{\text{tot}} \sim 1 \times 10^{15} M_\odot$ within 1 Mpc (e.g. Geller et al. 1999). Here, $M_\odot = 2 \times 10^{33}$ g is the solar mass. The value is more than an order of magnitude larger than that of the “visible mass”, i.e., the mass of the stellar components in galaxies estimated from their optical luminosities. This is so-called “missing mass” problem, which is now regarded as due to the existence of huge amount of dark matter as a major constituent of $M_{\text{tot}}$. The total kinetic energy of a cluster thus derived becomes $\frac{3}{2} M_{\text{total}} \times \sigma_v^2 \sim 10^{64}$ erg, which makes the cluster one of the most energetic objects in the universe.

In groups of galaxies, the velocity dispersion ranges from 100 km $^{-1}$ to 400 km $^{-1}$. They have $M_{\text{tot}} \sim$ several times $10^{13} M_\odot$ within $\sim 250$ kpc (e.g., Mulchaey et al. 1996), which is again dominated by the dark matter. Thus, the groups and clusters are similar in their physical states, and differs only in their scales. In other words, group of galaxies is a mini-sized cluster of galaxies. The kinetic energy of a group becomes $\sim 10^{61-62}$ erg, so that the groups are still among the most energetic objects in the universe.
Figure 2.1: (a) Optical image of the Coma cluster (1.5 × 1.5 Mpc scale), which is a rich, non-cD cluster. (b) The NGC 5044 group (0.5 × 0.5 Mpc scale), which is a poor, cD group.

2.1.3 X-ray observations

From the days of Uhuru, the first cosmic X-ray satellite launched in 1970, clusters of galaxy have been known as a strong X-ray emitters, with an X-ray luminosity of $L_X \sim 10^{44-45}$ erg s$^{-1}$. The X-ray emission is extended (Fig.2.2), so that there were two alternative explanations for its emission mechanism; inverse Compton (IC) of cosmic microwave background (CMB) photons by relativistic electrons (see § 2.3.3), and thermal bremsstrahlung from optically thin hot plasma (see § 2.2.2). Later, the detection of He-like Fe-K line emission (Mitchel et al. 1976) showed that the thermal explanation is correct; in fact the X-ray spectra of several brightest clusters were well fitted by a hot plasma emission model with a temperature of $3 \sim 10$ keV (Serlemitsos et al. 1977). These results indicate that clusters are filled with hot plasma, which is called intra-cluster medium (ICM). This has given a big surprise, because the presence of such a large amount of hot plasma had never been anticipated before. The ICM is considered to be confined by the gravitational potential of the cluster. This was justified by the fact that the galaxy velocity dispersion is generally consistent with the potential required to confine the ICM.

The X-ray study of clusters of galaxies has made a big progress with the Einstein observatory, the world’s first imaging X-ray mission launched in 1978. In addition to its high sensitivity, the observatory for the first time resolved the spatial distribution of the ICM of many clusters, and derived the total mass distribution in the cluster (e.g.,
Figure 2.2: The X-ray gray scale image of (a) the Coma cluster and (b) the NGC 5044 group. The images observed with the ROSAT PSPC (Position Sensitive Proportional Counter) are shown in the same scale as those in Fig.2.1. The image level is logarithmically spaced, by factors of 1.33.

Jones and Formann 1984). It was found that the ICM mass often exceeds that of the stellar component, while the total mass is about an order of magnitude larger than the sum of these two. The subsequent ROSAT mission, launched in 1990, with a better angular resolution and a higher sensitivity, has further advanced the X-ray imaging study of clusters. Furthermore, it has initiated the X-ray observation of groups of galaxies (e.g., Mulchaey et al. 1996), which had not been considered generally as X-ray emitters before. With ROSAT, it has become clear that groups host its own hot gas halo, called the intra-group medium (IGM), which is similar to the ICM of the cluster except its lower temperature, around 1 keV. The imaging instruments onboard the two satellites, however, are limited in the soft energy band, 0.2–4.5 keV for the former and 0.1–2.4 keV for the latter, and their spectroscopic resolving power was poor.

Spectroscopic studies of the cluster X-ray emission have been developed by satellites including OSO-8, HEAO-1, Tenma, EXOSAT, and Ginga. Although they lacked imaging capability, they had a wide energy pass-band, ranging from ~ 1 keV up to as high as ~ 30 keV, as well as moderate spectral resolution. From a number of clusters, they measured the spatially-integrated X-ray properties of ICM, such as the temperature and abundance of heavy elements, the latter determined mainly utilizing Fe-K line emission around ~ 6.7 keV.
The ASCA satellite, launched in 1993, is the first observatory to possess both the moderate imaging capability and the high spectroscopic resolving power over a wide energy band, ranging from 0.5 keV up to 10 keV. With ASCA, we have for the first time become able to measure accurately the spatial properties of the ICM temperature and metal abundances (e.g., Fukazawa et al. 2000, Markevitch 1998).

2.2 X-ray Properties of Clusters and Groups of Galaxies

In this section, we outline the basic physics underlying X-ray production in clusters and groups of galaxies, together with their observational results. We briefly summarize the general method of mass determination of the system using the X-ray data, and explain the mechanism of thermal emission from an optically thin hot gas. See Sarazin (1988) for details.

2.2.1 X-ray morphology and system mass determination

Hydrostatic equation of ICM hot gas

The typical value of the density, temperature and extent of the cluster ICM (as well as group IGM and elliptical galaxy ISM) are \( n_{\text{gas}} = 10^{-4} - 10^{-2} \, \text{cm}^{-3} \), \( T = 10^7 - 10^8 \, \text{K} \) and \( L = 0.3 - 3 \, \text{Mpc} \), respectively, while the age of a cluster is thought to be comparable to the Hubble time, \( \sim 10^{10} \, \text{yr} \). From these parameters, the mean free path of Coulomb collisions between ions and electron is given as \( 23 \left( \frac{T}{10^7 \, \text{K}} \right)^2 \left( \frac{n_{\text{gas}}}{10^{-5} \, \text{cm}^{-3}} \right) \, \text{kpc} \), which is much shorter than the cluster extent. Similarly the sound crossing time across the cluster is given as \( 6.6 \times 10^8 \left( \frac{T}{10^7 \, \text{K}} \right)^{-1/2} \left( \frac{R}{\text{Mpc}} \right) \, \text{yr} \) which is also much shorter than the cluster age. Therefore, the ICM is thought to be under hydrostatic equilibrium, satisfying the equation

\[
\nabla P_{\text{gas}} = -\mu m_p n_{\text{gas}} \nabla \phi
\]

Here \( P_{\text{gas}} \) is the ICM pressure, \( \phi \) is the gravitational potential, and \( \mu \sim 0.6 \) is the mean molecular weight of the ICM relative to the proton mass \( m_p \).

Although there are some clusters and groups showing irregular shape in their X-ray image, most of them have generally circular profiles (see Fig.2.1). Assuming a spherical symmetry, and substituting the ICM pressure by \( P_{\text{gas}} = n_{\text{gas}} kT \), where \( k \) is the Boltzmann
constant, equation 2.3 is re-written as
\[
\frac{kT(R)}{\mu m_p} \frac{d \ln [T(R)n_{\text{gas}}(R)]}{dR} = - \frac{d\phi(R)}{dR} .
\]  
(2.4)

Then, the total mass within a radius \( R \) is derived as
\[
M_{\text{tot}}(R) = - \frac{kT}{\mu m_p G} R \left( \frac{d \ln T}{d \ln R} + \frac{d \ln n_{\text{gas}}}{d \ln R} \right) .
\]  
(2.5)

Therefore, once the density distribution \( n_{\text{gas}}(R) \) and the temperature distribution \( T(R) \) of the ICM are known through X-ray observations, we can derive the total mass \( M_{\text{tot}}(R) \) of the system. Because we can also derive the ICM mass from \( n_{\text{gas}}(R) \), and the stellar mass from the optical luminosity of the member galaxies, we are able to construct the mass profiles of a cluster. In Fig.2.3, we show the mass profiles of the Fornax cluster, derived from the ASCA observations (Ikebe et al. 1996).

![Mass profile](image)

Figure 2.3: Integrated mass profile of total gravitating mass (solid lines), dark matter (dashed lines), X-ray emitting plasma (dot-dashed lines) and stellar component (dotted line). Three curves for the former three components show the little difference depending on the plasma modeling (see Ikebe et al 1996).

**Mass profiles**

As we have already mentioned in § 2.1.3, there are three mass components consisting a cluster; stars (= galaxies), ICM, and the dark matter. A contemporary consensus is that they have roughly a ratio of \( \sim 5:10:90 \) (e.g., Rous海底t al. 2000; see also Fig.2.3). Thus,
the majority of the mass is the dark matter, which may be considered as collision-less particles. For a self gravitating system consisting of such particles, hydrostatic equation under spherical symmetry can be written as

\[ \sigma_v(R)^2 \frac{d \ln \rho(R)}{dR} = - \frac{d \phi(R)}{dR} \quad . \]  

(2.6)

Here \( \sigma_v \) and \( \rho \) are the velocity dispersion and density of the particles, respectively. Combining this equation with the Poisson equation, \( \nabla^2 \phi = 4\pi G \rho \), King (1962) derived an analytic approximate solution, as already shown in equation 2.1.

By comparing equations 2.4 and 2.6 we obtain \( n_{gas} \propto \rho^\beta \), where \( \beta \) is the specific energy ratio between the gas and dark matter, given as

\[ \beta \equiv \frac{\mu m_p \sigma_v^2}{kT} = 0.726 \left( \frac{\sigma}{10^3 \text{kms}^{-1}} \right)^2 \left( \frac{T}{10^8 \text{K}} \right)^{-1} . \]  

(2.7)

When the ICM is isothermal, its density profile in a King potential is given as

\[ n_{gas}(R) = n_0 \left[ 1 + \left( \frac{R}{R_{core}} \right)^2 \right]^{-\frac{2}{3} \beta} . \]  

(2.8)

Thus, the parameter \( \beta \) also represents the steepness of the ICM distribution. This is known as a \( \beta \)-model (Cavaliere and Fusco-Femiano 1976).

The X-ray emissivity is expressed by \( n_{gas}^2 \Lambda(T,Z) \), where \( \Lambda \) is a function of temperature and metal abundance (see § 2.2.2). Therefore, assuming a uniform temperature and abundance we can calculate the surface brightness of the cluster X-ray emission by integrating this emissivity along the line-of-sight as

\[ S_B(r) = \int_{-\infty}^{+\infty} n_{gas}^2 \Lambda dl = S_0 \left[ 1 + \left( \frac{r}{R_{core}} \right)^2 \right]^{-3 \beta + \frac{3}{2}} . \]  

(2.9)

Here, \( r \) is the projected 2-dimensional radius. This formula is known to well reproduce the observed cluster surface brightness, except in the very central regions of some clusters (e.g., Jones and Forman 1984, Mohr et al. 1999; Fig. 2.4). Therefore, the \( \beta \)-model is generally used to parameterize the cluster mass distribution.

The central excess emission is generally associated with a cD galaxy (Jones and Forman 1984). In the excess region, there are frequently X-ray spectral evidence for cooler components. Together with short (~ \( 10^8 \) yr) cooling time (see next subsection) inferred in such a region, it has been interpreted as a signature of the cooling flow, i.e., ICM inflow driven by its radiative cooling (e.g. Fabian 1994). Alternative explanation for the phenomenon is that the central excess emission is simply due to the particular shape of the gravitational potential associated with the cD galaxy, and the cool component is the
interstellar medium (ISM) of the cD galaxy (e.g., Ikebe 1996, Matsushita et al. 1996, Makishima et al. 2001). In groups of galaxies, the excess emission coincident in position with the central bright elliptical galaxy is common (e.g. Mulchaey and Zabludoff 1998), which is also true of the X-ray brightest elliptical galaxies (e.g. Matsushita 1996).

Figure 2.4: Radial X-ray surface brightness profile of (a) the Abell 262 cluster and (b) the Abell 401 cluster. The former is fitted with a single \( \beta \)-model, while the latter is fitted by adding another \( \beta \)-model (2-\( \beta \)-model) to compensate for the central excess (Mohr et al. 1999). In the image, contour appears at factors of 2.5 in surface brightness, and the heavy contour corresponds to \( 4 \times 10^{-14} \) erg s\(^{-1}\) cm\(^{-2}\) arcmin\(^{-2}\).

Recent \( N \)-body simulation on the formation of clusters in a cold dark matter (CDM) universe has shown that, instead of a King-like profile with a central core, a profile with central cusp is formed (Navarro et al. 1996, 1997; Fukushige et al. 1997; Moore et al. 1998: hereafter NFW profile); it is represented as

\[
\rho(R) = \frac{\rho_0}{(R/R_s)(1 + R/R_s)^2}
\]

(2.10)

where \( \rho_0 \) is a normalization parameter, and \( r_s \) is a scale parameter. However, there are some observational results which cannot be explained by the NFW potential (e.g. Ikebe et al. 1996). Thus, the actual profile of the dark matter density is still under discussion. The gas density profile in the NFW potential calculated by Makino et al. (1998) was shown to be very similar to the \( \beta \)-model profile. Thus, the \( \beta \)-model still works as a reasonable description of a gas density profile.
All the above calculations assume that the gas pressure is the only force sustaining the hot gas against the gravitational potential. However, there may exist non-thermal pressures, originating from the magnetic field, and/or a population of high energy particles distributed in the ICM. Generally, their contributions are assumed to be small compared to the gas pressure, though we must carefully examine its possibility, which is one of the aim of this thesis.

Recent observations with ROSAT and ASCA have shown the existence of temperature and morphology sub-structures in some clusters. This is thought as an evidence of ongoing merger process. Because a galaxy group falling into a cluster has a kinematic energy of $\sim 10^{62-63}$ erg, the merger process is important in the ICM heating and, possibly, particle acceleration.

### 2.2.2 X-ray spectra from the ICM

The ICM (including the IGM and ISM) is an optically thin hot plasma, and its main radiation mechanism is thermal bremsstrahlung (free-free emission). The emissivity is given as

$$
eff^f(\nu) = 6.8 \times 10^{-38} Z^2 n_e n_i T^{-1/2} e^{-\nu/\kappa T} \bar{g}_{ff} \quad [\text{ergs}^{-1}\text{cm}^{-3}\text{Hz}^{-1}], \tag{2.11}$$

where $\nu$ is the frequency of the photons emitted, $n_e$ and $n_i$ are the densities of electron and ion, respectively, $Z$ is the effective charge number of the ion, and $T$ is the temperature of the plasma. The velocity averaged Gaunt factor $\bar{g}_{ff}$ has a value of $\sim 1$, and weakly dependent on $\nu$ and $T$ (Rybicki and Lightman 1979).

In addition to the free-free continuum, heavy elements in the ICM produce line emissions. When the ICM temperature is lower than $\sim 2$ keV, these lines carry as high luminosity as the thermal bremsstrahlung continuum. The emission line spectra from a hot plasma in an ionization equilibrium have been calculated by various authors, e.g. Raymond and Smith (1977), Masai (1984), Kaastra and Mewe (1993) and so on. Their predictions are consistent to one another, as well as the observed spectra, as least as to K-shell emission lines, such as those at 6.6–6.9 keV from Fe, and 1.8–2.0 keV from Si. However, the ionization and recombination rates of L-shell electrons are not easily calculated, and the results differ considerably among the authors (e.g. Masai 1997). In practice, this problem is most prominent for the Fe-L line complex observed in the 0.7–1.5 keV region (Arimoto et al. 1997, see Fig.2.5a). We have to be careful about this problem when fitting the observed spectra with these models. Examples of the calculated
model spectra are shown in Fig.2.5, and those from actual clusters and groups observed by ASCA are shown in Fig.2.6, together with the best fit thermal model.

(a) 1 keV Plasma  (b) 4 keV Plasma

![Graphs showing 1 keV and 4 keV plasma](image)

Figure 2.5: Optically thin thermal emission model from hot plasma with metal abundances of one solar value (Mewe et al. 1985, 1986; Kaasra et al. 1992, Liedahl et al. 1995; black lines), at a temperature of (a) 1 keV and (b) 4 keV. In panel (a), we also plot the model spectrum from other emission code (Raymond and Smith 1977), which has the same parameteres, except the normalization, to show the difference among the models.

The total volume emissivity of a plasma, including continuum and line emissions and integrated over whole frequency, is expressed as

$$\epsilon = n_{\text{gas}}^2 \Lambda(T, Z) \quad \text{[erg s}^{-1} \text{ cm}^{-3}]$$

Here $\Lambda(T, Z)$ is called the cooling function and $Z$ represents the heavy element abundances. From this equation, the cooling time of a plasma is derived as $t_{\text{cool}} = n_{\text{gas}} kT / n_{\text{gas}}^2 \Lambda(T, Z)$. When we consider only the thermal bremsstrahlung continuum, it becomes

$$t_{\text{cool}} = 8.5 \times 10^{10} \left( \frac{n_{\text{gas}}}{10^{-3} \text{cm}^{-3}} \right) \left( \frac{T}{10^8 \text{K}} \right) \text{ [yr]}$$

which is longer than the cluster age for most cases.

Before detected by the X-ray detectors in orbit, photons emitted from a cluster travel along the vast universe. Thus, it is red-shifted by the Hubble’s law, and suffers absorption from materials along its journey. The latter is mainly due to the gas and dust of our Galaxy, which can be estimated from radio observations (e.g. Dicky and Lockmann 1990).

In calculating the emission models, the abundances of heavy elements ($Z$) must be specified. They are usually defined as a ratio to so-called solar abundances ($Z_{\odot}$). In this
Figure 2.6: X-ray spectra from (a) the NGC 5044 group (this thesis) and (b) the Abell 2199 cluster (Fukazawa 1996), observed with ASCA. Data from the GIS and SIS detectors are presented with crosses. Solid histograms are the best fit single temperature thermal emission models, with (a) $kT = 1.02$ keV and (b) 4.1 keV. Both spectra include the instrumental responses.

Figure 2.7: The Fe abundance of the ICM of various clusters and groups, plotted as a function of the ICM temperature. The data are derived from the spectra obtained with ASCA. X-ray emission from the cluster central regions are excluded (Fukazawa 1997).
thesis, we use the solar abundances given by Anders and Grevesse (1989), listed in Table 2.1. The metal abundances of ICM and IGM, derived from the spectral fitting, generally range $Z = 0.1 \sim 0.5 \ Z_\odot$, which are typically $\sim 0.3 \ Z_\odot$ (e.g. Fukazawa 1997; Fig.2.7).

Table 2.1: Definitions of the solar abundances by number, employed in the present thesis

<table>
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<tr>
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<tr>
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<td>O</td>
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<tr>
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<td>Cl</td>
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</tr>
<tr>
<td>Ni</td>
<td>1.78e-6</td>
</tr>
</tbody>
</table>


2.2.3 Correlations between the observed parameters

There are several correlations in the X-ray, optical and radio properties of clusters, groups and elliptical galaxies. Some are theoretically predicted, while others are empirical (e.g. Sarazin 1988). Among them, we here review a few of the highest importance.

$kT - L_X$ relation

As exemplified by Fig.2.8, a clear correlation has been observed between the temperature of the ICM and the X-ray luminosity (e.g., Mushotzky 1984; David et al 1993; Markevitch 1998; Fukazawa 1997). This can be expressed as

$$L_X = (kT)^\alpha,$$

with $\alpha \sim 3$. The intrinsic scatter in luminosity is very large, factor of $\sim 10$ for the same temperature. This is partly due to the central excess emission, and the scatter decreases by eliminating the contribution from this region (Markevitch 1998). By introducing another parameter, the central gas density derived after excluding the central excess component, Fujita and Takahara (1999) found that clusters of galaxy do form a two parameter family, which is called the X-ray fundamental plane of clusters. They showed that the $kT - L_X$ plane is slightly offset from the plane, which causes the scatter. From the $kT - L_X$ relation, $L_X \sim 10^{41-42}$ erg s$^{-1}$ is expected for a galaxy group with $kT = 1$ keV.
Figure 2.8: $kT - L_X$ relation of cluster of galaxies obtained with ASCA. The X-ray luminosity is measured in 0.5–10 keV (Fukazawa 1996).

$kT - \sigma$ relation

Galaxies in a cluster can be treated as a collision-less particles. Therefore, the velocity dispersion ($\sigma_v$) of the member galaxies of a cluster should be the same as that of the dark matter. As a result, equation 2.7 predicts a strong correlation between the galaxy velocity dispersion $\sigma_v$ and the ICM temperature, so that the ratio

$$\beta_{\text{spec}} = \frac{\mu m_p \sigma_v^2}{kT_{\text{gas}}} ,$$

becomes close to unity. As shown in Fig.2.9, this relation is observationally confirmed. For a galaxy group with $kT = 1$ keV, $\sigma_v = 400$ km s$^{-1}$ is predicted.

2.2.4 X-ray emission from discrete sources

Apart from the diffuse ICM emission, there are X-rays from discrete sources contained in the cluster. One of them is the emission from active galactic nuclei (AGNs) of the individual member galaxies of the cluster. The other is compact stellar-mass discrete sources, accreting mass from their companions. Among them, the most abundant and luminous population is so called low mass X-ray binaries (LMXBs), consisting of low-mass stars and weakly-magnetized neutron stars. When these X-ray sources are not negligible compared with the ICM, we must be careful in fitting the spectra.
Figure 2.9: $kT - \sigma$ relation of clusters and groups of galaxies (Xue and Wu 2000). Data from 66 groups and 274 clusters drawn from the literature are shown. Solid line indicates the relation, $\mu m_p \sigma_{Vr}^2 = kT_{gas}$.

Figure 2.10: The X-ray luminosity of several AGN as compared with the radio luminosity of core region (Matsumoto et al. 2001).
An AGN is considered to be a huge black-hole with a mass of $\sim 10^{6-8} M_\odot$, sitting in the center of some, if not all, galaxies. Matters falling into the black-hole emit significant fraction of their gravitational energy in various wave-bands, from radio to $\gamma$-rays. We plot the X-ray luminosity plotted with the radio luminosity of the core region of the AGN in Fig.2.10. They are one of the brightest X-ray sources in the sky, sometimes up to a luminosity of $\sim 10^{45}$ erg s$^{-1}$. Their spectra are rather hard, and can be generally represented with a power law model with $\Gamma = 1 \sim 2$. Because an AGN is associated with a galaxy, most of the X-ray bright AGNs can be identified as point-like X-ray sources, coincident in position with galaxies in the optical image. AGNs are also identified by radio observations and optical spectroscopy, which are generally cataloged.

![Graph](image)

Figure 2.11: X-ray luminosity of the galaxy as compared with the optical B-band luminosity. (a) Einstein results by Canizares et al. (1987). X-ray luminosity is in the 0.5–4.5 keV band. Long-dashed line represents the LMXB component estimated from the early-type spiral galaxies and their bulge emission. (b) ASCA by Matsushita (1998). X-ray luminosity is in the 0.5–10 keV band. Solid line is the same as the long-dashed line in panel (a), converted for the energy band. Filled circles are the luminosity of the hard component in the X-ray spectra of elliptical galaxies, while the open circles are those of the ICM component. Double circles indicate the galaxies possibly hosting an AGN.

The X-ray spectra of LMXB are known to be approximated by a $\sim 10$ keV thermal
bremsstrahlung emission model (e.g. Makishima et al. 1989, Matsushita et al. 1994, Matsumoto et al. 1997). Although the X-ray luminosity of the individual LMXBs are fairly low ($\sim 10^{36-37}$ erg s$^{-1}$), their integrated luminosity within a galaxy is as much as $\sim 10^{40}$ erg s$^{-1}$. The latter luminosity is considered to be proportional to its optical luminosity, since the number of X-ray binaries in a galaxy should be roughly proportional to its total stellar content. By analyzing the X-ray luminosity of early-type spirals observed with Einstein, Canizares et al. (1987) found a linear relation of $L_X = 10^{-3.82}L_B$, between the optical B-band luminosity and the X-ray luminosity. Here, we converted the latter value from the original 0.5–4.5 keV band to the 0.5–10 keV band, assuming a 10 keV bremsstrahlung emission model. Later, Matsushita (1998) analyzed 27 elliptical galaxies observed with ASCA, and found that there is a hard emission distinct from the ISM emission, which can be attributed to LMXBs. By fitting the former component with a $kT = 10$ keV bremsstrahlung model, they confirmed a similar relation of $L_X = 10^{-3.81}L_B$. This can be converted to the 2–10 keV luminosity as,

$$L_X(2 - 10 \text{ keV}) = 4.1 \times 10^{39}(L_B/10^{10}L_\odot) \text{ [erg s}^{-1}] . \quad (2.16)$$
2.3 Theoretical Backgrounds of High Energy Electrons in Diffuse Plasma

2.3.1 Power law population of high energy electrons

As we show in § 2.4 and 2.5, there are observational pieces of evidence for high energy electrons in celestial diffuse plasma sources. They show non-thermal emission through various processes, such as synchrotron, inverse Compton and bremsstrahlung mechanisms. In this section, we briefly review theories of these emissions and estimate life times of high energy particles, (in practice, electrons).

High energy particles are considered to be produced via shock acceleration. One possible scenario is the 1st order Fermi acceleration in various shocks in cosmic plasma. Another is the 2nd order Fermi acceleration by randomly moving scatterers, such as magneto-hydro-dynamical turbulence. There are various energy sources powering these process, including supernova (SN), active galactic nuclei (AGN), galaxy motion through the plasma, merging events between galaxies, and those between groups and clusters.

Relativistic particles thus generated exhibit a power-law like energy distribution, in the form of

$$ N(\gamma) = N_0 \gamma^{-\mu} \quad . \quad (2.17) $$

Here, $\gamma$ is the Lorentz factor of the electrons, so that their energy is $\gamma m_e c^2$, $N(\gamma)$ is a number of electrons within energy range of $\gamma \sim \gamma + d\gamma$, and $\mu$ is the power-law index. Power-law energy distribution of high energy particles are observed in the cosmic rays reaching at the top of earth’s atmosphere, and also at the geomagnetic shock-front of the solar wind.

2.3.2 Synchrotron emission

The relativistic electrons interact with magnetic field and produces a synchrotron emission. When an electron with energy $\gamma m_e c^2$ moves across a magnetic field $B$, it emits a synchrotron photon with a frequency of

$$ \nu_{\text{sync}} = 4.2 \left( \frac{B}{\mu \text{G}} \right) \gamma^2 \quad [\text{Hz}] \quad . \quad (2.18) $$

The energy loss function due to this emission is then

$$ b_{\text{sync}} = \frac{4}{3} \frac{\sigma_T}{m_e c} \gamma^2 U_B \quad [\text{s}^{-1}] \quad . \quad (2.19) $$
Here, $\sigma_T = 6.65 \times 10^{-25}$ cm$^{-2}$ is the Thomson cross section, $m_e = 9.1 \times 10^{-28}$ g is the electron mass, $c = 3 \times 10^{10}$ cm s$^{-1}$ is the light speed, and $U_B = \frac{1}{8\pi} B^2$ erg cm$^{-3}$ is the energy density of the magnetic field (Sarazin 1999).

Assuming a power-law distribution of electrons given by equation 2.17, the spectrum of the synchrotron emission becomes also a power-law, with energy index of $\alpha = (\mu - 1)/2$. It is represented as

$$\frac{dL_{\text{sync}}}{d\nu} = \frac{\sqrt{3} e^3 B N_0 \Gamma\left(\frac{3\mu+10}{12}\right) \Gamma\left(\frac{3\mu+1}{12}\right)}{m_e c^2 (\mu + 1)} \left(\frac{3eB}{2\pi m_e c \nu_{\text{sync}}}\right)^\alpha,$$  

(2.20)

where $e = 4.8 \times 10^{-10}$ is the electron charge in cgs (gauss) unit, and $\Gamma$ is the gamma function (Rybicki and Lightman 1979).

### 2.3.3 Inverse Compton (IC) emission

The relativistic electrons also scatters off low energy photons via inverse-compton (IC) scattering. The mechanism is similar to the synchrotron process, and the formulae describing the IC process also resemble those of it. When an electron with energy $\gamma m_e c^2$ scatters off a photon with energy $h\nu_{\text{seed}}$, the frequency of the resulting IC photon is given as

$$\nu_{\text{IC}} = \frac{4}{3} \gamma^2 \nu_{\text{seed}} \text{ [Hz]} \quad ,$$  

(2.21)

for the energy region of $h\nu_{\text{IC}} \ll \gamma m_e c^2$. Here, $h$ is the Planck constant. The energy loss function due to this emission is given as

$$b_{\text{IC}} = \frac{4}{3} \frac{\sigma_T}{m_e c^2} \gamma^2 U_{\text{seed}} \text{ [s$^{-1}$]} \quad ,$$  

(2.22)

where $U_{\text{seed}}$ is the energy density of the seed photons.

The low energy photons that is present everywhere and dominates the overall photon density in the universe is the cosmic microwave background radiation (CMB), a black body radiation with $T_{\text{CMB}} = 2.73$ K. We therefore take it as the seed photons. By equation 2.17, the spectrum of the IC emission again becomes a power-law, with energy index of $\alpha = (\mu - 1)/2$, the same as that of the synchrotron emission. The spectrum is represented as

$$\frac{dL_{\text{IC}}}{d\nu} = \frac{3\pi \sigma_{\text{rms}} T_{\text{CMB}}}{h^2 c^2} b(\mu) N_0 (kT_{\text{CMB}})^3 \left(kT_{\text{CMB}}\right)^\alpha,$$  

(2.23)

where $b(\mu) = \frac{2^{\mu+5} (\mu^2+4\mu+11) \Gamma\left(\frac{\mu+5}{3}\right) (\zeta(\mu+5))}{(\mu+3)^2 (\mu+1) (\mu+5)}$, and $\zeta$ is the Riemann zeta function (Sarazin 1999).

From above equations, the total luminosity ratio of the synchrotron and IC emissions is simply given as

$$\frac{L_{\text{IC}}}{L_{\text{sync}}} = \frac{U_{\text{CMB}}}{U_B} \quad .$$  

(2.24)
Because the CMB energy density \( U_{\text{CMB}} \) is known, we can obtain \( U_B \), and hence the cluster averaged magnetic field strength using only the observables.

### 2.3.4 Non-thermal bremsstrahlung emission

The above two emissions are from the relativistic electrons. An alternative mechanism for the production of non-thermal X-rays is the bremsstrahlung from suprathermal population of electrons, colliding with low energy (mostly thermal) plasma (e.g. Ensslin et al. 1998, Sarazin and Kempner 2000). Following Sarazin and Kempner (2000), we introduce a power-law momentum distribution for these electrons. We define \( N(p)dp \) to be the number of electrons with momenta in the range \( P \) to \( P + dP \) as,

\[
N(p) = N_0 p^{-\mu} .
\]

(2.25)

Here, \( p \equiv P/m_e c \) is the normalized momentum and \( \mu \) is the power-law index which becomes the same as that used in equation 2.17 at the relativistic limit.

In the non-relativistic limit, the Bethe-Heitler bremsstrahlung cross section (Heitler 1954) is

\[
\frac{d\sigma(p, \epsilon, Z)}{d\epsilon} = \frac{32\pi}{3} \frac{e^6}{m_e^2 c^4 h} \frac{Z^2}{\epsilon^3} \ln \left( \frac{p_f + p_i}{p_f - p_i} \right) ,
\]

(2.26)

where \( p_i \) and \( p_f \) is the initial and final values of the normalized electron momentum, \( Z \) is the atomic number of ions, and \( \epsilon \) is the produced photon energy in erg.

From equation 2.26, the non-thermal bremsstrahlung emission from electrons with a power-law momentum distribution (equation 2.25) is calculated as

\[
\frac{dL_e}{d\epsilon} = \frac{32\pi^{3/2}}{3} \frac{e^6}{m_e c^4 h} \frac{\Gamma\left(\frac{n}{2}\right)}{\mu \Gamma\left(\frac{\mu+1}{2}\right)} \left( \sum n_e Z^2 \right) N_0 \left( \frac{m_e c}{2\epsilon} \right)^{\mu/2} .
\]

(2.27)

By comparing the prediction from this formula with a spectrum calculated by fully including the trans-relativistic and relativistic effects, Sarazin et al. (2000) found that the formula is in good agreement when \( \mu \sim 4 \), and shows a short-fall of about a factor of 2 for \( 2 < \mu < 3 \). Thus, equation 2.27 provides a good approximation for the non-thermal bremsstrahlung emission.

In the relativistic region, the energy loss function of an electron with energy \( \gamma m_e c^2 \) due to the bremsstrahlung process is approximately given as (e.g. Blumenthal and Gould 1970)

\[
b_{\text{brems}}(\gamma) \sim 1.51 \times 10^{-26} n_e \gamma |\ln(\gamma) + 0.36| \quad [\text{s}^{-1}] ,
\]

(2.28)

including the electron-ion and electron-electron bremsstrahlung (Sarazin 1999).
2.3.5 Cooling times

High energy electrons lose their energies by interactions with fields and matters in the plasma, including the three channels listed above. Here we again focus on the relativistic case, and present the cooling time defined from these interactions.

One of the other major cooling mechanisms is the Coulomb losses due to collisions with thermal electrons, which is approximately given as (e.g. Rephaeli 1979)

\[ b_{\text{Coulomb}}(\gamma) \sim 1.2 \times 10^{-12} n_e \left[ 1.0 + \frac{\ln(\gamma/n_e)}{75} \right] \quad [\text{s}^{-1}] \quad , \quad (2.29) \]

Combining equations 2.19, 2.22, 2.29 and 2.28, we obtain the cumulative energy loss function as

\[ b(\gamma) = b_{\text{sync}} + b_{\text{IC}} + b_{\text{Coulomb}} + b_{\text{brems}} \quad [\text{s}^{-1}] \quad . \quad (2.30) \]

In Fig.2.12 we plot the individual components of this equation. The cooling time is then given as \( \tau_{\text{cool}} = \gamma / b(\gamma) \), which is also shown in the figure. Thus, the electrons with \( \gamma = 100 \sim 300 \) have the longest life time of \( \sim 10^9 \) yr.

![Diagram](image)

Figure 2.12: The energy loss function in condition of (a) \( n_e = 1 \times 10^{-3} \) cm\(^{-3}\) and \( B = 1 \mu\)G, and (b) \( n_e = 0.1 \times 10^{-3} \) cm\(^{-3}\) and \( B = 0.1 \mu\)G. Dotted lines indicate the cooling time of \( 10^8 \) yr and \( 10^9 \) yr, respectively.

2.4 Non-thermal Electrons in Clusters of Galaxies

So far, we have briefly reviewed the X-ray properties of clusters and groups of galaxies, the latter being the “theater” of this thesis (§ 2.2). From now on, we present observational
evidence for the high energy particles distributed in diffuse plasma, which is the “target” of this thesis. We deal with clusters of galaxies in this section, and other objects, such as supernova remnants (SNR), in the next section.

2.4.1 Cluster radio halos

From the radio observations, diffuse emission associated with some clusters has been detected; so-called radio halos and relics. The source is called a halo when it is located at the cluster center, and called a relic when located at the cluster peripheries. They have a power-law like spectra with steep energy index ($\alpha \sim 1$). This suggests that they are a synchrotron emission by relativistic electrons with a power law energy distribution, interacting with intra-cluster magnetic field of $\sim \mu$G. Thus, the radio halo and relic provide direct evidence for the existence of such population of electrons, as well as a magnetic field, distributed cluster-wide in the ICM.

Radio halos and relics have been thought to be a rare phenomenon. Their low surface brightness makes their detection difficult, and there had been only about ten objects known (Feretti and Giovannini 1996). Recently, their number is increasing (as much as $\sim 40$), due to improvements in the instrumental capability (e.g. Sarazin 2000), although it is not yet a popular phenomenon among clusters.

The most famous radio halo is Coma-C, associated with the Coma cluster. As shown in Fig.2.13 and 2.14, the halo shows a regular shape with a scale of $\sim 1$ Mpc, as extended as the X-ray emission (e.g. Deiss et al. 1997). It has a flux of $\sim 600$ Jy at 1.4 GHz, and is detected in the wave-band ranging from 30.9 MHz to 2.7 GHz. Here, $1$ Jy $= 1 \times 10^{-23}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$. It has a power-law like spectra with a steep energy index of $\alpha \sim 1.3$, and the total luminosity in 10 MHz to 10 GHz is $6.1 \times 10^{40}$ erg s$^{-1}$ (Feretti and Giovannini 1996).

Currently, about ten clusters are known to host a halo, including Coma, A2256, and A2319. We list them in Table 2.2. All of them are massive rich clusters with a high temperature ($kT > 7$ keV), and a high X-ray luminosity ($L_X > 5 \times 10^{44}$ erg s$^{-1}$). There energy index of the radio spectra is 1 $\sim$ 2. In the lower frequency ($\sim 100$ MHz), some halos show evidence of spectral hardening, such that $\alpha$ reaches $\sim 1$. This phenomena may suggesting the aging effect of the electrons with higher energies. No polarized flux has been detected so far in radio halos, with an upper limit of $\sim 10\%$.

Apart from its location, relics has properties generally similar to those of halos; a steep spectra, a large scale order on $\sim 100$ kpc, and low surface brightness. In addition,
Table 2.2: Observed properties of cluster radio halos (Feretti and Giovannini 1996, Liang 1999).

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<th>Size (kpc)</th>
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<th>$P_{\text{tot}}^{(2)}$ (erg s$^{-1}$)</th>
<th>$\alpha^{(4)}$</th>
</tr>
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<tbody>
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<td>Coma</td>
<td>550</td>
<td>$3.2 \times 10^{30}$</td>
<td>$6.1 \times 10^{40}$</td>
<td>1.34</td>
</tr>
<tr>
<td>A2163</td>
<td>–</td>
<td>$1.8 \times 10^{32}$</td>
<td>$3 \times 10^{41}$</td>
<td>–</td>
</tr>
<tr>
<td>A2218</td>
<td>250</td>
<td>$7.9 \times 10^{29}$</td>
<td>$9.0 \times 10^{39}$</td>
<td>1.1</td>
</tr>
<tr>
<td>A2256</td>
<td>700</td>
<td>$1.2 \times 10^{30}$</td>
<td>$1.6 \times 10^{41}$</td>
<td>&gt; 1.5</td>
</tr>
<tr>
<td>A2319</td>
<td>660</td>
<td>$5.1 \times 10^{30}$</td>
<td>$9.2 \times 10^{40}$</td>
<td>1.3</td>
</tr>
</tbody>
</table>

(1) Radio flux in 1.4 GHz.
(2) Radio luminosity in the range of 10 MHz – 10 GHz.
(3) Energy index of radio spectra.

Table 2.3: Observed properties of cluster radio relics (Feretti and Giovannini 1996). Columns are similar to those of Table 2.2.

<table>
<thead>
<tr>
<th>name</th>
<th>cluster</th>
<th>Size (kpc)</th>
<th>$P_{1.4}$ (erg Hz$^{-1}$)</th>
<th>$P_{\text{tot}}$ (erg s$^{-1}$)</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0038–096</td>
<td>A85</td>
<td>200</td>
<td>$5.1 \times 10^{30}$</td>
<td>$1.6 \times 10^{41}$</td>
<td>&gt; 1.5</td>
</tr>
<tr>
<td>0917+75</td>
<td>A786</td>
<td>780</td>
<td>$2.0 \times 10^{31}$</td>
<td>$1.7 \times 10^{41}$</td>
<td>1.34</td>
</tr>
<tr>
<td>1253+275</td>
<td>Coma</td>
<td>580</td>
<td>$1.7 \times 10^{30}$</td>
<td>$2.0 \times 10^{40}$</td>
<td>1.1</td>
</tr>
<tr>
<td>Coma Bridge</td>
<td>Coma</td>
<td>970</td>
<td>$4.9 \times 10^{29}$</td>
<td>$1.6 \times 10^{40}$</td>
<td>1.5</td>
</tr>
<tr>
<td>1401–33</td>
<td>AS753</td>
<td>220</td>
<td>$1.0 \times 10^{30}$</td>
<td>$2.5 \times 10^{40}$</td>
<td>1.4</td>
</tr>
<tr>
<td>2006–56</td>
<td>A3667</td>
<td>870</td>
<td>$2.6 \times 10^{31}$</td>
<td>$3.7 \times 10^{41}$</td>
<td>1.2</td>
</tr>
</tbody>
</table>
relics are sometimes highly polarized, up to \( \sim 30\% \). They are also detected in about ten clusters (Table 2.3), including A85, A1656 and A3667, which generally show evidence for on-going merger event. There are also several clusters hosting both a halo and relic(s), such as the Coma cluster (e.g. Deiss 1999).

Figure 2.13: (a) A contour image of the radio halo, Coma-C, at 1.4 GHz. The width of the image corresponds to \( \sim 3.2 h^{-1}_{75} \) Mpc. Point sources are subtracted. In the bottom right, there is a relic \((1253 + 275)\), and another relic (Coma Bridge) is also visible between Coma-C and \(1253 + 275\) (Deiss et al. 1997). Contours are 10 mJy beam\(^{-1}\) apart, where the dashed one represents the zero level. (b) A gray scale image of relics in A3667 at 843 MHz, superposed on the X-ray contour image from ROSAT (Röttgering et al. 1997). The width of the image corresponds to \( \sim 2.8 h^{-1}_{75} \) Mpc. X-ray contours are set at 2,8,18,32,50,72,98,128,162,200 and 242 times the background noise.

### 2.4.2 Hard X-ray emission

The relativistic electrons, inferred from the radio halo and relics, are expected to produce IC emission with a power-law spectra, scattering off the CMB photons (§ 2.3.3). Because the ICM thermal emission rapidly decreases above its temperature, the IC emission would be observed as a hard excess emission in X-ray spectra. Accordingly, extensive searches for the expected hard excess emission were conducted with HEAO-A1 (Rephaeli et al. 1987), OSSE (Rephaeli et al. 1994) and so on, all yielding only upper limits.

Recently the BeppoSAX and RXTE satellites with their superior sensitivity in the hard X-ray band above \( \sim 10 \) keV, have detected the excess hard emission from the Coma
Figure 2.14: Radio properties of Coma-C (Deiss et al. 1997). (a) Azimuthally averaged surface brightness profile from Fig.2.13a (solid curve). Dotted line represents the surface brightness of the X-ray emission. (b) Integrated flux density spectrum.

Figure 2.15: X-ray spectra of the Coma cluster observed with BeppoSAX (Fusco-Femiano et al. 1999). Combined spectra from the HPGSPC (High Pressure Gas Scintillator Proportional Counter) and PDS (Phoswich Detection System) detectors are fitted with a sum of a 8.5 keV thermal emission and a power law with a photon index of $\Gamma = 1.57$. 

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cluster (Fusco-Femiano et al. 1999, Rephaeli et al. 1999). The spectrum observed with SAX is shown in Fig.2.15. It clearly requires an excess hard component, and fitted well by a sum of a 8.5 keV thermal component and a power law with a photon index of $\Gamma = 1.6 \pm 0.9$ (energy index $\alpha = \Gamma - 1 = 0.6 \pm 0.9$), which is consistent with the radio observations (see Table 2.2). When the latter component is replaced with a thermal emission, a temperature higher than 40 keV is required. The 20–80 keV luminosity of the excess hard component is $5 \times 10^{43} h_{75}^{-2}$ erg s$^{-1}$, which is $\sim 10\%$ of the 2–10 keV luminosity of the ICM component.

If the observed hard X-ray emission is indeed the long-sought IC emission, we can obtain a cluster averaged magnetic field strength of $\sim 0.14 \mu G$, by combining equations 2.20 and 2.23. This value, however, seems to contradict with those derived from Faraday rotation measurements in radio band, which suggest $B = 1 \sim 10 \mu G$ (e.g. Kim 1990). Fusco-Femiano et al. (1999) suggest that this problem may be solved considering the positional difference in the magnetic field, in such a way that regions threaded by strong magnetic flux tubes are devoid of relativistic electrons.

If the IC interpretation works, the non-thermal energy density of the relativistic electrons and the cluster magnetic field are estimated as $\sim 7 \times 10^{-14}$ erg cm$^{-3}$ and $\sim 8 \times 10^{-16}$ erg cm$^{-3}$, respectively; they are small compared to the ICM energy density of $2 \times 10^{-11} \left( \frac{n_{\text{gas}}}{10^{-10} \text{cm}^{-3}} \right)$ erg cm$^{-3}$ (Fusco-Femiano 1999).

There also are different interpretations of the observed hard X-rays, including in particular the non-thermal bremsstrahlung emission from suprathermal electrons in the ICM (see § 2.3.4). As the populations of the electrons emitting the hard X-ray emission and radio synchrotron emission are different in this model, the derived magnetic field value can be regarded as a lower limit; we can thus avoid the discrepancy with the radio measurement.

Currently, there are only 3 detections of non-thermal emission; the Coma cluster, A2256 cluster and A2199 cluster. Parameters of their non-thermal components are listed in Table 2.4. The BeppoSAX spectra of A2256 show a clear excess hard emission in the PDS spectra above $\sim 20$ keV. The joint MECS (medium energy counter system) and PDS (phoswitch detector system) spectra are fitted with a sum of a thermal component with $kT = 6.9^{+0.45}_{-0.35}$ and a power-law with $\Gamma = 1.3 \sim 2.7$ (Fusco-Femiano et al. 2000). In the A2199 cluster, however, the hard excess is not positively detected in the PDS energy band ($> 20$ keV). Kaasstra et al. (1999) carefully fitted a thermal emission model to the broad band extreme ultra violet (EUV) and X-ray spectra of A2199, obtained from EUVE, ROSAT and SAX, ranging from $\sim 0.1$ keV up to $\sim 50$ keV. They found soft and hard
excess from the cluster outer regions, which is interpreted as a power-law with $\Gamma \sim 1.8$.

Together with the radio halo observations, these results are strong evidence that there is a population of high energy electrons in the ICM. However, as we have mentioned in §1, the limited number of clusters with detected hard excess and lack of imaging capabilities in these hard X-ray experiments make it difficult to understand the nature of these non-thermal emissions.

Table 2.4: Observed properties of cluster hard X-ray emission.

<table>
<thead>
<tr>
<th>cluster</th>
<th>redshift</th>
<th>$kT^{(2)}$</th>
<th>Hard$^{(2)}$ Flux</th>
<th>Hard$^{(3)}$ Luminosity</th>
<th>ICM$^{(4)}$ Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coma</td>
<td>0.0232</td>
<td>8.38 ± 0.34</td>
<td>(2.2 ± 0.2) $\times 10^{11}$</td>
<td>(2.4 ± 0.2) $\times 10^{43}$</td>
<td>3.6 $\times 10^{44}$</td>
</tr>
<tr>
<td>A2256</td>
<td>0.0581</td>
<td>7.08 ± 0.23</td>
<td>(1.2 ± 0.2) $\times 10^{11}$</td>
<td>(7.7 ± 1.2) $\times 10^{43}$</td>
<td>3.4 $\times 10^{44}$</td>
</tr>
<tr>
<td>A2199</td>
<td>0.0303</td>
<td>4.10 ± 0.08</td>
<td>(1.0 ± 0.25) $\times 10^{11}$</td>
<td>(1.8 ± 0.4) $\times 10^{43}$</td>
<td>1.3 $\times 10^{44}$</td>
</tr>
</tbody>
</table>

(1) ICM temperature in keV, from Fukazawa 1997.
(2) The 20–80 keV flux of the hard component in erg s$^{-1}$ cm$^{-2}$. For A2256, the error of 15% are derived from the PDS count rate error (1 $\sigma$) presented in Fusco-Femiano et al. (2000), and do not include any fitting errors. For the Coma cluster, we assumed $\sim 10$% error in flux by scaling the error of A2256 with their flux ratio. i.e. $1/\sqrt{2}$. For A2199, the original paper presents the flux in 0.1–100 keV range. This is converted to 20–80 keV band by assuming $\alpha = 1.8$.
(3) The 20–80 keV luminosity of the hard component in erg s$^{-1}$. Distances of 92.0 $h_{75}^{-1}$ Mpc, 232.7 $h_{75}^{-1}$ Mpc and 120.6 $h_{75}^{-1}$ Mpc are assumed for Coma, A2256 and A2199, respectively.
(4) The 2–10 keV ICM luminosity in erg s$^{-1}$.

2.5 Hard X-ray Emission from Other Diffuse Plasma Sources

2.5.1 Supernova remnant: SN 1006

From ASCA observations of galactic supernova remnant (SNR) SN 1006, Koyama et al. (1995) found that the edges of the remnant shell is dominated by a power-law X-ray emission with $\alpha \sim 1.95$ within 0.5–10 keV (Fig.2.16). It was interpreted as a synchrotron emission from electrons accelerated up to $\sim 100$ TeV in the shock front, interacting with $\sim$ mG magnetic field. This was further supported by the detection of TeV $\gamma$-ray from the north rim of the SNR, with the CANGAROO imaging air Cerenkov telescope (Tanimori et al. 1998). The $\gamma$-rays are attributed to be the IC scattering off the CMB photons. Because
the IC photon cannot exceed the incident electron energy, this is the direct evidence that the electrons are accelerated to at least several times 10 TeV in the region.

The SN 1006 is thought to be a type-Ia super nova remnant, with typical shell-type structure and no central engine for high energy particles, such as a neutron star or a black-hole. Therefore, this is the first direct evidence of a particle acceleration to such a high energy in the shock region around SNR.

(a) ASCA image of SN 1006
(b) X-ray spectrum of SN 1000

Figure 2.16: (a) X-ray image of SN 1006. (b) X-ray spectra, obtained from the rim region and interia region.

2.5.2 Galactic ridge X-ray emission

HEAO-1 satellite has discovered a diffusely distributed emission along the disk of Milky Way (Worrall et al. 1982). This phenomenon is generally called “galactic ridge X-ray emission” (GRXE). The X-ray image taken with EXOSAT is shown in Fig.2.17a. GRXE is considered to have a disk-like shape, with a radius of ~ 10 kpc and thickness of ~ 200 pc. Its total luminosity is estimated to be \((1 \sim 2) \times 10^{38} \text{ erg s}^{-1}\) in the energy band of 2–10 keV (e.g. Yamauchi and Koyama 1993). Although many studies are carried out to, the origin of GRXE is not yet clear.

Detection of Fe-K line emission with Tenma satellite (Koyama et al. 1986) revealed that a major component of GRXE is due to thermal emission from optically thin hot plasma. Using ASCA, Kaneda et al. (1997) found that GRXE consists of at least two thermal components in non-equilibrium ionization state; a soft component with \(kT \sim 0.8\)
keV and a hard component with $kT \sim 7$ keV. They also suggest that the equivalent width of the Fe-K line decreases with increasing galactic latitude, and the hard component gradually becomes power-law like (Fig.2.17b). By using Ginga and a balloon experiment Welcome-1, Yamasaki et al. (1997) found a hard tail, which cannot be explained by $kT \sim 7$ keV hot component. The combined spectra seems to continue up to the $\gamma$-ray region with a power-law spectra (Fig.2.17c). Vallinia and Marchall (1998) found similar results using the RXTE data.

From these observational results, it has become clear that GRXE consists of at least three components; soft and hard thermal components, and a non-thermal component. Among them, the soft component can be well explained by a sum of SNRs (Kaneda et al. 1997). On the other hand, origin of the later two components is not yet clear, which may be implying the existence of new type of heating and accelerating sources in the vast inter-stellar space of our galaxy (e.g. Kaneda et al. 1997).

### 2.5.3 Inverse Compton (IC) emission from the radio lobe

ASCA (Kaneda et al. 1995) and ROSAT (Feigelson et al. 1995) has discovered an X-ray emission from the radio lobe of Fornax-A, the forth strongest extra-galactic radio source in the GHz region. It has a prototypical double lobe morphology in radio band, with continuous spectra detected in the range of 408 MHz to 4.8 GHz. We show the X-ray image obtained with ASCA overlayed on the radio image in Fig.2.17. The source is located at a distance of 17 Mpc, and the size of each lobe is $\sim 200$ kpc in diameter.

The radio emission is considered to be a synchrotron emission from a population of high energy electrons, and the X-ray emission is interpreted as IC scattering off the CMB photons. The same as the case of the Coma cluster, we can obtain the lobe averaged magnetic field strength by combining equations 2.20 and 2.23. The value becomes $2 \sim 4\mu$G. This was the first case that the magnetic field strength of an extragalactic diffuse plasma with such a large scale is directly determined only from observables. From equation 2.18, the magnetic field of $\sim 3\mu$G implies that the relativistic electrons should reach the energy of $\sim 10$ GeV to produce the 4.8 GHz radio emission. The energy density of the relativistic electrons and the magnetic field are calculated to be $\sim 3 \times 10^{-13}$ erg cm$^{-3}$ and $3.6 \times 10^{-13}$ erg cm$^{-3}$, respectively. Their total energies are derived to be $4 \times 10^{58}$ erg and $6 \times 10^{58}$ erg, respectively, assuming a lobe volume of $1.3 \times 10^{71}$ cm$^3$. 

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Figure 2.17: X-ray image and spectra of GRXE. (a) The 2–6 keV band image from EXOSAT (Warwik et al. 1985). (b) ASCA spectra obtained from galactic latitudes of $0^\circ$, $0.5^\circ$, $1.1^\circ$ and $1.7^\circ$ (Kaneda et al. 1997). (c) Ginga X-ray and other $\gamma$-ray spectra (Yamasaki et al. 1997).
Figure 2.18: X-ray gray scale image from ASCA, overlaid on the 1.4 GHz radio contour map of Fornax-A. The solid circle represents the ASCA GIS field of view of $\sim 22'$ radius. In the X-ray image, contribution from a central source have been subtracted. Contours are at 125,187.5,250,375,1125 and 1375 mJy beam$^{-2}$. 
Chapter 3

THE ASCA SATELLITE

3.1 Spacecraft

The ASCA (Advanced Satellite for Cosmologies and Astrophysics; Tanaka et al. 1994) is the Japanese forth satellite devoted to cosmic X-ray researches, developed under US-Japan collaboration managed by ISAS (Institute for Space and Astronautical Science). The satellite was launched on 20 February 1993 at 11 a.m. JST, from Kagoshima Space Center (KSC) of ISAS at Uchinoura, Kagoshima, with the M-3S-II-7 three stage rocket. ASCA has achieved a near-circular orbit with perigee of 520 km, apogee of 620 km, an inclination of 31° and a period of 96 min.

In Fig.3.1, we show the in-orbit configuration of ASCA. The satellite has a length of 4.7 m and weights 420 kg, and is operated from the power supply from its solar panel, which looks like a wing. A schematic view of the scientific instruments onboard ASCA is shown in figure 3.2. The satellite is equipped with four identical X-ray telescopes (XRT; § 3.2) with a focal length of 3.5 m. At the four foci, two gas scintillation imaging proportional counters (GIS § 3.3) and two X-ray CCD camera (SIS; § 3.4) are located. ASCA is the first satellite that simultaneously performs imaging and spectroscopy in the wide energy band of 0.5-10.0 keV. The previous imaging missions such as Einstein and ROSAT were limited to energies below ~ 3 and 2.4 keV, respectively. The superior energy resolution of the SIS, high through-put of the GIS and low background levels of both instrument, particularly the latter, also characterize the satellite.

The satellite attitude is measured by gyros, geomagnetic sensors and star sensors. In reference to these real-time measurements, the satellite is controlled using four bias momentum reaction wheels and three-axis magnetic torquers. The absolute pointing accuracy is typically 1′, and we can reconstruct the resulting pointing position with a
Figure 3.1: In orbit configuration of ASCA.

Figure 3.2: Configuration of the onboard instruments.
\( \sim 0.5 \) accuracy from the telemetry data.

ASCA flies over KSC five times a day, each lasting \( \sim 10 \) minutes. All the necessary commanding and maintenance are done during these short contact intervals. The CPU-based onboard commanding unit keeps control of the satellite all the time, by handling the commanding time table uploaded from KSC. The observed data (\( \sim 75\% \) scientific and \( \sim 25\% \) housekeeping) are stored in the onboard data recorder with a 128 Mbits capacity. The data acquisition rate is commandable at either 32 (high bit-rate), 4 (medium bit-rate) or 1 (low bit-rate) kbit/s. The stored data are transmitted to ground via down-link telemetry at KSC, as well as the US NASA’s Deep Space Network stations. The data amounts to \( \sim 1 \) Gbits a day.

### 3.2 X-Ray Telescope (XRT)

#### 3.2.1 Design and structure

The X-ray telescope (XRT) onboard ASCA has for the first time enabled the cosmic X-ray imaging up to 10 keV (Serlemitsos et al. 1995). Soft X-rays are totally reflected off a smooth surface, when their incident angle is less than a certain critical value. This phenomenon is known as a grazing incident reflection. The critical angle of order \( \sim 1^\circ \) is inversely proportional to the X-ray energy, and proportional to the electron density of the reflecting material.

The XRT is design to form a Wolter type I optics, consisting of two mirrors with paraboloid and hyperboloid sections (Fig.3.3). This optics are used in many cosmic X-ray satellites, including Einstein (1978–81), EXOSAT (1983–86), ROSAT (1991–1999) and Yohkoh (1991–). All these missions use a polished glass or glass ceramic with heavy metal, such as gold, evaporated as a reflecting material. The effective area is usually increased by having multiple nested set of mirrors with a common focus. For example, both Einstein and ROSAT telescopes use four nesting.

To reflect higher energy X-rays, the incident angle must be very small; hence the projected area also becomes very small. To overcome this dilemma, the ASCA XRT adopted “multiple thin foil” optics. This design makes each shell extremely thin, by using metal foils instead of polished glass, and drastically increases the number of nesting. Because it is very difficult to shape a thin foil into a paraboloid or a hyperboloid, a conical surface is used as an approximation. A prototype multiple thin-foil mirrors were successfully used in the BBXRT experiment onboard Space Shuttle in December 1990.
The reflector shells are all made of 127 \( \mu \text{m} \) thick aluminium foils. The foils are \( \sim 10 \ \mu \text{m} \) lacquer-coated to improve the surface smoothness, and then \( \sim 50 \ \text{nm} \) gold-evaporated to increase the reflectivity. The 120 of these foils are closely packed together in an onion-ring configuration with a typical space of 1 mm. The foils are packed and manufactured in four quadrants, and aligned by 13 alignment bars into 14 sectors. Four quadrants make up the first mirror section of 100 mm long, and another set make up the second mirror. One mirror assembly weighs 9.8 kg. In Table 3.1, we summarize the design parameters and performance of the ASCA XRT. Because the focal length is 3500 mm, a 1' distance in the sky corresponds to 1 mm distance on the focal plane.

Although the imaging resolution is moderate (\( \sim 3' \)), the weight of the telescope is significantly saved. For example, the X-ray telescope onboard the Chandra satellite, which is characterized by its high imaging quality with resolution better than 1", has a weight of 1.5 tones. This is about 150 times that of an ASCA XRT, and even larger by a factor of 4 than the whole ASCA satellite weight. In spite of the huge weight difference, the effective area of the ASCA XRTs is comparable to that of the Chandra mirror. Thus, the ASCA XRT is optimized to achieve a large effective area.

![Walter type I optics](image)

**Figure 3.3:** Walter type I optics.

### 3.2.2 Effective area and point spread function (PSF)

The effective area of the ASCA XRT compared with the earlier missions are shown in Fig.3.5a. It shows an M-edge structure of gold around 2.2 keV, and gradually decreases with increasing photon energies. This is because the critical angle of higher energy X-rays is smaller, so that the outer shell of the XRT gradually becomes ineffective toward higher energies.

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Figure 3.4: The schematic view of the ASCA XRT. A top view of a quadrant (left) and a cross section of one telescope (right).

For the same reason, the ineffective region increases as the off-axis angle gets larger. It also suffers shadowing effects between the foil shells. Therefore, the effective area depends on both the incident angle ($\theta$) and the energy of the X-rays. This is called the vignetting effect. In addition, because of the quadrant structure of the XRT, it also depends on the roll angle ($\phi$). In Fig. 3.5b, we present the $\theta - \phi$ dependence of the effective area. The actual effective area, including its position dependences, is calibrated in-flight using the Crab nebula, which is a standard candle in X-ray astronomy.

Figure 3.5: (a) Effective area of the four X-ray telescopes on boresight position. (b) The incident angle ($\theta$) dependence of the effective area (vignetting).

Due to the waviness of the aluminum foils as well as the conical approximation of paraboloid and hyperboloid, the angular resolution of the XRT is limited to $\sim 3'$. Furthermore, the point spread function (PSF), i.e., the image of the point source is the
Figure 3.6: (a) X-ray contour image of a point source observed with GIS2. The actual images of Cyg X-1 obtained from three different observations are plotted together. (b) Radial profile of the XRT+GIS PSF at 1′.8 offset (position 1 in panel a). (c) Radial profile of the PSF at 8′ offset (position 3 in panel a).
Table 3.1: Design parameters and performance of the ASCA XRT.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror substrate</td>
<td>Aluminum foil (127 μm)</td>
</tr>
<tr>
<td>Mirror surface</td>
<td>Acrylic lacquer (10 μm) + Au (50 nm)</td>
</tr>
<tr>
<td>Mirror length</td>
<td>100 mm</td>
</tr>
<tr>
<td>Number of foils per quadrant</td>
<td>120 foils</td>
</tr>
<tr>
<td>Inner / outer diameter</td>
<td>120 mm / 345 mm</td>
</tr>
<tr>
<td>Focal length</td>
<td>3500 mm</td>
</tr>
<tr>
<td>Incident angle</td>
<td>(0.24^\circ \sim 0.7^\circ)</td>
</tr>
<tr>
<td>Total weight of four XRTs</td>
<td>(\sim 40 \text{ kg})</td>
</tr>
<tr>
<td>Geometrical area</td>
<td>558 cm(^2) / telescope</td>
</tr>
<tr>
<td>Field of view</td>
<td>(\sim 24') (FWHM at 1 keV) / (\sim 16')  (FWHM at 7 keV)</td>
</tr>
<tr>
<td>Energy range</td>
<td>(\lesssim 10) keV</td>
</tr>
<tr>
<td>Effective area of four XRTs</td>
<td>(\sim 1300) cm(^2) (1 keV) / (\sim 600) cm(^2) (7 keV)</td>
</tr>
<tr>
<td>Half power diameter</td>
<td>(\sim 3) arcmin</td>
</tr>
</tbody>
</table>

energy- and position-dependent. In Fig.3.6a, we plot the actual images of Cyg X-1, which can be regarded as a point source at infinity observed with the GIS detector. The radial brightness profile in different energy bands for two source positions are shown in Fig.3.6b and c. The PSF has a sharply peaked core, although it is somewhat broadened in the image by the finite position resolution of the GIS. For the on-axis image, half the detected counts are contained within a diameter of \(3'.2\) on the focal plane. This diameter, called half-power diameter, gives a rough measure of the combined XRT+GIS angular resolution. The PSF has a rather wide tail outside the core, which depends on the source position as well as the X-ray energy (Fig.3.6b and c). There is an additional cross shaped component in the tail due to the quadrant structure of the XRT (Fig.3.6a). These structures depend not only on the position, but also on the X-ray energy. The PSF is calibrated with a pre-launch beam line data, and a set of actual images of Cyg X-1 (Takahashi et al., 1995 ASCA News Letters No.3, 25).
3.3 Gas Imaging Spectrometer (GIS)

The Gas Imaging Spectrometer (GIS) has been developed mainly by the University of Tokyo, ISAS, Tokyo Metropolitan University, Meisei Electric Co.Ltd. and Japan Radio Corporation Co.Ltd., with collaborators at Institute of Physical and Chemical Researches (RIKEN), Kyoto University (Department of Physics), NASA/Goddard Space Flight Center (GSFC), and so on (Ohashi et al. 1996; Makishima et al. 1996). The GIS design is mainly based on the GSPC experiment (Koyama et al. 1984) onboard Tenma (Tanaka et al. 1984) which was operating for 1983–1984.

3.3.1 Design and structure

The GIS is a general-purpose X-ray imaging spectroscopy system. It consists of the two detector assemblies (GIS-S), namely GIS2 and GIS3 serving as X-ray detectors, and the main electronics called GIS-E. GIS2 and GIS3 are almost identical except that there is a Radiation Belt Monitor (RBM), a small PIN-diode particle monitor, attached to the bottom of GIS2. GIS2 and GIS3 are coupled to two of the four XRTs, and measure pulse-heights and positions of X-rays reflected by the XRTs, photon-by-photon basis. Design parameters and performance of the GIS are summarized in Table 3.2.

Table 3.2: Design parameters and performance of the GIS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Band</td>
<td>0.7–15 keV</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>8% at 5.9 keV (FWHM)</td>
</tr>
<tr>
<td>Effective Area</td>
<td>50 mm diameter</td>
</tr>
<tr>
<td>Entrance Window</td>
<td>10 μm beryllium</td>
</tr>
<tr>
<td>Absorption Material</td>
<td>Xe (96%) + He (4%), 10 mm depth, 1.2 atm at 0 °C</td>
</tr>
<tr>
<td>Positional Resolution</td>
<td>0.5 mm (FWHM)</td>
</tr>
<tr>
<td>Time Resolution</td>
<td>~ 61 μsec (Minimum in PH Mode)</td>
</tr>
<tr>
<td></td>
<td>1.95 msec (Minimum in MPC Mode)</td>
</tr>
<tr>
<td>Weight</td>
<td>4.30 kg (GIS2), 4.16 kg (GIS3)</td>
</tr>
</tbody>
</table>

The structure of GIS2 sensor is shown in Fig.3.7. Each sensor consists of a detector assembly and a high-voltage supply unit. Each detector assembly in turn consists of a gas cell, an imaging photo-multiplier tube (IPMT) and front-end electronics, all of which are placed in a housing made of magnesium-alloy. The top section forms a hood, which limits the field of view of the GIS into the XRT direction. In order to prevent ionospheric
plasma from entering into the gas cell section, an aluminized mylar film of 540 nm thick with 37 nm of aluminum (plasma shield) is placed inside.

Figure 3.7: Cross section view of the GIS detector.

The middle section accommodates the gas cell and the phototube. The gas cell is made of ceramic tube with a beryllium entrance window and a quartz exit window. It is filled with a mixture of 96% xenon and 4% helium of 1.2 atm at 0°C. The gas volume is divided by a mesh electrode made of molybdenum into two parts, the drift region in the top 10 mm and the scintillation region in the bottom 15 mm. Figure 3.8 shows a schematic performance of the GIS sensor system. X-rays reflected by the XRT enter through the window, whose electric potential is held at −6000 V, and are absorbed in the drift region. Through photo-ionization, primary electrons are generated on average at the rate of one electron per 21.5 eV. The electron cloud thus created slowly drifts to the intermediate mesh (−5300 keV), and then is accelerated due to the strong field toward the ground mesh which is placed in front of the quartz window. In this process, the electrons excite Xe and produce a large number of UV photons of ∼ 170 nm wavelength. The excitation energy for one UV photon is ∼ 10 eV. Through the quartz window, these UV photons are collected by the IPMT which measures light distribution and the overall intensity of the UV flux, the latter being proportional to the X-ray energy to an accuracy of several %.

The entrance window is made of vacuum tight 10 μm thick beryllium foil, which has a 10% transmission at 0.7 keV. The window support is made of a thin molybdenum grid
Figure 3.8: Schematic view of the GIS sensor system.
plated with copper, and a stainless steel mesh coated with tin is placed between the grid and the beryllium foil to provide a fine support. To stand against several atmospheric pressure, the molybdenum grid has a height of 3.5 mm and a thickness of 0.1 mm and runs at 5 mm pitch. The shadow of the grid onto the X-ray image is not a major problem since the wall thickness is smaller than the point spread function (~ 3 mm) of the XRT. The fine-supporting mesh has 1.2 mm pitch and 84% transmission with a wire thickness of about 80 μm. The exit window is made of 2.5 mm thick quartz plate with a diameter of 72 mm. Quartz has short-wavelength cutoff of ~ 150 nm and a relatively high transmission for the UV lights (λ ~ 170 nm).

The IPMT is positioned beneath the exit window. We employ Hamamatsu Photonics type R4268 IPMT, which is equipped with a quartz window and 10-stage dynodes. The anode has a cross-wire configuration with 16 wires running in each X and Y direction at an interval of 3.75 mm. From the anode signals, the onboard CPU calculates the width (spread: SP) of the distribution together with the position (RAW_X, RAW_Y) of the event. A pencil-beam light input to the IPMT shows a distribution of the output charge of about 7 ± 1 mm FWHM and the intrinsic position resolution of the phototube to be about 0.1 mm FWHM. From the last dynode, we derive the pulse-height (PH) and the rise-time (RT) information.

Figure 3.9 illustrates the resulting quantum efficiency and energy resolution of the GIS as a function of incoming X-ray energy. Thus the GIS sensitivity covers approximately 0.7–10 keV, with a spectral resolving power of ~ 8%.

### 3.3.2 Data processing

One of the major design goals of the GIS is to achieve a very low level of non X-ray background (NXB). For this purpose, the GIS employs both hard-wired and software-based rejection.

One of the selection processes is the RT discrimination (RTD). All the X-ray events properly absorbed in the drift region should exhibit a RT of 3 μsec, which corresponds to the drift time of electrons in the scintillation region. On the other hand, particle events creating a long electron track in the drift region exhibit longer RT. By controlling the levels of upper (RTUD) and lower discriminators (RTLD) for the rise time, we can efficiently remove NXB by hard-wire electronics. However, the RT distribution broadens significantly toward lower values of PH, because the signal to noise ratio gets worse. Therefore we set the RT window rather loose in orbit. We can further reduce NXB by

43
Figure 3.9: (a) Quantum efficiency of the GIS detector. Energy dependence of the thermal shield transmission (thin solid line), 10.5 μm thick Be window transmission (dashed line), and total GIS quantum efficiency including thermal shield, plasma shield, Be window, and meshes (thick solid line). (b) Energy dependence of the energy resolution (FWHM) of the GIS.

applying a $PH$ dependent $RT$ mask on ground processing. Here, the position dependent $RT$ is converted to a position independent value $RTI$ (rise-time invariant). Figs.3.10 demonstrates the background rejection with the strict $RT$ mask on ground.

Besides the $RT$ discrimination, we utilize another background rejection logic called $SP$ discrimination (SPD). SPD is sensitive to the direction of a charge track perpendicular to the electric field. If an ionizing particle runs in parallel to the window plane, RTD does not work efficiently. By SPD, we can reject these events, which have much larger $SP$ than those for the X-ray events. As shown in figure 3.11, $SP$ is usually plotted against the squared radius from the detector center. Figure 3.11 also indicates the thresholds of SPD employed in orbit. SPD was enabled on 28 May 1993.

Apart from the position, pulse-height and the rise-time information of each event, the GIS provides scaler data using the combined signals from upper (UD) and lower discriminators (LD) of the signal pulse hight, and upper (RTUD) and lower discriminators (RTLD) for the rise time. In Fig.3.12, we plot a schematic of the 6 monitoring scalar counts, $L0,1,2$ and $H0,1,2$, in the $PH$–$RT$ space. These values are used to estimate the residual non X-ray background ($§$ 3.3.4).

The raw GIS outputs for an event, $PH$, $RT$, and calculated position ($RAWX$, $RAWY$), are subject to various non-ideal instrumental properties of the GIS. Therefore, we convert them into linearized quantities: $PI$, $RTI$, and $(DEX, DEXY)$, respec-
Figure 3.10: Rise time discrimination. (a) An example of RAWX-RAWY image of a celestial X-ray point source, obtained with GIS2 in a very early observation. No background rejection was applied, except the pulse-height UD. (b) The X-ray events contained in the image of panel (a), displayed on the plane of PH vs. RT. Two horizontal lines represent the standard onboard RT window. Panel (c) and (d) are the same as (a) and (b), respectively, but after the strict RT mask is applied.
Figure 3.11: A scatter plot of events from a blank sky displayed on the plane of squared radial distance from the center in $RAWX$-$RAWY$ image vs. $SP$. A nearly horizontal branch is formed by signal X-rays of the CXB, while a nearly vertical branch, which means a large scatter in the spread of UV light, originates from background near the detector wall. Two slant lines indicate the standard SPD window.

Figure 3.12: Schematic view of the 6 monitor data in the PH vs RT plane.
tively on ground. In these linearized values, \( RTI \) is utilized to apply the strict \( RT \) mask described above. We finally use \( PI \) and \( (DET_X, DET_Y) \) for scientific analyses.

The position linearization are performed with the calibration table obtained from pre-launch scanning measurements with collimated X-ray beams. The tables have been confirmed in orbit in reference to the shadows caused by the window support girds and various observations.

When accumulating X-ray photons into an X-ray spectrum, we usually convert \( PH \) (pulse-height) of each detected event into \( PI \) (pulse-invariant) so that X-rays of the same energy give the same \( PI \) value (except the finite energy resolution) independently of the position, the temperature of phototube or the observation period. The conversion factor from \( PH \) to \( PI \) is called gain. The gain depends on three factors: (1) detected position of the incoming X-rays, (2) the temperature of the GIS, and (3) the long-term gain drift.

![Gain Maps for GIS2 and GIS3](image)

Figure 3.13: The gain maps in \((RAW_X, RAW_Y)\) coordinates for GIS2 (left panel) and GIS3 (right panel). Contour levels are every 10 steps from 350.

The GIS gain is position dependent by \( \sim \pm 10\% \) peak-to-peak due to non-uniformity in the IPMT gain. Calibration of this effect involves a look-up table called “gain map”, which summarizes relative gains of each detector as a function of the position of event occurrence. The gain map is based on the pre-launch scanning measurements and also on the in-orbit data using the instrumental Cu-K line seen in the NXB spectrum (§ 3.3.4) after a long data integration. The gain maps are found to change gradually, especially for the GIS3 (Idesawa et al. 1997 ASCA News Letters No.5). The change of gain maps is
approximately represented as a function of radii from the detector center. This additional correction is \( \sim 0.5\% \) and \( \sim 3\% \) for GIS2 and 3, respectively. The reliability of the gain map is within \( \pm 1\% \) and \( \pm 2\% \) for the regions of radius < 15 mm and 15–20 mm, respectively, for both detectors.

The GIS gain depends significantly on the temperature, because of the temperature dependence in the IPMT and gas cell. The GIS gain is monitored continuously in orbit in reference to the built-in \(^{55}\)Fe isotope, and so is the IPMT temperature. In Fig.3.14a, we show the gain vs. temperature relation thus calibrated in orbit. This relation is frequently updated taking into account the long-term gain change (see next paragraph), and is used to correct the GIS gain for the temperature variance. This relation between the temperature and the GIS gain, including the long-term gain change, is called “gain history”. The temperatures of the two GIS detectors vary by \( \sim 10 \degree C \) in orbit, mainly in response to satellite attitude changes.

Figure 3.14: (a) Peak \( PH \) channels of the \(^{55}\)Fe calibration isotope, plotted against the detector temperature measured in orbit on the side wall of IPMT. (b) Long-term gain history since the launch till July 2000, expressed in terms of the temperature-corrected \(^{55}\)Fe \( PH \). In both plots, upper and lower panels are for GIS2 and GIS3, respectively.

Figure 3.14b shows the long-term GIS gain history in reference to the \(^{55}\)Fe isotope, after correction for the temperature variation. Thus, the gain of both detectors are gradually decreasing. This gradual gain decrease is unlikely to be caused by out-gassing in the detector, since the \( RT \) characteristics have remained constant. Therefore, the phenomenon is possibly due to a slow degradation in the UV transmission of quartz windows of the gas cell and the IPMT, or changes in the IPMT performance. In any way,
Figure 3.15: The spectra of the Crab Nebula obtained with (a) the GIS2 and (b) GIS 3. Both spectra are fitted by a power law model with $\Gamma = 2.09$, which is consistent with previously observed results of $\Gamma = 2.08 \sim 2.11$ (Toor and Seward 1974). In the lower panels, the data to model ratios are plotted, which demonstrate the accuracy of the current understanding of the instrumental responses.

the secular gain decrease is so slow that it does not affect scientific objectives at all.

All these gain correction process are confirmed using the instrumental Cu-K line seen in the NXB spectrum and other stellar sources such as SNR and clusters of galaxies. In addition, the X-rays from the Crab nebula, which is the standard candle of the X-ray sky, are used; this is also useful for the effective area calibration. In Fig.3.15, we plot the Crab Nebula spectra obtained with the GIS, fitted by the generally accepted power law emission model. From the residual plot, we can see that the calculated model well reproduces the data by an accuracy of $\sim 1\%$. Together with many other calibration results, we believe that the absolute GIS response thus established is accurate to $\sim 1.2\%$.

3.3.3 Background estimation of the GIS

Even though the RT and SP discriminations (see § 3.3.2) very efficiently reject particle- or gamma-ray induced GIS events, the NXB left over after these discriminations (“residual NXB”) still dominates over faint signal X-rays. In addition, the sky itself emits X-rays, which is called the Cosmic X-ray Background (CXB). This emission is considered to originate from numerous faint X-ray sources distributed in the universe, and is observationally shown to be almost isotropic in the sky. We must carefully estimate these two background components, and subtract them from the on-source images and spectra. This
process is technically of crucial importance to the subject of the present thesis.

Figure 3.16a gives three typical GIS background spectra, accumulated over the entire detector area for sufficiently long times while the XRT is pointing onto night earth, sunlit earth, and blank skies. The night-earth spectrum represents the residual NXB itself (see § 3.3.2). The day-earth spectrum in addition contains bright solar X-rays scattered by the earth’s atmosphere. The blank-sky spectrum consists of the Cosmic X-ray Background (CXB; § 3.3.5), as well as the residual NXB. Thus, the difference between the blank-sky spectrum and the NXB spectrum shows the pure CXB component. The NXB exceeds the CXB above ~ 5 keV. In Fig.3.16b, we show projected profiles of the CXB and NXB components of GIS2, in the 1–2 keV and 4–8 keV bands. The CXB is brightest at the XRT optical axis because of the vignetting effect of the XRT, while the NXB brightness is virtually flat across the detector area.

We used the blank-sky data to obtain the averaged CXB (§3.3.5), and used the night earth data as a template for the NXB. In the latter case, we scale the night earth spectra or image by referring to the event rate rejected through the on-board processing in the on-source observation (§3.3.6), and further trim it by referring to the image brightness in the outer region of the detector during the observation (§3.3.4).

3.3.4 Subtraction of non X-ray background (NXB)

To estimate the NXB, we need in turn to know its basic properties, including its time variation in particular. The NXB properties have been studied extensively by many authors, including Ishisaki (1995) in particular. He showed that its time variation is predominantly correlated with geomagnetic cut-off rigidity (COR) for cosmic rays along the satellite orbit; COR is the minimum momentum of charged particles that can penetrate the terrestrial magnetism. However, the COR is merely one of the many factors that affect NXB, and several features cannot be explained by COR alone. Ishisaki (1995) searched the GIS monitor data for a more direct indicator of NXB. By analyzing the night-earth data, he has found that “H02 counts”, defined as a sum of two monitor counts, H0 and H2 (see § 3.3.2), are tightly correlated with the residual NXB counts. The H02 counts are believed to express the count rate of the particle induced events, rejected in the on-board processing, and is almost free from signal X-rays even during the observations of bright X-ray sources. Therefore, it can be used as a good indicator of the residual NXB contained in the on-source data.

Figure 3.17 shows the H02 count against the COR during the night-earth observations.
Figure 3.16: (a) Long-exposure GIS2+GIS3 spectra accumulated over the whole field of view, from day-earth pointings (smooth line; representing the NXB plus scattered solar X-rays), night-earth pointings (filled circles; the NXB only), and blank skies observations (crosses; the NXB plus the CXB). The exposure time is given in parentheses. Identifications of the atomic lines, either celestial or instrumental, are also given in the figure together with their energies in keV. The flare-cut (Table 3.3) is NOT applied. (b) Projected count-rate profiles of the blank-sky and night-earth data in a strip of $-5 \text{ mm} \leq \text{XRTY} \leq +5 \text{ mm}$ for GIS2. Here “cm$^2$” is defined on the actual detector dimension of the GIS, and is not the effective area of the XRT. Upper panel shows a profile in the 1–2 keV energy band, and lower panel 4–8 keV. The origin of the coordinates for $XRTX$-$XRTY$ is the optical axis defined on the $DETX$-$DETY$ plane. Filled circles, crosses, and diamonds represents the raw CXB including NXB, the NXB, and the CXB after subtracting the NXB, respectively. The flare-cut (Table 3.3) is applied for both the CXB and the residual night-earth data.
Figure 3.17: Correlation between $COR$ and $H02$ counts during the night-earth observations. $H02$ is integrated for every 32 s. A dashed line means a function $f(x) = (109.3 - 17.05x + 1.127x^2 - 0.02627x^3)/32$ derived from fitting. Two solid lines below and above show $f(x)$ scaled by a factor of 0.9 and 1.5, respectively. A vertical branch observed around $COR \sim 12 \text{ GeV} \text{ c}^{-1}$ is caused by some flares. The flare-cut (Table 3.3) is NOT applied.
Figure 3.18: Distribution map for flares on the Earth surface. The symbols “.” and “+” represent positions of the detected flares. The symbol “.” represents positions where the COR-map is suspected to be inaccurate. Two regions surrounded by solid lines define the dangerous areas where flare events can frequently take place.
A clear correlation is found between the two quantities. Nevertheless, the H02 count exhibits a considerable scatter for a given COR, partly due to suspected inaccuracy of the COR map (in particular, over north Atlantic regions; Fig.3.18). This makes the H02 count a better NXB indicator than the COR. In addition, a sudden increase in the GIS background rate, called a flare event, sometimes happens, producing an upward branch in Fig.3.17. Ishisaki (1995) clarified that these flares tend to occur in two particular regions ("dangerous regions") around south Atlantic and north Pacific (Fig.3.18). Taking these pieces of information into account, Ishisaki (1995) finally developed criteria, called "flare cut", used to exclude the data portion contaminated by these flare events. As listed in Table 3.3, the criteria are based on a combined use of the H02 rate, the satellite position, and the RBM count rate. We apply the flare cut processing to both the on-source data and the background data (see below).

Table 3.3: The "flare cut" screening criteria for the GIS. Time region satisfying this criteria are excluded from the analysis.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>$15 \text{ c/s} \leq \text{H02} \leq 45 \text{ c/s}$</td>
<td>to avoid high NXB</td>
</tr>
<tr>
<td>$\text{H02} \leq 1.5 \times f(\text{COR}) , \dagger , \text{c/s}$</td>
<td>for flares</td>
</tr>
<tr>
<td>$\text{RBM} \leq 300 , \text{c/16 s} = 18.75 , \text{c/s everywhere}$</td>
<td>for flares</td>
</tr>
<tr>
<td>$\text{RBM} \leq 100 , \text{c/16 s} = 6.25 , \text{c/s in the dangerous areas (figure 3.18)}$</td>
<td>for flares</td>
</tr>
</tbody>
</table>

$\dagger \, f(x) = 0.5(109.3 - 17.05x + 1.127x^2 - 0.02627x^3) \, \text{c/16 s}.$

Our basic strategy of constructing the NXB data, to be subtracted from the on-source images or spectra, is to utilize the night-earth GIS pointing data accumulated over very long periods (up to the entire mission lifetime of ASCA). We process all these background data in the same manner as the on-source data, by applying the $RT$, $SP$, and flare cuts. We then sort all these background events according to appropriate intervals of the H02 counts, in every 5 c/s step, as 15–20 c/s, 20–25 c/s, 25–30 c/s, etc. This yields a large number of NXB events for each H02 interval. We call this datasets "NXB templates". In Fig.3.19, we plot the spectra and radial profiles of these NXB templates for five H02 intervals. As $H02$ increases, the spectrum gets softer and the slope of the radial profile gets steeper towards the detector rim.

Now that the NXB templates have been prepared, we can estimate the NXB spectrum
$H$ contained in a particular on-source datasets as

$$H(PI) = \sum_i H_i^{NTE}(PI) \frac{T_i^{OBS}}{T_i^{NTE}}. \quad (3.1)$$

Here $i$ is the sorting interval of the H02 counts, $H_i^{NTE}$ is the night-earth spectrum of the $i$-th interval, $T_i^{OBS}$ is the total exposure of the on-source data in that H02 interval, and $T_i^{NTE}$ is that of the NXB template. We call this method “H02 method”. In order to examine the validity of this method, in Fig.3.19b we calculated the residual NXB counts for individual night-earth observations comprising the NXB template, and compared them with the H02-method prediction. Clearly, the actual NXB exhibits a secular change. It is thought to reflect a combination of various effects, such as changes in the solar activity, a gradual decrease in the satellite orbit altitude, build-up of the radio-active material in the detector and spacecraft, and so on. Accordingly, we have modified the above equation as

$$H(PI) = F(t) \times \sum_i H_i^{NTE}(PI) \frac{T_i^{OBS}}{T_i^{NTE}}, \quad (3.2)$$

where $F(t)$ is an empirical factor describing the secular change. It has been determined as shown in the top panel of Fig.3.19b, in terms of a polynomial function. After subtracting $F(t)$ (which is equivalent to using equation 3.2 instead of 3.1), the NXB count-rate history becomes as shown in the lower panel of Fig.3.19b. Thus, the systematic error included in the NXB subtraction is typically $5 \sim 6\%$ for a 40 ks observation.

### 3.3.5 Derivation of the cosmic X-ray background (CXB)

In the study of faint diffuse emission, we must accurately subtract not only the NXB but also the CXB that inevitably contributes to the on-source data. We may reproduce and subtract the CXB in two alternative ways. One is to use the actual CXB data acquired from blank sky fields; by subtracting the NXB contribution in them (using the same procedure as described above), we can obtain the pure CXB data, or “CXB template”. The other is to start from the CXB model spectrum with a given constant brightness, and convert them through instrumental responses into predicted GIS data. This method is feasible because the CXB surface brightness is quite uniform, and its spectral shape is known to a reasonable accuracy. Among the two methods, the former allows a more reliable CXB subtraction, because it is free from any systematic error involved in the instrumental response. Accordingly, we here employ the former method. Specifically, we use “Master Background Database” prepared by Ikebe (1994) which consists of 20
Figure 3.19: (a) The 0.6–7.0 keV radial profiles (upper panel) and spectra (lower panel) of the NXB templates, produced from the GIS data during the night-earth observations. The five H02 intervals are indicated by '+' (50–80 c/s), 'o' (40–45 c/s), '●' (30–35 c/s), and '×' (20–25 c/s). The H02 counts are integrated for every 16 s. The flare-cut (table 3.3) is applied. (b) Long-term histories of the actual 0.7–7.0 keV night-earth counts, normalized to the H02-method prediction before correction for secular changes. Each data point represents an exposure of 40 ks. The solid line shows the best fit 4-th order polynomial, of which the coefficients are given in the figure inset. Lower panel shows the residual after subtracting the polynomial fit.
observations of 4 different blank sky fields: “Draco”, “NEP”, “QSF3” and “SA57”. All these fields are in high Galactic latitudes with $|b| > 29^\circ$ (Ishisaki 1995).

This method of CXB subtraction, however, has one drawback, that there is no “blank sky” in its strict sense. Every sky field contains a number of faint X-ray sources that ultimately compose the CXB, and sometimes relatively bright discrete sources appear above the detection limit due to statistical fluctuations. We must remove such contaminating discrete sources from the blank-sky data. To do this, Ikebe (1994) discarded the regions in his Master Background Database where the photon counts exceed that in the surrounding region by more than 2.5 $\sigma$. This process eliminates all the sources resolvable with the GIS, at a threshold of $\sim 1 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in the 2-10 keV band for a typical observation parameters. Figure 3.20 exemplifies a GIS image of a blank sky, and the associated mask image utilized to eliminate faint discrete sources found in it.

We reprocessed each blank sky datum with flare cut condition, as the original database was not processed in that way. The CXB data were then generated by summing the 20 observations, filtered with corresponding masks. The NXB contribution was subtracted via the H02 method. Thus, the total exposure map is a mosaic of 20 masks weighted by corresponding exposures. The resulting CXB data have a total exposure of 645 ksec, and an average exposure of 623 ksec when considering the mask. When subtracting the CXB spectrum or image from particular on-source data, we produce a “CXB template” from the above-mentioned CXB data. Namely, we extract the CXB events in the CXB template falling onto the same integration region as is used for the on-source data, and correct the former data for exposure using the mosaic exposure map. Then, the CXB template (either a spectrum or an image) is subtracted from the on-source data.

3.3.6 A finer adjustment of the NXB level

Although the H02 method (§ 3.3.4) allows us to subtract the NXB contribution from the on-source data, its reproducibility is limited to a level of $\sim 6\%$. Presumably, this is because there are still unknown factors affecting the NXB variation. We need to overcome this limit and improve the accuracy as much as possible, because this will ultimately limit our study of faint, diffuse, hard emission. For this purpose, we may recollect that, even in the on-source data, hard-band events detected in the outer regions of the GIS field-of-view are dominated by the NXB (see Fig.3.16a,b). Then, we can apply a fine adjustment to the NXB template to be subtracted, so that the on-source data and the NXB template agree with each other in a hard energy band and over the detector periphery (e.g., Fukazawa
Figure 3.20: An example of blank-sky GIS image. (a) A 0.5–10 keV GIS2 image of NEP field observed in July 1993, smoothed by convolution with the XRT PSF model. The contours are linearly spaced by $4 \times 10^{-4}$ cts s$^{-1}$ arcmin$^{-2}$. (b) The associated mask image to eliminate faint discrete sources.

et al. 2001).

To conduct the above idea, we utilize an energy region of 5.9–10.6 keV, and a detector region of $r > 15'$ from the detector center. The upper-limit of the energy range is set by the calibration uncertainty, and the lower-limit is near the crossing point of the NXB and CXB. About 80% of the events thus obtained are NXB events. We then determine “NXB correction factor” $f_{\text{cor}}$ through error minimization of the equation as

$$\text{Data}_{\text{out}}(E) = \text{CXB}_{\text{out}}(E) + f_{\text{cor}} \times \text{NXB}_{\text{H02}}^\text{out}(E).$$

(3.3)

Here, $\text{Data}_{\text{out}}$ is the hard-band spectrum obtained from the on-source data in the specified outer region, $\text{CXB}_{\text{out}}$ is that of the template CXB, and $\text{NXB}_{\text{H02}}^\text{out}$ is that of NXB estimated by the H02 method. Evidently, $f_{\text{cor}}$ is expected to take a value close to 1.0. We plot an example of these spectra in Fig.3.21.

Once $f_{\text{cor}}$ is determined for a particular on-source data set, we can defined the background $\text{BGD}_{\text{in}}$ (either spectrum or image) in an inner region used for the actual data analysis, as

$$\text{BGD}_{\text{in}} = \text{CXB}_{\text{in}} + f_{\text{cor}} \times \text{NXB}_{\text{H02}}^\text{in}.$$  

(3.4)

Here, $\text{CXB}_{\text{in}}$ and $\text{NXB}_{\text{H02}}^\text{in}$ are the CXB and NXB templates for the same region, respectively. In this case, various systematic errors originally associated with the NXB
Figure 3.21: Example of the determination of the NXB correction factor $f_{\text{cor}}$, in terms of the pulse-height spectrum. Abscissa is Pulse Invariant (PI), and ordinate is the number of events. Open boxes represent the on-source spectrum ($\text{Data}_{\text{out}}(E)$), crosses are the CXB spectrum ($\text{CXB}_{\text{out}}(E)$) and filled boxes are the NXB template spectrum derived with the H02 method ($\text{NXB}_{\text{out}}^{\text{H02}}(E)$).
estimation are absorbed into the statistical error of the $f_{\text{cor}}$ determination. To confirm it, we divided the night earth data into $\sim 60$ subsets, each with $\sim 100$ ksec exposure and an intergration time of a month, and applied this method to them. The estimated background was consistent with the actual data within the statistical error.

Then, how high is the statistical accuracy of the $f_{\text{cor}}$ determination? For example, a 80 ks exposure will provide $\sim 2000$ counts in the 5.9–10.6 keV band of the outer region. This allows us to estimate $f_{\text{cor}}$ with an accuracy of $\sim 1/\sqrt{2000} = 2.2\%$, which is better than the 6 % error of the H02 method. Even when the observation was split into several pointings, we can use the quadrature sum of the errors of the individual pointings for the averaged data, because the NXB estimation errors derived by this correction method are based on the actual data of each pointing and independent to one another. This is not true of the original H02 method.

Strictly speaking, the improved background estimation described above is still subject to fluctuations in the CXB counts, mostly due to the presence of discrete sources. Such a contribution has already removed from the CXB template (first term on the right-hand side of equation 3.3), but that in the on-source data (left-hand side) has not. Accordingly, when we utilize equation 3.3, we exclude, in advance, sources visible in the on-source data. The detection threshold for this process is set again at $1 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in the 2–10 keV band; a source with the 2–10 keV flux four times higher than this threshold, located 18’ from the optical axis, will contribute $\sim 2\%$ of the overall event counts in the outer region. When the emission from the target source is greatly extended, which is often the case with the clusters and groups of galaxies, we cannot use the same source-finding procedure as used for the CXB template ($\S$ 3.3.5). In such a case, we utilize the images from other instruments, particularly the ROSAT image if available, to find these sources.
3.4 Solid-state Imaging Spectrometer (SIS)

The Solid State Spectrometer (SIS) experiment is the first X-ray detector in orbit that utilizes CCDs (charge coupled devices) in the photon counting mode. It was jointly developed by Massachusetts Institute of Technology (MIT), Pennsylvania State University, ISAS, and Osaka University (Burke et al. 1991).

3.4.1 Design and structure

The SIS experiment consists of two detectors (SIS camera; SIS0 and SIS1), an analog electronics unit (SIS-AE), and a digital processing unit (SIS-DE) which is combined with the satellite data processor (DP). Figure 3.22 shows a cross section view of the SIS camera.

![Cross section view of the SIS camera.](image)

Each SIS detector is made up of four CCD chips of 11 mm square each developed in the MIT Lincoln laboratory, to achieve a 22 mm × 22 mm square area for X-ray detection. Each chip has 4096 by 4096 pixels of 27 μm square each, and a depletion layer of about 40 μm thick which ensures an improved efficiency for harder X-rays than conventional CCDs. Design parameters and performance of the SIS are summarized in table 3.4.
Table 3.4: Design parameters and performance of the SIS

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiation Method</td>
<td>Front irradiation</td>
</tr>
<tr>
<td>Charge Transfer Method</td>
<td>Frame Transfer</td>
</tr>
<tr>
<td>Clock</td>
<td>3-phase drive</td>
</tr>
<tr>
<td>Number of pixels in Image Region</td>
<td>420 pixels × 422 lines per chip</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>27 μm</td>
</tr>
<tr>
<td>Area</td>
<td>11×11 mm square per chip</td>
</tr>
<tr>
<td></td>
<td>22×22 mm square per detector</td>
</tr>
<tr>
<td>Field of View</td>
<td>11×11 arcmin square per chip</td>
</tr>
<tr>
<td></td>
<td>22×22 arcmin square per detector</td>
</tr>
<tr>
<td>Thickness of Depletion Layer</td>
<td>~ 40 μm</td>
</tr>
<tr>
<td>Optical Blocking Filter</td>
<td>100 nm Lexan film coated with 40 nm aluminum</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>~ −62 °C</td>
</tr>
<tr>
<td>Energy Band</td>
<td>0.4–12 keV</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>~ 80% at 5.9 keV</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>2% at 5.9 keV (FWHM)</td>
</tr>
</tbody>
</table>

The CCD chip used for the SIS is a frame transfer type CCD and has the same structure as an optical CCD of the same type. Its detection part is made of an Si semiconductor of p-type and n-type connected each other through p-n junction. An insulator layer made of SiO₂ are attached on the front surface of the n-type Si, and electrodes are built on it. By supplying specific patterns of voltages on the electrodes charges in a pixel are transferred from a pixel to a next pixel. An electrode is also attached on the back. A depletion layer is developed in the device by supplying a bias voltage between the electrodes on the front and on the back.

Electric signals from the SIS camera are fed into SIS-AE and their pulse height are converted into digital signals with analog-to-digital converters. SIS-AE also generates driving clocks for the CCD chips, and monitors and controls temperature of the CCD chips. SIS-DE picks up X-ray events in the digital signals from SIS-AE with two digital signal processor (DSP) and sends them to the satellite data processor (DP), which commonly processes data from the SIS and the GIS and edits them into a telemetry format.

Figure 3.23a illustrates the quantum efficiency of the SIS as a function of incoming X-ray energy. Thus the SIS sensitivity covers approximately 0.4–10 keV. The CCD chips
Figure 3.23: (a) Detection efficiency of the SIS as a function of incoming X-ray energy. K-edges of O (0.53keV), Al (1.56keV), and Si (1.84keV) are clearly seen in the figure. This efficiency does not include optical blocking filter. (b) Energy resolutions of the SIS as a function of incoming X-ray energy for the single event. Energy resolutions with different read-out noise $N$ are plotted ($N \sim 5$ for the SIS). The read-out noise levels are given as the equivalent number of electrons.

and preamplifiers are cooled down to $-60$ °C with a thermo-electric cooler (TEC) from the backside of the chips in order to reduce thermal noise down to $N \sim 5$ electrons level. Thus the SIS achieves an energy resolution of about 150 eV FWHM over the whole energy range (Fig.3.23b); this is the best energy resolution ever achieved by non-dispersive X-ray spectrometers so far put into orbit.

3.4.2 Data processing

In order to perform proper photon-counting spectroscopy, the CCD frame must be scanned and read out fast enough so that event pile up (i.e. one pixel receiving more than one X-rays) is virtually negligible. Since the read out cycle is usually limited by the telemetry capacity, the SIS performs an extensive onboard CPU processing to compress the information. Instead of sending data from all the pixels to ground, the SIS basically picks up only those pixels in which the charge exceeds a certain threshold, and sends out their positions and pulse-heights. Moreover, to handle targets with different X-ray intensities and angular sizes under different telemetry rates, the SIS uses three different clocking modes; 1CCD, 2CCD and 4CCD modes. In the $n$CCD mode ($n = 1, 2, 4$), data from $n$ chips for each detector are read out. Because the time required to read a chip is fixed, this means that the integration time per chip per read out sequence is proportional to $n$. In the 1CCD mode, e.g., the usable field of view becomes limited to a quarter of the detector,
but the event pile up becomes least severe so that we can observe brighter sources than in other clocking modes. In view of background events and hot pixels (see below), this also means that the telemetry limit is relaxed.

The electrons produced in the depletion layer by an X-ray photon may be split into several adjacent pixels. The pattern of charge splitting over 3 × 3 pixels is called “event grade”. Because the splitting pattern of the particle induced events are generally different from that of the X-ray events, we can reduce the background by selecting the correct grades. When the charge is spread over more than 3 × 3 pixels, the event is rejected by the onboard CPU as a background event. In order to cope with the splitting of normal X-ray events, the SIS incorporates several data selection modes. For example, in so called “faint mode”, pulse-height of a certain pixel with event detection is always accompanied with pulse-heights of the eight surrounding pixels. We can then examine the event grade on ground, and restore the total pulse-height if necessary. In so called “bright mode”, the onboard CPU recognizes the charge splitting pattern, and sends only the total pulse-height for events with specified grades. The faint mode requires a larger telemetry capacity, but provides more information than the bright mode. Actually we can convert the faint mode data into the bright mode data on ground, but the reverse is impossible.

After the launch, several additional complications have been recognized with the SIS. One is so called “hot pixels”, i.e. particular pixels (though not necessarily fixed ones) which report false event detections too frequently. We must carefully remove these hot pixels in data analysis. When the hot pixels become too many, the SIS data suffer from significant telemetry deadtime. The hot pixels are increasing, and it has become almost impossible to utilize 4CCD mode with the faint mode before the end of 1994. Another problem is the light leakage, particularly in chip 2 and chip 3 of SIS0 (S0C2 and S0C3, respectively), presumably caused by a damage in the optical blocking filter. This makes the observation with S0C2 and S0C3 almost impossible when the day Earth is within ~ 25° from the target. It also affects the dark current of the whole CCDs in the daytime, and causes a subtle change in the energy to pulse-height relation.

In addition to the hot pixel rejection, the data filtering processing includes grade selections, and good time selection such as to avoid the influence of the day Earth. The major contents of the standard screening criteria (called rev.2 standard criteria) are listed in Table 3.5. See The ASCA Data Reduction Guide for details. Such as the case with the GIS, the PH information of the raw data is corrected for gain difference depending on the detector position. This is calibrated using the line features in the intrinsic background and the observed data of SNRs, particularly that of Cas-A. The position information is also
corrected. Thus, the raw data are converted to a set of event lists with $PI, DET\times Y/Y$, and some other quantities. We use these filtered and corrected event lists in our analysis.

Table 3.5: The major contents of "rev.2 standard" data screening criteria for the SIS (from The ASCA Data Reduction Guide).

<table>
<thead>
<tr>
<th>Condition</th>
<th>meaning</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRADE=0,2,3,4</td>
<td>reject particle events</td>
<td>to reduce the background</td>
</tr>
<tr>
<td>SAA=0</td>
<td>not in the south atlantic region</td>
<td>to avoid high background region</td>
</tr>
<tr>
<td>COR&gt;6</td>
<td></td>
<td>to avoid high background region</td>
</tr>
<tr>
<td>BR_EARTH&gt;20</td>
<td>target is far from day Earth rim</td>
<td>to avoid the day Earth effects</td>
</tr>
<tr>
<td>ELV&gt;10</td>
<td>target is far from night Earth rim</td>
<td>to avoid obscuration by atmosphere</td>
</tr>
</tbody>
</table>

### 3.4.3 SIS background

The background of the SIS is described in Gendreau (1994 ASCA News Letters No.2, p5) in detail. Here we describe it briefly. Like in the case with the GIS, the SIS background consists of the CXB and the internal background (NXB). The NXB of the SIS is sub-divided into two components; that accumulated on the imaging region, and that accumulated on the frame store region. The first component is proportional to the sky exposure time, while the second is proportional to the number of readouts and thus dependent on the SIS mode. Due to this second component, the count rate ratio of the internal background between 1 CCD mode and 4 CCD mode is $\sim 1.2$. In Fig.3.24, the internal background and the total background including CXB for 4 CCD mode are shown. The internal background consists of a flat continuum, as well as several fluorescence lines due to Fe-K (6.4, 7.0 keV), Ni-K (7.5, 8.3 keV), Au-L (9.7 keV), and Al-K (1.5 keV). The count rate of the internal background is reported to be constant for 2 years after launch, except in the soft band of 4 CCD mode (Ueda et al. 1996 ASCA News Letters No.4, p28 ; Ueda 1996).

### 3.4.4 Degradation of the SIS performance

The SIS energy resolution have been decreasing with time. The value at 6.7 keV was $\sim 168$ eV just after the launch, $\sim 180$ eV in 1996, and getting worse afterwards. Furthermore, the quantum efficiency of the detector is decreasing with time, which is significant in the lower end of the spectra below $\sim 1$ keV. This phenomena is known to have been growing since 1994, possibly from immediately after the launch.
Figure 3.24: The SIS background spectra of 4 CCD mode, integrated over all the chips.

The loss of quantum efficiency in the lower energy band is observed as an artificial excess absorption in the spectral fitting. This value was equivalent to the column density of $\leq 1 \times 10^{20} \text{ cm}^{-2}$ in 1994, $2 \sim 7 \times 10^{20} \text{ cm}^{-2}$ in 1996, and $7 \sim 10 \times 10^{20} \text{ cm}^{-2}$ in 2000. Because the column density at high galactic latitude is typically several times $10^{20} \text{ cm}^{-2}$, this can affect low-energy part of the SIS spectra taken after $\sim 1997$, although the data statistics often make it insignificant. A work is currently undergoing to understand the nature of this phenomenon and solve it, but there is no established correction method at this time. The "excess absorption" interpretation is solely empirical.

3.5 Comparison of the GIS and the SIS

As presented in the preceding sections, the two detectors have slightly different and complementary characteristics. In Fig.3.25a, we plot the effective area of the two detectors, which shows that the GIS has a larger effective area above $\sim 5 \text{ keV}$, while that of the SIS is larger below $\sim 2 \text{ keV}$. In Fig.3.25b, we plot the normalized background spectra of the two detectors. In general, both detectors have very low and stable background compared to other X-ray instruments. What is more, the GIS background can be estimated very well, up to an accuracy of $\sim 2\%$, and shape of the GIS background is nearly constant in
energies above $\sim 4$ keV, even though the background normalization varies (§3.3.6). For the SIS, the accuracy is $\sim 10\%$ (Ueda 1995).

The higher energy resolving power and efficiency for the soft X-rays make the SIS a better tool to study the hot gas component in groups of galaxies. In contrast, the accurate background estimation and the higher efficiency for the hard X-rays make the GIS more suited to the search for diffuse hard X-rays. This combination makes ASCA the best satellite for studying the hard X-rays from groups of galaxies.

Figure 3.25: Comparison of the GIS (black) and SIS (gray); (a) the effective area, and (b) the background spectra. The latter is normalized by a solid angle of arcmin$^2$. 
Chapter 4

THE HCG 62 GROUP

In this chapter, we analyze the ASCA data of the HCG 62 group, which is a near-by, X-ray bright group with the strongest evidence for a diffuse hard X-ray emission.

4.1 Overview

4.1.1 The HCG 62 Group

The HCG 62 group is one of the compact groups identified from the optical plates by Hickson and his colleges (e.g. Hickson 1982). It originally consists of four galaxies, NGC 4761, NGC 4759, NGC 4764 and HCG 062d. NGC 4761, the brightest among the four, is optically identified as a low luminosity AGN (LLAGN) by Coziol et al. (1998). None of them is a bright infrared source (e.g. Verdes-Montenegro et al. 1998).

Zabludoff and Mulchaey (1998a) extensively surveyed a 1°.5 × 1°.5 region around the group and measured the redshifts of 106 galaxies. They identified 45 of them as members of the group, and derived the mean recession velocity of 4385 ± 59 km s⁻¹, which indicates a redshift of 0.0146 and a distance of 58.5 h_{75}⁻¹ Mpc. Here H₀ = 75 h_{75} km s⁻¹ Mpc⁻¹ is the Hubble constant. The velocity dispersion was measured to be 376⁺52⁻46 km s⁻¹, which is a typical value for galaxy groups.

The central four galaxies are located extremely close to one another, within 3°.7 on the sky (Fig 4.1). In fact, NGC 4761 and NGC 4759 are separated by only 0'.4. Here, 1' corresponds to 17 h_{75}⁻¹ kpc. Such a high galaxy density and a fairly low velocity dispersion are thought to lead to galaxy merger. From comparison with N-body simulations, these four galaxies are suspected to merge into a large elliptical galaxy in ∼ 1 Gyr (Ponman and Bertram 1993).
Table 4.1: Optical properties of the central four galaxies of HCG 62

<table>
<thead>
<tr>
<th>name</th>
<th>HCG name</th>
<th>Pøs (1)</th>
<th>type (2)</th>
<th>$m_B$ (3)</th>
<th>$V$ (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 4761</td>
<td>HCG 62a</td>
<td>(193.274, -9.20444)</td>
<td>E3</td>
<td>13.30</td>
<td>4259 ± 10</td>
</tr>
<tr>
<td>NGC 4759</td>
<td>HCG 62b</td>
<td>(193.269, -9.20056)</td>
<td>S0</td>
<td>13.91</td>
<td>3561 ± 18</td>
</tr>
<tr>
<td>NGC 4764</td>
<td>HCG 62c</td>
<td>(193.291, -9.19861)</td>
<td>S0</td>
<td>14.97</td>
<td>4432 ± 17</td>
</tr>
<tr>
<td>HCG 62d</td>
<td>HCG 62d</td>
<td>(193.278, -9.25833)</td>
<td>E2</td>
<td>15.92</td>
<td>4174 ± 33</td>
</tr>
</tbody>
</table>

(2) Morphological type (Hickson et al. 1989).
(3) Blue magnitude (Carvalho et al. 1997).
(4) Recession velocity and error, in km/s (Carvalho et al. 1997).

Figure 4.1: Optical image of the central $6' \times 6'$ region of the HCG 62 group. The four central galaxies are visible. A bright source with a ring and a cross near the center is a foreground star.
4.1.2 Previous X-ray observations

Figure 4.2: The 0.5–2.3 keV PSPC X-ray image of HCG 62, smoothed with a Gaussian filter of $\sigma = 0'25$. The contours are logarithmically spaced, by factors of 1.34, where the lowest one corresponds to $7.2 \times 10^{-4}$ counts sec$^{-1}$ arcmin$^{-2}$. The dotted circle indicates the region 15$'$ around the group center, and solid circles shows the detected contaminating sources.

The HCG 62 group is known as the first compact group in which the X-ray emission from the extended hot gas, namely IGM (intra-group medium; § 2.1.3) has been confirmed (Ponman and Bertram 1993). Many authors have subsequently published results of their analysis of the ROSAT data of this group (e.g. Pildis et al. 1995; Saracco et al. 1995; Mulchaey et al. 1996; Ponman et al. 1996; Mulchaey and Zabludoff 1998; Davis 2000; Finoguenov et al 1999; Boute 2000; Nevalainen et al. 2000; Helsdon et al. 2000; Lloyd-Davies et al. 2000). They found a bright emission centered on the NGC 4761 galaxy, extending up to, at least, 15$'$ from the center (Fig.4.2). The emission is elongated a little toward the north east direction. The overall 0.5–2.3 keV spectrum was well fitted by a hot plasma model of temperature $kT \sim 1$ keV and metal abundance of $Z \sim 0.2Z_\odot$, with a mild temperature gradient as shown in Fig.4.3. The bolometric luminosity of the IGM component within a projected radius $r < 22'4$ is $L_{bol} = 3.9 \times 10^{42}h_{75}^{-2}$ erg s$^{-1}$ (Mulchaey and Zabludoff 1998).

The azimuthally averaged radial X-ray surface brightness profile shows a clear central peak compared with the canonical beta-model profile, requiring a narrower second
Figure 4.3: Temperature of the IGM obtained with Raymond-Smith model fits to the ring sorted PSPC spectra. Errors are in 1 $\sigma$ (Zabludoff and Mulchaey 1998).

Figure 4.4: Radial count-rate profile of the 0.6–2.3 keV PSPC image, fitted with a double-beta model (Zabludoff and Mulchaey 1998).
beta-model component (Fig.4.4). The component larger in scale is called “extended” component and the smaller one “central” component. The best fit parameters of the double beta-model, however, differs significantly among the authors. This is possibly due to a little difference in the background modeling of the PSPC detector, which will affect the “extended” component parameters and then those of the “central” component through parameter coupling between the two model components.

Using the parameters by Ponman and Bertran (1993), the gas mass within a three dimensional radius of \( R = 340 h_{75}^{-1} \) kpc (20') from the group center is calculated as \( M_{\text{gas}} = 9.0 \times 10^{11} h_{75}^{-2.5} M_\odot \), and the total gravitating mass as \( M_{\text{total}} = 1.7 \times 10^{13} h_{75}^{-1} M_\odot \). These values are thought to be typical of X-ray luminous groups. Using results of other authors change these values by a factor of up to \( \sim 3 \).

In the \( r < 15' \) region of the PSPC image (Fig.4.2), there are 5 point sources clearly visible. We mask out the regions within \( r < 3' \) from these sources, when we analyze the spectra of the data in the following sections.

4.2 ASCA Observations and Images

We observed the HCG 62 group five times with ASCA, covering a \( \sim 1^\circ \times 1^\circ \) region with the GIS. These consist of a pointing at the group center performed in the AO-1 phase (1994 January), and additional four surrounding pointings performed in the AO-6 phase (1998 January). These pointing positions are shown in Fig.4.5a. In all observations, the GIS was operated in PH-mode with nominal bit assignment, and the SIS was operated in 2 CCD clocking mode. The SIS data-format of the first observation was faint-mode throughout the observation, while that of the latter four observations was faint-mode for high bit-rate data and bright-mode for medium bit-rate data.

All the data are processed through the standard analysis procedure as described in Chapter 3. For the GIS, we selected the time interval when the source elevation angle from the earth rim is greater than 5\(^\circ\), and the data satisfy the “flare cut” condition listed in Table 3.3. For the SIS, we used the “\textit{rev.2 standard}” screening criteria listed in Table 3.5.

Each observation yielded a good exposure of \( 21 \sim 29 \) ksec for the GIS, and the obtained net exposure sums up to be 121 ksec. For the GIS, we use the data from all observations in both image and spectral analysis. The SIS exposure was 17 ksec for the first observation, and \( 21 \sim 23 \) ksec for the latter four. For analysis of the SIS spectra, we however use only the data from the first observation, because the strong performance degradation in
late years made it difficult to use the last four SIS data in combination with the first observation (see § 3.4.4 for detail).

<table>
<thead>
<tr>
<th>Obs. ID</th>
<th>date</th>
<th>sequence ID(1)</th>
<th>GIS-2 center position (Ra, Dec, Roll(2))_{(deg)}</th>
<th>GIS exposure (sec)</th>
<th>SIS mode(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14 Jan 1994</td>
<td>81012000</td>
<td>(193.34, -9.10, 269.24)</td>
<td>29293</td>
<td>2 CCD F/F</td>
</tr>
<tr>
<td>2</td>
<td>13 Jan 1998</td>
<td>86008000</td>
<td>(193.26, -9.06, 238.73)</td>
<td>21467</td>
<td>2 CCD F/B</td>
</tr>
<tr>
<td>3</td>
<td>14 Jan 1998</td>
<td>86008010</td>
<td>(193.49, -9.06, 238.73)</td>
<td>23290</td>
<td>2 CCD F/B</td>
</tr>
<tr>
<td>4</td>
<td>15 Jan 1998</td>
<td>86008020</td>
<td>(193.54, -9.23, 238.73)</td>
<td>25466</td>
<td>2 CCD F/B</td>
</tr>
<tr>
<td>5</td>
<td>16 Jan 1998</td>
<td>86008030</td>
<td>(193.30, -9.29, 238.73)</td>
<td>21962</td>
<td>2 CCD F/B</td>
</tr>
</tbody>
</table>

(1) PI of the first observation is Yasuhiro Sakima, and that of the latter four observations is Yasushi Fukazawa.

(2) Roll of the satellite is defined as the angle from the north to the satellite Y-axis, measured clockwise; 270° means that the satellite Y-axis is pointing to the east.

(3) SIS clocking-mode and data-mode. See text for detail.

In Fig.4.5b, we show the obtained 0.5–10 keV GIS image of the HCG 62 group, overlaid on an optical image. We have subtracted the background in a standard manner (§ 3.3) and combined the data from the two GIS sensors. Then we combined images from the five observing positions and corrected the result for exposure difference among them. We also corrected the satellite attitude for thermal distortion of the star sensor axis, using a software `offsetcoord`.

Figure 4.5 clearly reveals diffuse X-ray emission, which extends up to \( \sim 15' \) from the group center, in agreement with the PSPC image (Fig.4.2). X-ray centroid of the GIS image is within \( \sim 0'.2 \) from NGC 4761, which is well within the astrometric accuracy of ASCA (\( \sim 0'.5 \)).

In Figs.4.6 and 4.7, we show two-band X-ray images, obtained with the GIS and the SIS, respectively. The largely extended emission is dominant in the soft-band image, below 2.0 keV, because of the low temperature of the IGM. The extended emission is also observable in the hard-band image. In these GIS/SIS images, the five ROSAT point sources (Fig.4.2) are generally recognized. We must hence remove them in the following data analysis. Precisely speaking, some sources clearly visible in the PSPC image are not so clear in, for example, the GIS hard band image. This is naturally explained by the difference of the spectra among these sources and the band pass among three detectors (PSPC, GIS and SIS).
Figure 4.5: (a) The GIS 0.5–10.0 keV X-ray mosaic image synthesized from five pointings, plotted with their observing positions (indicated by numbers). North is top, and east is to the left. Contours are logarithmically spaced, by factors of 1.7 starting from $1.9 \times 10^{-5}$ cts s$^{-1}$ arcmin$^{-2}$. The image is presented after background subtraction, correction for exposure (but not for the vignetting), and smoothing with a Gaussian function with $\sigma = 0.5\arcmin$. Solid circle represents the region $15\arcmin$ from the group center. (b) The same GIS contour image, overlaid on an optical gray scale image from Digitized Sky Survey.
Figure 4.6: The same as Fig.4.5 but in 0.5–2.0 keV (left) and 2.0–10 keV (right). The contours are logarithmically spaced, by factors of 1.7 starting from 1.6 and 1.3 \times 10^{-5} \text{ cts s}^{-1} \text{ arcmin}^{-2} for the left and right panels, respectively. Small and large circles centered on the X-ray peak represent 3' and 15' from NGC 4761, respectively. Other circles indicate regions eliminated to exclude the five point sources detected with the ROSAT PSPC.

Figure 4.7: The SIS image in 0.5–2.0 keV (left) and 2.0–7.5 keV (right) obtained by combining the five pointings. Both images are smoothed with a $\sigma = 0'3$ Gaussian kernel. Background is inclusive and exposure is corrected. The contours are logarithmically spaced, by factors of 1.7 starting from 8.1 and 6.5 \times 10^{-5} \text{ cts s}^{-1} \text{ arcmin}^{-2} for the left and right panels, respectively. Circles are the same as those of Fig.4.6. Boxes show the region observed with the first pointing, part of which is used for the spectral study.
4.3 Spectral Analysis

4.3.1 Derivation of the spectra

![Graphs showing spectral analysis](image)

Figure 4.8: The raw GIS spectra of the HCG 62 group obtained in the five observations. The on-source spectra and the estimated background are shown. The numbers plotted indicates the observation ID.

We extracted the spectra from a circular region of radius 15' centered on the X-ray centroid, where the regions 3' around the five point sources were masked out (see Figs. 4.5 and 4.7). For the GIS, we first collected the spectra of each observation separately. Note that the spectral accumulation region is only partially covered by most of the latter four pointings. We next added spectra from the two GIS detectors (GIS2 and GIS 3) into a single GIS spectrum, after appropriate corrections for their gain differences. In Fig.4.8, we show the obtained spectra together with the background (CXB+NXB; § 3.3.5 and 3.3.4), which were obtained from blank-sky observations and corrected for the NXB variation. The background estimation error for each observation ranges from 3.7 to 4.7%, and we added these values as a systematic error in the background spectra in Fig.4.8 (see § 4.5.2).

Then, we added the five spectra to obtain an average GIS spectrum, which is shown in Fig.4.9a. We divided the spectrum of each observation with the averaged spectrum,
after correcting it for the difference of the XRT effective area. The ratio spectra become almost flat, and fittings with a constant value were acceptable for all observations. This indicates that the five spectra have generally similar shapes. The derived relative spectral normalization ranges from 0.8 to 1.1; this is not surprising because the region \( r < 15' \) is not completely covered by some observations. In the following analysis, we therefore mainly use the averaged spectrum which has the best photon statistics. The background estimation error involved in this averaged spectrum reduced to 1.9%, which is considered as a systematic error in the spectral evaluation. The background subtraction procedure is evaluated in further detail later in § 4.5.2.

For the SIS, we added data from the two SIS detectors (SIS0 and SIS1) of the first observation into a single SIS spectrum. Again, regions around the five point sources were masked out. The background spectrum was obtained from blank-sky observations. We show this spectrum in Fig.4.9b. As noted before, we did not analyzed the SIS spectra of the other four pointings.

In the GIS spectra (Fig 4.9a), the majority of signal photons are in low energies (< 2 keV), but the signal is detectable up to \( \sim 8 \) keV. Above \( \sim 8 \) keV, the on-source spectrum agrees very well with the background spectrum, indicating that our background estimation is accurate. In the SIS spectra (Fig 4.9b), the signal photons are detected up to \( \sim 4 \) keV. Clear peaks at 6.4 keV and 7.5 keV, both observable in the on-source and background spectra, are instrumental Fe-K and Ni-K lines, respectively.

Both the GIS and SIS spectra show bumpy structures around 1 keV, 1.4 keV and 1.8 keV. They are line emissions from Fe-L shell, Mg-K and Si-K shell, respectively, which are characteristic of emission from optically thin hot plasma with \( kT \sim 1 \) keV.

### 4.3.2 Single component fits

By using the background and on-source spectra in Fig.4.9, we have obtained background-subtracted GIS and SIS spectra, as shown together in Fig.4.10. We jointly fitted them with an optically thin thermal plasma emission model, which is based on the emissivity calculations of Mewe and Kaastra (Mewe et al. 1985, 1986; Kaastra et al. 1992), with Fe-L calculations by Liedahl et al. (1995). Hereafter, we call this model MEKAL model. We also tried a model by Raymond and Smith (hereafter Raymond-Smith model; Raymond and Smith 1977). The mutual abundance ratios of the metals were constrained to be the same as the solar ratios (see § 2.2.2), while the overall metal normalization was set free. We fixed the redshift to 0.0146, and the hydrogen column density to the Galactic value
Figure 4.9: Raw spectra of the HCG 62 group. (a) The raw GIS spectrum extracted from a circular region of radius 15' centered on the X-ray centroid, co-adding the five spectra shown in Fig.4.8. Shown for comparison is the background spectrum. (b) The raw SIS spectrum extracted from the same circular region, compared with that of background derived from blank-sky observations. Note that the SIS does not cover the whole region within 15'.

\[ N_H = 3.01 \times 10^{20} \text{ cm}^{-2} \], derived from HI radio emission map by Dickey and Lockmann (1990). We used XSPEC v10.0 (Arnaud 1996) package throughout the spectrum fitting. To compensate the difference in the integration region between the GIS and SIS, we allowed the model normalization to change separately between the two types of detectors.

Compared to the GIS, the SIS has a better energy resolution together with a larger effective area around \( \sim 1 \) keV. Because the X-ray emission from hot plasma with \( kT \sim 1 \) keV is characterized by strong line emissions around \( \sim 1 \) keV, the SIS mainly determines the parameters of the IGM component. On the other hand, the GIS has a larger effective area above \( \sim 2 \) keV with a well calibrated and even lower detector background, which dominates the spectra in the hard band. Therefore, the GIS is sensitive to any excess hard X-ray emission above the IGM component, though it can also determine the IGM component to a modest extent. In the spectral fitting, we accordingly use the 0.9–9.0 keV energy band for the GIS and the 0.7–4.0 keV energy band for the SIS.

The results of the single component fits are summarized in Fig.4.10 and Table 4.3. When we fitted spectra jointly over the full energy band, we obtained a temperature of \( \sim 1 \) keV with either plasma model, in agreement with the ROSAT results. The fit, however, is very poor with reduced \( \chi^2 \) of \( \sim 3 \). The data clearly shows a strong hard X-ray excess above the model prediction. In contrast, when we fitted the spectra in the hard
Figure 4.10: The background-subtracted GIS (black) and SIS (gray) spectra of HCG 62, accumulated within 15' from the group center. The histogram in the upper panels show the best fit hot gas model (MEKAL model), and the lower panels present the residual spectra. The joint GIS and SIS fit is performed over the full energy range (left), and in the range above 2.5 keV (right).

Table 4.3: Best fit parameters from the joint fit to the GIS and SIS spectra obtain from the circular region of $r < 15'$.  

<table>
<thead>
<tr>
<th>MEKAL model fit</th>
<th>Raymond-Smith model fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$kT$ ( keV )</td>
<td>$kT$ ( keV )</td>
</tr>
<tr>
<td>Abun. ($Z_\odot$)</td>
<td>Abun. ($Z_\odot$)</td>
</tr>
<tr>
<td>$\chi^2/d.o.f$</td>
<td>$\chi^2/d.o.f$</td>
</tr>
<tr>
<td>1.03$^{+0.03}_{-0.02}$</td>
<td>1.01$^{+0.02}_{-0.02}$</td>
</tr>
<tr>
<td>0.13$^{+0.02}_{-0.01}$</td>
<td>0.18$^{+0.02}_{-0.03}$</td>
</tr>
<tr>
<td>241.2/74</td>
<td>247.0/74</td>
</tr>
</tbody>
</table>
energy band above 2.5 keV with the same spectral model, we obtained $kT = 2.35^{+0.66}_{-0.42}$ keV. This is inconsistent with the temperature derived from the full-band fitting, and the structure around $\sim 1$ keV in the data remain unexplained (Fig.4.10 right panel).

In general, there is a relation between the galaxy velocity dispersion and the IGM temperature as $\beta_{\text{spec}} = \frac{\mu_{\text{gas}}^2}{kT_{\text{gas}}} \sim 1.0$ ($kT-\sigma$ relation; equation 2.15). Using the fitted temperature and the measured velocity dispersion of the HCG 62 group (376$^{+52}_{-46}$ km s$^{-1}$), the ratio becomes $\beta_{\text{spec}} = 0.86^{+0.27}_{-0.22}$ for the full-band fitting and $\beta_{\text{spec}} = 0.38^{+0.21}_{-0.15}$ for the hard-band fitting. The later value largely deviates from the general value of 1.0, suggesting strongly that the $kT \sim 1$ keV component is the “real” IGM of the group, and there is some additional hard X-ray emission from this sky region.

### 4.3.3 Two component fits

Now that the spectra of HCG 62 cannot be fitted with a single temperature plasma model, we attempt two-component fits. We first fitted the spectra with a sum of a single temperature MEKAL and a power law model (hereafter, MEKAL+PL model). Because our aim here is to quantify the amount of the “excess hard X-ray emission”, we fixed the photon index $\Gamma$ to 2.0, which is a representative value for various non-thermal emission from energetic particles. Then, as shown in Table 4.4 and Fig.4.11a, the fit has been dramatically improved and become acceptable, at 99% confidence level. The hard component dominates the spectra above $\sim 4$ keV, and the 2–10 keV flux of the hard component is $\sim 20\%$ of the 0.5–10 keV flux of the IGM component.

We also examined the fit with $\Gamma$ set free. As shown in Table 4.4 and Fig.4.11b, the index becomes $\Gamma = 2.63^{+0.69}_{-0.38}$, and the power law component dominates the spectra, above 1.5 keV as well as bellow 0.8 keV. The flux of the hard component increased by 15% compared to the case of $\Gamma = 2.0$. Although the $\chi^2$ value decreases by $\sim 3$, we may not use this result since it implies too large a contribution from the hard component, and hence unrealistic.

We also tried a second MEKAL component with a higher temperature (hereafter, 2-MEKAL model), in place of the power law component. In the fitting, the metal abundances for the two MEKAL components were constrained to be the same, because we cannot constrain them separately. As shown in Table 4.4 and Fig.4.11c, this gave a hot component temperature of $kT_{\text{hot}} > 4.4$ keV. The goodness of the fit is very similar to that from the MEKAL+PL model fit, and the fluxes of the hard component are also similar. With this high temperature, the hot component is very similar in shape to the power law
component with $\Gamma = 2.0$.

Table 4.4: Results of the joint fit to the GIS and SIS spectra with two component models.

<table>
<thead>
<tr>
<th>model ID</th>
<th>$kT$ (keV)</th>
<th>Abun. $(Z_\odot)$</th>
<th>$\Gamma$ or $kT_{\text{hot}}$</th>
<th>Soft Flux (erg s$^{-1}$ cm$^{-2}$)</th>
<th>Hard Flux (erg s$^{-1}$ cm$^{-2}$)</th>
<th>$\chi^2/d.o.f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEKAL+PL</td>
<td>$0.98^{+0.04}_{-0.04}$</td>
<td>$0.59^{+2.5}_{-0.4}$</td>
<td>$2.63^{+0.09}_{-0.38}$</td>
<td>$3.16 \times 10^{-12}$</td>
<td>$1.34 \times 10^{-12}$</td>
<td>98.5/72</td>
</tr>
<tr>
<td></td>
<td>$0.95^{+0.05}_{-0.04}$</td>
<td>$0.21^{+0.04}_{-0.04}$</td>
<td>2.0 (fixed)</td>
<td>$4.84 \times 10^{-12}$</td>
<td>$1.16^{+0.16}_{-0.17} \times 10^{-12}$</td>
<td>101.6/73</td>
</tr>
<tr>
<td>2-MEKAL</td>
<td>$0.96^{+0.03}_{-0.04}$</td>
<td>$0.17^{+0.03}_{-0.03}$</td>
<td>$11.8^{+\infty}_{-7.4}$</td>
<td>$5.37 \times 10^{-12}$</td>
<td>$1.10^{+0.17}_{-0.17} \times 10^{-12}$</td>
<td>102.3/72</td>
</tr>
</tbody>
</table>

(1) The 0.5–10 keV flux of the (cooler) MEKAL component.

(2) The 2–10 keV flux of the power-law or hotter MEKAL component.

### 4.3.4 Improved modeling of the IGM emission

Although the spectral fit has been improved considerably by introducing the two component models, the $\chi^2$ values of both MEKAL+PL model and 2-MEKAL model are still unacceptable at 90% confidence level. This is mainly due to two peaks visible in the residual spectra, around 1.1 keV and 1.8 keV. The former is in the Fe-L line region, and the latter is in the Si-K line region, suggesting that the modeling of these lines needs improvements. This may occur when the abundance ratio between the Si and Fe is different from the solar ratio and/or the IGM involves multiple temperature as suggested by the PSPC results (Fig.4.3).

We set the abundance ratios free, by introducing a variable-abundance MEKAL model (vMEKAL model), where the abundance of each heavy element can be changed separately. For simplicity, we group major heavy elements into two groups in view of their origin, following Matsushita (1996); O, Ne, Na, Mg, Al, Si, S, Ar and Ca; and Fe and Ni. Majority of the first group is the “$\alpha$-elements”, which are mainly produced through $\alpha$-process in type-II supernova (e.g. Nomoto et al. 1984). The second group is mainly synthesized in type-Ia supernova. Abundances of the other elements (He, C and N) are fixed at the solar value. Hereafter, we denote the abundance of the first group $Z_\alpha$, and that of the second group $Z_\text{Fe}$. We jointly fitted the GIS and SIS spectra with a sum of a vMEKAL and a power law model (vMEKAL+PL model). As shown in Fig.4.12a and Table 4.5, the $\chi^2$ value decreased and the obtained two abundances are reasonable in comparison with previous ASCA works (e.g. Matsushita 1997), but the fit is not yet acceptable: the residual around 1.8 keV has decreased but that around 1.1 keV has not.
Figure 4.11: Tow component joint fits to the GIS and SIS spectra as in Fig.4.10. (a) A sum of a MEKAL and a power law model with photon index fixed at $\Gamma = 2.0$. (b) The same as (a), but the photon index is set free. (c) A sum of two MEKAL components.
We accordingly fixed again the abundance ratio back to the solar ratios, and tried a model with two MEKAL components and a power law (2-MEKAL+PL model), to represent non-isothermality of the IGM. The metal abundances of the two MEKAL component are constrained to be the same. As shown in Fig.4.12b and Table 4.5, the fit has further been improved, but still unacceptable. In this case, the residual feature around 1.1 keV has decreased but that around 1.8 keV remained. Thus, we need to consider both the non-isothermal effect and non-solar abundance ratios of the IGM.

Then we fitted the spectra with a sum of two vMEKAL components and a power law component (2-vMEKAL+PL model). Both \( Z_\alpha \) and \( Z_{Fe} \) are constrained to be the same between the two vMEKAL components. The results are shown in Fig.4.12c and Table 4.5. The fit has finally attained an acceptable level at 90%. The derived temperatures of 0.73 keV and 1.14 keV are consistent with the PSPC result in general. The 0.5–10 keV flux of the IGM components is \( 5.05^{+0.36}_{-0.32} \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \), and the 2-10 keV flux of the hard component is \( 1.08^{+0.18}_{-0.22} \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \), the latter being similar to that derived from the MEKAL+PL model fit in the last subsection.

We also tried a fit where we set \( \Gamma \) free, and obtained \( \Gamma = 1.55^{+1.21}_{-0.80} \) with \( \chi^2 = 81.5 \) for 69 dof. If we put another (i.e., a third) vMEKAL component in place of the power law component, the resulting temperature is \( kT = 32.0^{+8.9}_{-28.3} \text{ keV} \) with \( \chi^2 = 81.6 \) for 69 dof. Again these results are similar to the MEKAL+PL model fit in the last subsection. In summary, we regard the 2-vMEKAL+PL model as our best favorite spectral model for the X-ray emission from HCG 62.

<table>
<thead>
<tr>
<th>model ID</th>
<th>( kT_1 ) (keV)</th>
<th>( kT_2 ) (keV)</th>
<th>( Z_\alpha ) (Z(_\odot))</th>
<th>( Z_{Fe} ) (Z(_\odot))</th>
<th>( \Gamma ) (fixed)</th>
<th>( \chi^2/d.o.f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>vMEKAL+PL</td>
<td>0.94^{+0.04}_{-0.07}</td>
<td>0.33^{+0.13}_{-0.10}</td>
<td>0.23^{+0.06}_{-0.04}</td>
<td>2.0 (fixed)</td>
<td>97.3/72</td>
<td></td>
</tr>
<tr>
<td>2-MEKAL+PL</td>
<td>0.71^{+0.14}_{-0.18}</td>
<td>1.09^{+0.38}_{-0.33}</td>
<td>0.26^{+0.10}_{-0.05}</td>
<td>2.0 (fixed)</td>
<td>91.1/71</td>
<td></td>
</tr>
<tr>
<td>2-vMEKAL+PL</td>
<td>0.73^{+0.10}_{-0.21}</td>
<td>1.14^{+0.18}_{-0.64}</td>
<td>0.53^{+0.27}_{-0.18}</td>
<td>0.34^{+0.12}_{-0.08}</td>
<td>2.0 (fixed)</td>
<td>82.3/70</td>
</tr>
</tbody>
</table>

4.3.5 Possible origins of the hard excess emission

As shown in the preceding subsections, the spectra of the \( 0' < r < 15' \) region of HCG 62 have been found to exhibit a strong hard excess component. There are several possible
Figure 4.12: Joint fits to the same GIS and SIS spectra as in Fig.4.10 with a multi component models. In all cases, the photon index of the power law component is fixed at $\Gamma = 2.0$. (a) A sum of a vMEKAL and a power law. (b) A sum of two MEKAL components and a power law. (c) A sum of two vMEKAL components and a power law.
Table 4.6: Possible origins of the hard excess emission.

<table>
<thead>
<tr>
<th>type</th>
<th>item</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artifacts</td>
<td>background estimation</td>
<td>§ 4.5.2</td>
</tr>
<tr>
<td></td>
<td>NXB</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CXB(^{(1)})</td>
<td>§ 4.5.5, 4.5.6</td>
</tr>
<tr>
<td>XRT response</td>
<td>PSF and effective area</td>
<td>§ 4.5.3</td>
</tr>
<tr>
<td>IGM modeling</td>
<td></td>
<td>§ 4.5.4</td>
</tr>
<tr>
<td>Celestial</td>
<td>point-like</td>
<td>§ 4.4.1</td>
</tr>
<tr>
<td></td>
<td>central AGN</td>
<td></td>
</tr>
<tr>
<td>extended</td>
<td>LMXBs in the member galaxies</td>
<td>§ 4.6</td>
</tr>
<tr>
<td></td>
<td>AGNs in the member galaxies</td>
<td>§ 4.4.2</td>
</tr>
<tr>
<td></td>
<td>AGNs in the background sky (~ CXB)</td>
<td>§ 4.5.5, 4.5.6</td>
</tr>
<tr>
<td></td>
<td>diffuse (thermal)</td>
<td>§ 4.6</td>
</tr>
<tr>
<td></td>
<td>diffuse (non-thermal)</td>
<td></td>
</tr>
</tbody>
</table>

\(^{(1)}\) Also treated as a celestial origin.

candidates for the origin of this component, celestial and artificial, as listed in Table 4.6.

First of all, we must examine whether the hard X-ray emission is artificial or not. Apart from its statistical significance, we have to consider all systematic origins. We must critically examine the background estimation, which is crucial to this study. There are two components, the NXB (§ 3.3.4) and the CXB (§ 3.3.5). The former is completely instrumental, while the CXB, considered to be a sum of discrete sources among the sky, is partially celestial. Other possibilities include the effect of the complicated point spread function (PSF) of the XRT+GIS and wrong modeling of the IGM emission.

If the hard X-ray emission truly has a celestial origin, it may be a discrete source, a sum of many discrete sources, or a diffuse source. Candidates for the discrete sources are, AGN(s) and LMXBs of the member galaxies of the group, and also AGN(s) in the background sky. As a diffuse source, it may be either of a thermal origin, with high temperature such as \(~ 10 \text{ keV}\), or of a non-thermal origin, such as the relativistic electrons distributed in the vicinity of the group.

In the following sections, we examine all these possibilities one by one. No matter whether the origin is instrumental or celestial, the spatial distribution of the detected hard excess gives us a strong clue to the nature of the hard excess. In the next section, we therefore start with analyzing the spatial extent of the emission.
4.4 Spatial Distribution of the Hard X-ray Emission

4.4.1 Radial dependence of the spectra

To see the spatial distribution of the excess hard X-ray emission, we divided the spectral integration region into three annular regions; \( r < 3' \), \( 3' < r < 7.5' \) and \( 7.5' < r < 15' \), with \( r \) denoting the projected radius from the X-ray centroid. We also examined the added spectra of the latter two regions (\( 3' < r < 15' \)). The obtained spectra are shown in Fig.4.13, and the fit results are listed in Tables 4.7 and 4.8. All of them show similar shape to the spectra of the \( 0' < r < 15' \) region (see Fig.4.10): majority of signal photons are in low energies (\(< 2 \) keV), while the signal is detectable up to \( \sim 8 \) keV with the GIS. When we fit them with a single temperature vMEKAL model, they show clear hard tails which make the fits unacceptable, with reduced \( \chi^2 \) ranging from 1.5 to 2.2. By adding a power law component with \( \Gamma = 2.0 \) (vMEKAL+PL model), the fits became acceptable except that of the central region, which in turn became acceptable by adding another vMEKAL component (2-vMEKAL+PL model). This is reasonable, because the IGM temperature gradient is strongest within the central 1'5 (Fig.4.3).

Thus, the excess hard X-ray emission is visible in all the four spectra. Furthermore, the hard component appears to become progressively prominent, relative to the IGM component, toward the outer regions. Because \( \sim 80\% \) of the photons from a point source falls within 3' of the image centroid, the hard component may not be attributed to any point-like source located around the group center. Thus, we have ruled out one particular candidate in Table 4.6 (i.e., “central AGN”).

Table 4.7: Best fit parameters to the radially sorted GIS and SIS spectra, fitted with a sum of a single temperature vMEKAL component and a power law component with \( \Gamma = 2.0 \) (vMEKAL+PL model).

<table>
<thead>
<tr>
<th>data ID</th>
<th>( kT )</th>
<th>( Z_\alpha )</th>
<th>( Z_{Fe} )</th>
<th>( \text{Flux}^{\text{MEKAL}}_{(0.5-10 \text{ keV})} )</th>
<th>( \text{Flux}^{\text{PL}}_{(2-10 \text{ keV})} )</th>
<th>( \chi^2/d.o.f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0' &lt; r &lt; 3' )</td>
<td>0.88^{+0.09}_{-0.03}</td>
<td>0.63^{+0.41}_{-0.25}</td>
<td>0.34^{+0.16}_{-0.08}</td>
<td>1.38^{+0.06}_{-0.04} \times 10^{-12}</td>
<td>2.56^{+0.29}_{-0.49} \times 10^{-13}</td>
<td>88.3/72</td>
</tr>
<tr>
<td>( 3' &lt; r &lt; 7.5' )</td>
<td>0.99^{+0.06}_{-0.07}</td>
<td>0.39^{+0.27}_{-0.17}</td>
<td>0.21^{+0.10}_{-0.06}</td>
<td>1.40^{+0.08}_{-0.06} \times 10^{-12}</td>
<td>2.99^{+0.70}_{-0.80} \times 10^{-13}</td>
<td>71.9/72</td>
</tr>
<tr>
<td>( 7.5' &lt; r &lt; 15' )</td>
<td>0.85^{+0.12}_{-0.08}</td>
<td>0.11^{+0.21}_{-0.11}</td>
<td>0.15^{+0.06}_{-0.05}</td>
<td>2.12^{+0.14}_{-0.16} \times 10^{-12}</td>
<td>6.68^{+1.53}_{-1.55} \times 10^{-13}</td>
<td>59.3/60</td>
</tr>
<tr>
<td>( 3' &lt; r &lt; 15' )</td>
<td>0.96^{+0.06}_{-0.08}</td>
<td>0.21^{+0.15}_{-0.11}</td>
<td>0.19^{+0.06}_{-0.05}</td>
<td>3.43^{+0.23}_{-0.13} \times 10^{-12}</td>
<td>9.17^{+1.85}_{-1.90} \times 10^{-13}</td>
<td>81.9/72</td>
</tr>
</tbody>
</table>
Figure 4.13: Ring sorted spectra of HCG 62, fitted with vMEKAL+PL model, shown for (a) \(0' < r < 3'\), (b) \(3' < r < 7.5'\), (c) \(7.5' < r < 15'\) and (d) \(3' < r < 15'\). (a') is the same as panel (a), but fitted with 2-vMEKAL+PL model. \(\Gamma\) is fixed at 2.0 in all cases.
Table 4.8: Best fit parameters of the $0' < r < 3'$ GIS and SIS spectra, fitted with a sum of double vMEKAL components and a power law component with $\Gamma = 2.0$ (2-vMEKAL+PL model).

<table>
<thead>
<tr>
<th>$kT_1$</th>
<th>$kT_2$</th>
<th>$Z_\odot$</th>
<th>$Z_{Fe}$</th>
<th>Flux$^{\text{MEKAL}}_{(0.5-10\text{ keV})}$</th>
<th>Flux$^{\text{PL}}_{(2-10\text{ keV})}$</th>
<th>$\chi^2/d.o.f$</th>
</tr>
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<tr>
<td>(keV)</td>
<td>(keV)</td>
<td>($Z_\odot$)</td>
<td>($Z_\odot$)</td>
<td>(erg/s/cm$^2$)</td>
<td>(erg/s/cm$^2$)</td>
<td></td>
</tr>
<tr>
<td>0.69$^{+0.12}_{-0.20}$</td>
<td>1.12$^{+0.22}_{-0.14}$</td>
<td>1.17$^{+1.09}_{-0.52}$</td>
<td>0.66$^{+0.35}_{-0.25}$</td>
<td>1.36$^{+0.04}_{-0.03}$ $\times$ $10^{-12}$</td>
<td>2.19$^{+0.44}_{-0.50}$ $\times$ $10^{-13}$</td>
<td>74.0/70</td>
</tr>
</tbody>
</table>

### 4.4.2 Radial surface brightness profiles

In order to complement the analyses of the last subsection, we have directly analyzed the spatial extent of the hard component utilizing the GIS images. From the spectral fittings shown in Fig.4.13, the hard component is dominant above $\sim 4$ keV. We therefore made an X-ray image in the highest 4.0–8.0 keV range. The result is shown in Fig.4.14a, where the positions of the galaxies around HCG 62 are also plotted. We also plot the 0.5–4.0 keV band image in Fig.4.14b, which represents the distribution of the hot gas component. The X-ray image of the hard component is rather clumpy and occasionally becomes even negative. This is due to the poor photon statistics ($\sim 700$ cts in the encircled region; see § 4.5.1) and the clumpy nature of the CXB. Here, the CXB fluctuation level is estimated to be $\sim 0.5 \times 10^{-5}$ cts s$^{-1}$ arcmin$^{-2}$ at 1$\sigma$ level, which can naturally explain the image clumpiness (see also Appendix B.1). Two out of the five ROSAT point sources are detectable in both images, especially in the hard band. However, there is no correlation between the galaxies and hard X-ray distribution, implying that the galaxies contribute little in the 4.0–8.0 keV band image (see Appendix B.2). We have hence excluded another candidate origin, i.e., “AGNs in the member galaxies” in Table 4.6. We also searched the 4.0–8.0 keV band image for any azimuthal anisotropy of the hard component, and found no statistically significant evidence for it, when we take the CXB fluctuation into account (see Appendix B.3).

We then made an azimuthally-averaged radial profile of both images, excluding the region around the five point sources as before. The results, given in Fig.4.14c, show that the 4.0–8.0 keV emission is detectable up to $\sim 15'$, and is nearly as extended as the soft X-ray emission, which is significantly more extended than the instrumental PSF. Since the 4.0–8.0 keV emission is dominated by the hard component, the hard component itself is inferred to be significantly extended, at least to the level of the IGM emission.
Figure 4.14: (a) The 4.0–8.0 keV GIS gray scale image for the central 35′ × 35′ of HCG 62, corrected for the exposure after subtracting the background. The image was smoothed with a σ = 1′ Gaussian function. The contour is linearly spaced with separations of 0.5 × 10^{-5} cts s^{-1} arcmin^{-2}, which roughly corresponds to the 1σ level of the CXB fluctuation. The thick line shows the extraction region of the spectra. Crosses represents the position of the galaxies (Zabludoff and Mulchaey 1998). (b) Similar to panel (a), but for the 0.5–4.0 keV band. The contour is scaled by the central brightness to that of panel (a), linearly spaced with separations of 1.2 × 10^{-4} cts s^{-1} arcmin^{-2}. A supplemental contour of 0.6 × 10^{-4} cts s^{-1} arcmin^{-2} is also plotted in dotted lines. (c) Radial profiles of the X-ray emission, in 4.0–8.0 keV (filled boxes) and 0.5–4.0 keV (open circles with histograms). Thick solid histograms indicate the XRT+GIS PSF in the 4.0–8.0 keV band. X-axis is shown in arcmin, while Y-axis is in cts s^{-1} arcmin^{-2}. The later two profiles are rescaled to match the former at the center.
From these spatial analyses, we confirm that the excess hard X-ray emission is widely distributed in the vicinity of the group, rather than localized to particular regions, such as the group center or the member galaxies. However, the emission is far less extended than could be explained by wrong background subtraction, since the NXB and CXB have very flat distributions across the field of view; a more detailed examination is carried out in § 4.5.

### 4.5 Significance of the Hard X-ray Emission

The analyses in § 4.3 and 4.4 have revealed a strong evidence of an extended hard X-ray emission from HCG 62. However, we have not yet taken into account all the systematic errors and artifacts pointed out in § 4.3.5. In this section, we examine these effects in detail.

#### 4.5.1 Photon counts of the hard X-ray emission

**Table 4.9:** Photon counts in the 4.0–8.0 keV band detected in each pointing within the 0' < r < 15' region of HCG 62. Errors are 1 σ.

<table>
<thead>
<tr>
<th>Obs. ID</th>
<th>Data counts (N_{src})</th>
<th>BGD counts (N_{bgd})</th>
<th>Signal counts (N_{sig})</th>
<th>(N_{cxb}/N_{nxb})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs. 1</td>
<td>1416 ± 37.6</td>
<td>1237.3 ± 7.7 ± 48.2</td>
<td>618.4/618.4</td>
<td>178.7 ± 38.4 ± 48.2</td>
</tr>
<tr>
<td>Obs. 2</td>
<td>1107 ± 33.3</td>
<td>865.4 ± 5.4 ± 31.6</td>
<td>427.2/438.1</td>
<td>241.6 ± 33.7 ± 31.6</td>
</tr>
<tr>
<td>Obs. 3</td>
<td>799 ± 28.3</td>
<td>717.8 ± 5.2 ± 32.4</td>
<td>298.9/418.9</td>
<td>81.2 ± 28.8 ± 32.4</td>
</tr>
<tr>
<td>Obs. 4</td>
<td>800 ± 28.3</td>
<td>750.7 ± 5.6 ± 34.8</td>
<td>321.6/429.1</td>
<td>49.3 ± 28.8 ± 34.8</td>
</tr>
<tr>
<td>Obs. 5</td>
<td>1059 ± 32.5</td>
<td>879.1 ± 5.6 ± 35.6</td>
<td>425.8/453.3</td>
<td>170.9 ± 33.0 ± 35.6</td>
</tr>
<tr>
<td>Sum</td>
<td>5181 ± 72.0</td>
<td>4450.3 ± 13.3 ± 82.8</td>
<td>2092.4/2357.8</td>
<td>730.7 ± 73.2 ± 82.8</td>
</tr>
</tbody>
</table>

(1) The first errors represent the photon statistics and the seconds are the systematic errors in the NXB estimation (see § 4.5.2).

(2) Estimated CXB and NXB counts in the total background counts.

In Table 4.9, we have evaluated photon counts in the 4.0–8.0 keV band detected within the 0' < r < 15' region of HCG 62, where the five point sources were masked out as before. By subtracting the background counts (N_{bgd}) from the on-source data counts (N_{src}), we have obtained the signal counts of N_{sig} = N_{src} - N_{bgd} = 50 ~ 240. The errors (a quadrature sum of those in N_{src} and N_{bgd}) are typically ~ 45 counts, which is sometimes comparable to N_{sig}. The values of N_{sig} differ significantly among pointings, because the
Table 4.10: Sum of photon counts derived from Table 4.9, with the estimated IGM contribution.

<table>
<thead>
<tr>
<th>IGM model(1)</th>
<th>Signal counts ((N_{\text{sig}}))</th>
<th>IGM counts ((N_{\text{IGM}}))</th>
<th>excess counts ((N_{\text{excess}}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>best</td>
<td>730.7 ± 73.2 ± 82.8</td>
<td>111.5</td>
<td>619.2 ± 73.2 ± 82.8</td>
</tr>
<tr>
<td>high</td>
<td>97.9</td>
<td>632.8 ± 73.2 ± 82.8</td>
<td></td>
</tr>
<tr>
<td>low</td>
<td>192.3</td>
<td>538.4 ± 73.2 ± 82.8</td>
<td></td>
</tr>
</tbody>
</table>

(1) Calculated from the 2-vMEKAL+PL model in § 4.3.4. The best fit model is labeled “best”, and the 90% upper and lower-limit values, “high” and “low”, respectively. It corresponds to a 1 σ error of \((192.3 - 97.9)/1.65/2 = 28.6\) cts.

data accumulation regions, though identical in the sky plane, were different in the GIS field of view. Further examination follows in § 4.5.3.

Because the spectra of the five observations have already been shown to be consistent with one another (see § 4.3.1), we added all on-source data from the five observations to obtain the counts with the best statistics. The summed results are listed in Table 4.10, together with the estimated contribution from the IGM emission, \(N_{\text{IGM}}\), using the spectral fitting performed in § 4.3.4. We quoted three alternatives for \(N_{\text{IGM}}\), representing the best fit, 90% upper and lower-limit values. Thus, the excess signal counts in the 4.0–8.0 keV band have become

\[
N_{\text{excess}} = 619.2 ± 73.2 ± 87.6
\]

where the first error is the statistical 1 σ error, and the second one is systematic. This reconfirms the statistical significance of the hard X-ray emission, in a more straightforward manner than in previous sections.

### 4.5.2 Justification of the NXB estimation

In § 4.3, § 4.4, and § 4.5.1, we have subtracted the NXB from the on-source data employing the procedure described in § 3.3.6. Judging from the radial profile of the signal hard photons (Fig.4.14), we are already confident of the reliability of our NXB subtraction. Nevertheless, the issue has such a high technical importance, that we wish to describe below in some detail what we have actually done in estimating and subtracting the NXB from the five on-source datasets.

Our NXB estimation is based primarily on the “H02 sorting method” using the 5.2 Msec night earth data as an NXB template (§ 3.3.4). Because this method involves a systematic error of about 6% for a typical observation, we apply a finer adjustment to
the NXB level of each on-source dataset, by comparing it with the blank-sky data over a source-free outer region and in a sufficiently hard energy band, in which the NXB is dominant (§ 3.3.6). In the present case, we carried out this comparison using the 5.9–10.6 keV range, and over a region > 15′ from the detector center. Because all the pointing positions are offset from HCG 62, the on-source data accumulation circle (< 15′ from the HCG 62 centroid) partially falls on this “NXB adjustment region”; we masked out such overlapping regions in order for the IGM emission not to affect the background determination. We also excluded regions around bright discrete sources detected in the PSPC and the GIS images (see § 3.3.6).

For each of the five pointings, we obtained the the 5.9–10.6 keV spectrum in the NXB adjustment region defined in the above manner. The resulting event counts are given in the first column of Table 4.11. By comparing this value with those predicted from the background templates (2nd and 3rd column of the same Table), we have estimated the NXB correction factor $f_{\text{cor}}$, according to equation 3.3. The values of $f_{\text{cor}}$ thus derived, given in the last column of Table 4.11, range from 0.848 to 1.026 with a typical uncertainty of ~ 0.075. Because $f_{\text{cor}}$ is the ratio between the real data and the “H02 method” prediction, they must obey the ~ 6% systematic scatter of the “H02 method” (§ 3.3.4). Actually, all the values of $f_{\text{cor}}$ are acceptable in this respect, except for the second pointing. Although the probability of obtaining a value of $f_{\text{cor}} = 0.848$ is 5%, there is a 22% probability to obtain such a value from one out of five independent trials. We therefore conclude that the derived NXB correction factors behave well.

<table>
<thead>
<tr>
<th>Obs. ID</th>
<th>Data$_{\text{out}}$</th>
<th>CXB$_{\text{out}}^{(2)}$</th>
<th>NXB$_{\text{out}}^{H02 (3)}$</th>
<th>$f_{\text{cor}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs. 1</td>
<td>564</td>
<td>102.0</td>
<td>454.5</td>
<td>1.026 ± 0.078</td>
</tr>
<tr>
<td>Obs. 2</td>
<td>413</td>
<td>71.8</td>
<td>400.5</td>
<td>0.848 ± 0.072</td>
</tr>
<tr>
<td>Obs. 3</td>
<td>503</td>
<td>78.8</td>
<td>428.4</td>
<td>0.992 ± 0.077</td>
</tr>
<tr>
<td>Obs. 4</td>
<td>465</td>
<td>70.4</td>
<td>392.4</td>
<td>0.994 ± 0.081</td>
</tr>
<tr>
<td>Obs. 5</td>
<td>443</td>
<td>76.3</td>
<td>398.2</td>
<td>0.913 ± 0.079</td>
</tr>
<tr>
<td>sum</td>
<td>2388</td>
<td>399.3</td>
<td>2074.0</td>
<td>0.959 ± 0.035$^{(4)}$</td>
</tr>
</tbody>
</table>

(1) The 5.9–10.6 keV spectra detected in the NXB adjustment regions of the five pointings are compared with the estimated CXB and NXB spectra in the same region through equation 3.3.

(2) Event counts of the blank sky observations after subtracting their own NXB contribution estimated with “H02 sorting method”.

(3) NXB counts of the data estimated with “H02 sorting method”.

(4) Average weighted by the photon counts.

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Figure 4.15: The GIS radial count-rate profile from the group center in the (a) 5.9–10.6 keV band and (b) 4.0–8.0 keV band. The on-source data are shown with black crosses and the background with gray crosses. X-axis is shown in arcmin, while Y-axis is in cts s\(^{-1}\) arcmin\(^{-2}\).

In order to visualize that \(f_{\text{cor}}\) has been determined correctly, in Fig. 4.15a we plot the 5.9–10.6 keV radial count-rate profiles of the on-source and background data, averaged over all five observations. Except at the very center of the group, which was excluded when we calculated \(f_{\text{cor}}\), the data profile thus matches very well with that of the adjusted background. Examination of the profiles of individual pointings leads to the same conclusion (see Appendix A.2). Figure 4.15b performs the same comparison in the 4.0–8.0 keV band; their difference yields the hard-band radial profile in Fig. 4.14b. Again, the data and background agree well in the region \(r > 15'\), even though we clearly see the excess signal inside \(~15'\). From these results, we conclude that the NXB estimation has been performed correctly.

Thus, we have determined the correction factor \(f_{\text{cor}}\) with a typical accuracy of \(~7.5\%\) for each pointing (Table 4.11). Because \(f_{\text{cor}}\) has been determined by the individual on-source dataset, the uncertainties associated with the five values are independent of one another. This allows us to average them to obtain \(f_{\text{cor}}^{\text{ave}} = 0.959 \pm 0.035\). We regard this final error, 3.5\%, as the systematic uncertainty associated with the NXB estimation. This value translates into 1.9\% (= 82.8 counts) of the overall 4.0–8.0 keV background (CXB+NXB). We therefore quote 1.9\% as the systematic uncertainty in the background subtraction. This value has already been included in Tables 4.9 and 4.10.
4.5.3 Effects of the XRT+GIS point spread function (PSF)

Another possible instrumental origin for the hard component is artifacts of the point spread function (PSF) of the XRT+GIS, which depends in a complex way on the detector position and the photon energy (§ 3.2.2). In particular, harder photons are more heavily scattered outside the PSF core into its outskirts, making the PSF wider for higher energies. As a result, peripheral regions of a soft X-ray source, such as a group of galaxies, artificially exhibit harder spectra than they are. Therefore, the observed excess hard X-rays could be the scattered IGM emission, artificially hardened by the above mechanism.

Of course, the spectral response files, used in fitting the ASCA spectra, properly takes these effects into account, as long as the source is pointlike. However, for the spectral analysis of an extended source, such as was performed in § 4.3 and 4.4, the spectral response is averaged over the detector surface weighted by the event count distribution. This process makes the response file less accurate, because what we ought to use in the averaging process is the true surface distribution of the source on the sky, rather than the observed distorted image on the detector plane. Consequently, an artificial “hard X-ray halo” could arise around a soft IGM emission.

To evaluate the suspected PSF artifacts, we use the instrument simulator “SimASCA” (e.g. Ikebe 1996). This is a Monte-Carlo simulation tool, and works completely in the “forward” manner, incorporating all the known instrumental responses. That is, we start from a numerically modeled X-ray source, and generate Monte-Carlo photons by specifying their spectral and spatial probability distributions on the sky coordinate. The Monte-Carlo photons are subjected to the XRT and GIS simulators, to become a set of simulated GIS events. We then analyze these events exactly in the same way as the real events, and produce fake spectra as well as fake X-ray images. By quantitatively comparing these fake results against the actual spectra and images, we can judge whether the assumed source model is appropriate or not.

We have actually used this simulator to examine whether the simulated IGM emission of HCG62 bears an artificial “hard X-ray halo” around it. Specifically, after Mulchaey and Zabludoff (1998), we modeled the IGM surface brightness distribution with a double-beta model, using $\left(R_{\text{core}}, \beta\right) = (0'.56, 0.79)$ for the “central” $\beta$ component and $(10'.5, 0.67)$ for the “extended” $\beta$ component (§ 4.1.2). The spectrum for the model IGM emission was approximated by a single component Raymond-Smith model with $kT = 1.2$ keV and $Z = 0.3Z_\odot$, which exhibits a little harder spectrum compared to the best-fit twotemperature vMEKAL model found in § 4.3.4.
Using the simulated IGM model, we have generated $\sim 3 \times 10^6$ fake GIS photons, separately for each of the five observations. In Fig.4.16, we compare the soft-band (0.5–4.0 keV) radial count-rate profiles of the fake and actual data sets. The good agreement between the two datasets confirms that the surface brightness distribution assumed for the model source is correct.

We finally accumulated the Monte-Carlo GIS events over the $0' < r < 15'$ regions of the five fake images, into a single fake GIS spectrum. Then, employing the same response files as used for the actual spectrum in § 4.3, we fitted the fake spectrum with the Raymond-Smith spectral model, of which the parameters except for normalization were fixed to the simulation input values. We have found that the 4.0–8.0 keV photon counts contained in the simulated data are larger by 8.4% than the prediction of the fitted spectral model. This excess is thought to represent the suspected PSF artifact. As the IGM contribution to the 4.0–8.0 keV counts is estimated to be $92 \sim 178$ counts (§ 4.5.1), the PSF effect will increase this number by $8 \sim 15$ counts. This is only $1 \sim 3\%$ of the actually observed excess counts, and negligible compared to the statistical error of 73.2 counts. We therefore conclude that the PSF artifacts contribute little to the observed excess hard X-ray emission.

![Figure 4.16](image.png)

Figure 4.16: The 0.5–4.0 keV azimuthally averaged surface brightness profile of the first observation (plotted with crosses), compared with the simulation (histograms), in cts s$^{-1}$ arcmin$^{-2}$. The “central” and the “extended” components of the simulated profile are shown together with their sum. X-axis is shown in arcmin.

Using the simulator, we also examined whether the hard signal counts, $N_{\text{sig}}$ in Table 4.10, are consistent among the five observations. Here, the hard X-ray emission was
assumed to be spherically symmetric, and follow the radial distribution similar to the double-beta IGM profile employed above. As the spectral model, we used a thermal bremsstrahlung emission with $kT = 10.0$ keV. The simulated counts for the five pointings are shown in Fig.4.17, normalized to fit the actual signal counts, $N_{\text{sig}}$ in Table 4.10. The simulation compares with the actual measurements with $\chi^2 = 4.65$ for 4 dof. Therefore, the hard signal counts, $N_{\text{sig}}$, detected in the five pointings are confirmed to be consistent to one another.

![Graph](image)

Figure 4.17: The 4.0–8.0 keV counts in the $0' < r < 15'$ region of the five observations (points with error bars) compared with the simulated counts (dashed line). X-axis is shown in channel.

### 4.5.4 Problems with the IGM modeling

Another systematic error is the theoretical uncertainty of the IGM spectral calculation. As we have estimated the contribution from the IGM emission, $N_{\text{IGM}}$ (Table 4.10), by fitting these models to the actual spectra, there is a possibility that we under-estimate the value.

As reviewed in § 2.2.2, there are several plasma emission codes, such as the Raymond-Smith model and the MEKAL model. They differ mainly in the treatment of the Fe-L atomic physics (e.g. Masai 1997), and they produce considerably different emission spectra in the Fe-L line region ($\sim 0.8$–1.6 keV) when the plasma temperature is $kT \sim 1$ keV.

As already described in § 4.3.2, the two plasma codes were not much different (both unacceptable) in terms of the single-temperature fit. Then, what happens if we replace the vMEKAL code in our improved fitting model (vMEKAL+PL model in Table 4.5) by a variable-abundance Raymond-Smith (vRS) component? Actually, a sum of a vRS
component and a power law with $\Gamma = 2.0$ (vRS+PL model) gives a somewhat better fit with $\chi^2 = 86.5$ for 72 dof than the vMEKAL+PL model. The derived IGM parameters are $kT = 0.92^{+0.04}_{-0.02}$ keV, $Z_\alpha = 0.37^{+0.14}_{-0.12}$ and $Z_{Fe} = 0.29^{+0.08}_{-0.05}$, which are generally similar to those obtained from the vMEKAL+PL model fitting (see Table 4.5). The fit does not improve by adding another vRS component (2-vRS+PL model), which is different from the vMEKAL case where a significant improvement has been shown between the vMEKAL+PL model and the 2-vMEKAL+PL model.

The IGM counts in the 4.0–8.0 keV band, $N_{IGM}$, has slightly decreased from 111.5 to 74.8. Therefore, in view of the difference in the plasma model, our nominal value of 111.5 (Table 4.10) may not be underestimated. Furthermore, the spectra from some other groups, such as the NGC 5044 group and the NGC 4325 group, are generally fitted well with the IGM model with parameters similar to those of HCG 62, with requiring almost no hard component (see Chapter 5). Therefore, the theoretical error in the IGM modeling is thought to be rather small. For simplicity, we quote the difference derived above, $\Delta N_{IGM} = 37$ counts, as the typical error in the IGM spectral calculation.

### 4.5.5 Fluctuation of the CXB

<table>
<thead>
<tr>
<th>Instrument</th>
<th>HEAO-1 A2$^{(1)}$</th>
<th>Ginga LAC$^{(2)}$</th>
<th>ASCA XRT+GIS$^{(3)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>698 sample</td>
<td>151 sample</td>
<td>10 sample</td>
</tr>
<tr>
<td>Effective Area</td>
<td>530 cm$^2$</td>
<td>4,000 cm$^2$</td>
<td>200 cm$^2$</td>
</tr>
<tr>
<td>Energy Band</td>
<td>2.5–46 keV</td>
<td>2–10 keV</td>
<td>0.6–10.0 keV</td>
</tr>
<tr>
<td>FOV</td>
<td>$3^\circ \times 3^\circ$</td>
<td>$1^\circ \times 2^\circ$</td>
<td>$r = 20'$ with $\sim 3'$ imaging</td>
</tr>
<tr>
<td>$\Omega_\chi^{(4)}$</td>
<td>15.8 deg$^2$</td>
<td>1.3deg$^2$</td>
<td>$\sim 0.5$ deg$^2$/sample</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.14deg$^2$/pointing)</td>
</tr>
<tr>
<td>$S_\chi^{(5)}$ (erg s$^{-1}$cm$^{-2}$)</td>
<td>$8 \times 10^{-11}$</td>
<td>$6 \times 10^{-12}$</td>
<td>$2 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\sigma_{CXB}/I_{CXB}$ $^{(6)}$</td>
<td>2.8%</td>
<td>$\sim 6%$</td>
<td>$\leq 3.4%$</td>
</tr>
</tbody>
</table>

(4) Effective solid angle of the observations (see appendix C).
(5) Upper cut-off of the 2–10 keV flux from discrete sources in the FOV.
(6) Observed fractional rms CXB fluctuation, i.e., excess variance after subtracting statistical errors and NXB estimation errors.

Since all the instrumental artifacts have so far been shown to be small compared to the detected excess hard counts, the phenomenon must be of celestial origin. One of such candidates is the fluctuation of the CXB. The CXB is considered to be a sum of numerous
discrete sources distributed in the sky, most of which are thought to be AGNs. Therefore, the CXB surface brightness $I_{\text{CXB}}$ fluctuates due to the statistical fluctuation of the source number counts in the detector field of view (FOV).

In Table 4.12, we list the value of the fractional CXB fluctuation, $\sigma_{\text{CXB}}/I_{\text{CXB}}$, in the 2.0–10.0 keV band derived from the past studies. As shown in Appendix C, it is described as

$$\sigma_{\text{CXB}}/I_{\text{CXB}} \propto \Omega_e^{-0.5} S_e^{0.25},$$

(4.2)

where $\Omega_e$ represents the effective solid angle of the observation and $S_e$ represents the upper cut-off flux of the detectable (hence removable) discrete sources in the detector FOV. This equation assumes the Euclidean log$N$-log$S$ relation, represented as $N(> S) \propto S^{-1.5}$. Results from the three experiments given in Table 4.12 satisfy this scaling relation.

The integration area we used, $r < 15'$, or 0.196 deg$^2$, yields $\Omega_e = 0.1$ deg$^2$, when weighted with the detector angular transmission (see Appendix C). When the value is scaled with the integration area of 0.164 deg$^2$ after masking out the five sources, the effective solid angle reduces to $\Omega_e = 0.084$ deg$^2$. As the upper cut-off flux in 2–10 keV is typically $S_e = 1 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in our analysis (see § 4.5.6), the fractional CXB fluctuation is estimated as $\sigma_{\text{CXB}}/I_{\text{CXB}} = 2.8 \times (15.8/0.084)^{0.5} \times (8 \times 10^{-11}/1 \times 10^{-13})^{-0.25} = 7.2\%$, by scaling the HEAO-1 A2 results with equation 4.2. By multiplying this value to the estimated CXB count of $N_{\text{CXB}} = 2092.3$ in the 4.0–8.0 keV band (Table 4.9), we estimate the CXB fluctuation counts in our integration region as 150.6 counts.

We cross check the above estimate experimentally with the 20 blank-sky observations that we used to construct the CXB template (§ 3.3.5). From each of them, we collected photon counts using the same detector regions we used for the five on-source observations, after adjusting the NXB variance using the counts from its outer region. Hence, we obtained 100 samples. As a blank-sky observation itself has regions masked out to avoid contributions from the contaminating sources (§ 3.3.5), we corrected the obtained photon counts for the difference in the integration area. The results are shown in Fig.4.18. To improve the statistics, each data point is given as a sum of five on-source masks. The obtained CXB counts, $N_{\text{CXB}}$, ranges from 1801 to 2370 with a typical statistic error of $\sim 100$ counts. Their rms scatter is 167.4 counts, which gives an intrinsic scatter of 127.9 after subtracting the Poisson errors. This result is consistent with the value, 150.6, obtained above.
Figure 4.18: Distribution of the 4.0–8.0 keV CXB counts summed over the five on-source masks, among the 20 blank sky observations. Also plotted is a Gaussian function with $\sigma = 180$ counts, which is the quadrature sum of the typical Poisson error of $\sim 100$ counts and predicted CXB fluctuation of $\sim 150$ counts.

4.5.6 Effect of the fainter contaminating sources

In the last subsection, we found that the expected CXB fluctuation falls short of the detected excess hard photon counts. Hence, the hard X-ray emission cannot be explained by the contribution from the background AGNs behind HCG 62, provided they belong to the ordinary population. Furthermore, we have already eliminated five point sources (Fig.4.2) at the earliest stage of our data analysis. Nevertheless, we cannot rule out the possibility that there is peculiar over-density of fainter point sources in the present field, and their sum produces the observed excess hard X-rays. In this subsection, we search for such point source candidates in the $0' < r < 15'$ region of HCG 62.

Because the IGM emission fills up the analysis field, it is difficult to find sources only from the GIS image. Therefore, as we have done in § 4.5.2, we used the ROSAT PSPC, which has a higher sensitivity to the point sources. From the PSPC point source catalog (2RXP catalog; http://wave.xray.mpe.mpg.de/rosat/rra/rospspc) supplied by the German ROSAT team, there are five sources with count-rate exceeding $4 \times 10^{-3}$ counts s$^{-1}$, and additional six sources exceeding $2 \times 10^{-3}$ counts s$^{-1}$. We plot their positions in Fig.4.19. The former are the very sources that we have eliminated in § 4.3 and afterwards, so our results are not affected by them. The latter six sources may also be negligible, by the following reasons. Their number count is consistent with the ordinary CXB population (e.g. Hasinger 1998), and their 2–10 keV flux is $\sim 0.5 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, about half the typical cut-off flux in our analysis. Here we assumed a power law emission with $\Gamma = 1.7$.  

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These two characteristics mean that they belong to ordinary population, and hence their contribution has already been included in the CXB fluctuation estimates. This conclusion is supported by the general absence of emission associated with these sources in the GIS 2–10 keV image (Fig.4.19b). In summary, we found no peculiar over-density of faint point sources in the analysis region, at least down to the 2–10 keV flux limit of \( \sim 0.5 \times 10^{-13} \) erg s\(^{-1}\) cm\(^{-2}\).

Figure 4.19: Positions of the discrete sources plotted on the (a) 0.4–2.4 PSPC image, and (b) 2–10 keV GIS image. The images are smoothed with a Gaussian filter of \( \sigma = 0'.25 \) and 0'.5 for the left and right panels, respectively. The scale levels are shown in the right side of each panel, in units of cts s\(^{-1}\) arcmin\(^{-2}\). Thick dashed line indicates 3' and 15' from the group center and thick solid circles represent the five sources already eliminated. Boxes represent the six sources with PSPC count-rate in the range of \( 2.0 \sim 4.0 \times 10^{-3} \) counts s\(^{-1}\).

### 4.5.7 Overall errors

By considering the analyses made in § 4.5.1 through § 4.5.6, we summarize in Table 4.13 all the conceivable errors, statistical and systematic, that can affect the excess hard X-ray emission from HCG 62. From this table, we finally quote

\[
N_{\text{excess}} = 609.8 \pm 73.2 \pm 178.5
\]  

(4.3)

for the excess hard X-ray counts over the \( r < 15' \) region in the 4.0–8.0 keV band. Here, the first and second errors represent statistical and systematic errors, respectively. The
difference in $N_{\text{excess}}$ between equations 4.1 and 4.3 is due to the subtraction of the PSF effect. We thus conclude that the phenomenon is significant at about 3.2 sigma level.

Table 4.13: Summary of the excess hard photons in the $r < 15'$ region. Contributions from all examined components are listed, with the estimated errors.

<table>
<thead>
<tr>
<th>item</th>
<th>error estimation</th>
<th>counts</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson errors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>data</td>
<td>$\sqrt{5181}$</td>
<td>$N_{\text{Data}} = 5181 \pm 72.0$</td>
<td></td>
</tr>
<tr>
<td>NXB$^{(1)}$</td>
<td></td>
<td>$N_{\text{NXB}} = -2357.8 \pm 1.9$</td>
<td></td>
</tr>
<tr>
<td>CXB$^{(2)}$</td>
<td></td>
<td>$N_{\text{CXB}} = -2092.4 \pm 13.3$</td>
<td></td>
</tr>
<tr>
<td>sum</td>
<td></td>
<td>$\text{excess counts} = 730.7 \pm 73.2$</td>
<td></td>
</tr>
<tr>
<td>systematic errors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NXB estimation error</td>
<td>$2357.8 \times 0.035$</td>
<td>$-$</td>
<td>$\pm 82.8$</td>
</tr>
<tr>
<td>CXB fluctuation</td>
<td>$2092.3 \times 0.072$</td>
<td>$-$</td>
<td>$\pm 150.6$</td>
</tr>
<tr>
<td>IGM contribution</td>
<td></td>
<td>$N_{\text{IGM}} = -111.5$</td>
<td>$+13.6/-80.8$</td>
</tr>
<tr>
<td>XRT PSF effect</td>
<td>$-9.4$</td>
<td></td>
<td>$+1.1/-6.8$</td>
</tr>
<tr>
<td>IGM modeling error</td>
<td></td>
<td>$-$</td>
<td>$\pm 37$</td>
</tr>
<tr>
<td>sum</td>
<td></td>
<td>$\text{excess counts} = 609.8 \pm 178.5^{(3)}$</td>
<td></td>
</tr>
<tr>
<td>sum of all errors</td>
<td></td>
<td>$\text{excess counts} = N_{\text{excess}} = 609.8 \pm 73.2 \pm 178.5$</td>
<td></td>
</tr>
</tbody>
</table>

(1) Statistical error of the NXB template (§ 3.3.4).
(2) From the sum of background (CXB+NXB) count.
(3) Quadrature sum of the systematic errors. “IGM contribution” error, including the PSF effect, was converted to $\sim 1\sigma$ error from $N(90\%pk - pk) = 101.5$ to $101.5/1.65/2.0 = 30.7$ counts.

### 4.6 Summary of the Analysis

Table 4.14: Luminosities of the soft and hard components of HCG 62.

<table>
<thead>
<tr>
<th>Component</th>
<th>Energy Range (keV)</th>
<th>luminosity ($h_{75}^{-2}$ erg s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGM</td>
<td>0.5–10</td>
<td>$1.95^{+0.14}_{-0.12} \times 10^{42}$</td>
</tr>
<tr>
<td>hard X-rays</td>
<td>2–10</td>
<td>$4.18^{+0.70}_{-0.85} \times 10^{41}$</td>
</tr>
<tr>
<td>LMXB</td>
<td>2–10</td>
<td>$0.35 \times 10^{41}$</td>
</tr>
</tbody>
</table>

We have analyzed extensively the five ASCA observations of HCG 62. In addition to the $kT \sim 1$ keV IGM component extending at least up to $r = 15'$ from the group center, we have found a clear hard excess emission. We obtained a successful fit by
modeling the spectra with two IGM components of $kT_1 = 0.73$ keV and $kT_2 = 1.14$ keV with $Z_\alpha = 0.53Z_\odot$ and $Z_{Fe} = 0.34Z_\odot$, and a power law component with photon index $\Gamma$ fixed to 2.0 (§ 4.3.4). The $\Gamma$ is poorly constrained if we set it free, and it can be also replaced by a thermal component with $kT > 5.7$ keV. In Table 4.14, we summarize the luminosities of the IGM component and the hard X-ray emission, derived from the spectral fitting in § 4.3.4. The former is in good agreement with the previous PSPC result of $2.16 \times 10^{42} h_{75}^{-2}$ erg s$^{-1}$, where no hard component is included in the fitting. The PSPC value was scaled from the original result by Mulchaey and Zabludoff (1998), for the difference of the integration region, the energy range and the Hubble constant. The hard component luminosity is $\sim 20\%$ of the IGM.

We have examined the excess hard X-ray emission against various experimental artifacts; wrong NXB estimation (§ 4.5.2), PSF effects (§ 4.5.3), and IGM modeling error (§ 4.5.4). All of them have fallen short of the observed hard excess. Hence, we confirmed that the phenomenon is celestial.

Among the celestial candidates (Table 4.6), we have already excluded the “central AGN” in § 4.4.1, and the “AGNs in the member galaxies” in § 4.4.2. Furthermore, our investigation in § 4.5.5 and 4.5.6 have also ruled out the CXB fluctuation scenario and the contribution from the contaminating sources, respectively.

Then, how about the LMXB component? From the optical B-band magnitude of the 13 member galaxies of HCG 62 (Carvalho et al. 1997), the sum of their luminosity is $L_B = 6.0 \times 10^{10} h_{75}^{-2}$ $L_\odot$. Using equation 2.16, the 2–10 keV flux from LMXBs in these galaxies is estimated as $2.5 \times 10^{10} h_{75}^{-2}$ erg s$^{-1}$, which is more than an order of magnitude small compared to the observed hard X-ray flux.

Thus, the only possibility left is that the excess hard X-ray emission comes from a diffuse source associated with HCG 62 itself. Its surface brightness profile is similar to, or somewhat more extended than, that of the IGM emission. From the current data alone, however, we cannot tell whether the emission is of thermal or non-thermal origin (§ 4.3.4). We further discuss the origin of the hard excess emission in Chapter 6.
Chapter 5

DATA ANALYSIS AND RESULTS OF OTHER GROUPS

In the last Chapter, we have shown that the HCG 62 group exhibits strong evidence of a diffuse hard X-ray emission. Then, the next question is whether the phenomenon is observed in other groups or not, and how common it is among them. In this Chapter, we accordingly analyze the ASCA data of 17 other galaxy groups in the same way as HCG 62.

5.1 Observations and Targets

To search for the hard X-ray emission, we have surveyed all the groups of galaxies available in the ASCA archival data. In practice, we checked every target which were observed as a group, and also as an elliptical galaxy, because some groups are known to be formed around such galaxies. As we have to separate the hard X-rays from the IGM emission, we need sufficient photon statistics. Therefore, the source must be bright with the 0.5–10 keV flux higher than $\sim 1 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$. For the same reason, it should not contain any bright AGN, and the IGM emission itself must be “soft”, i.e., with a temperature lower than $\sim 1.7$ keV. We also exclude the sources with luminosity less than $5 \times 10^{41}$ erg s$^{-1}$, most of which are elliptical galaxies and not groups. The sample thus selected consists of 18 groups, including HCG 62. Among them, data for two targets are not yet archived, but the data right belongs to the present author (five offset pointings of NGC 1399 group, performed in 1999) or his supervisor (the NGC 1550 group). We list them in Table 5.1 with their optical properties. Although it is far from being complete, it includes three Hickson’s compact groups, another three (NGC 1132, NGC 1550 and NGC
6521) X-ray selected groups, and 11 relatively loose groups, with their velocity dispersion ranging from $\sigma = 169$ to 474 km s$^{-1}$. In addition, we analyze two X-ray bright elliptical galaxies (NGC 4472 and NGC 4636) for comparison, mainly to determine the level of hard X-ray emission from the underlying LMXBs. Because the sample is large, we sometimes show results only on several representative groups in this Chapter, leaving those of the remaining objects to Appendix D.

In Table 5.2, we summarize observational log of the objects in our sample. For the 17 groups, there are 34 observations in total, of which about one third are offset pointings. We obtained the data from both the GIS and the SIS, following the analysis procedure established for the HCG 62 group (see § 4). For the GIS, we used all the data available. For the SIS, we used the data from the earliest observation of the relevant group, unless otherwise noted, to avoid problems due to the variation of the SIS response (§ 3.4.4).

In Fig.5.1, we present the full band GIS and SIS images for three representative targets, the NGC 1399 group ($z = 0.0048$) and the RGH 80 group ($z = 0.0370$). The former is the nearest target in the sample, and the latter is the farthest. From every group, a diffuse emission with roughly circular profile was detected up to a radius of $r = 10' \sim 25'$, and the X-ray centroid was generally coincident in position with a bright elliptical galaxy. We defined the spectral integration region to be fully contained within the detected diffuse emission, as listed in Table 5.2 and illustrated in Fig.5.1. We also eliminated regions around bright contaminating sources, such as the NGC 1404 galaxy aside NGC 1399, and $3'$ around bright point sources detected with the PSPC. For example, the PSPC sources eliminated in the NGC 1399 group will contribute additional $\sim 0.4 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$, or $\sim 2\%$ increase in the 2–10 keV band flux. The region thus defined is completely covered by the GIS, but only partially by the SIS.

5.2 Spectral Analysis

5.2.1 Single component fits

We extracted spectra from both the GIS and the SIS within the integration regions as defined above. For the SIS, we used the bright-mode data for all the following analysis, while the faint-mode data were converted to bright-mode. The background was estimated with the same method as for HCG 62 (see § 4.3.1), and the NXB estimation errors are already included as a systematic error in the background data. Representative spectra obtained in this way are presented in Fig.5.2. All targets show soft spectra, peaking near
Table 5.1: The sample objects selected for the present study.

<table>
<thead>
<tr>
<th>target</th>
<th>position(^{(1)})</th>
<th>(D)^{(2)}</th>
<th>(z)^{(3)}</th>
<th>(\sigma_v)^{(4)}</th>
<th>(I_B)^{(5)}</th>
<th>(N_{\text{H gal}})^{(6)}</th>
<th>note</th>
</tr>
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<tr>
<td></td>
<td>(Ra, Dec )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCG 51</td>
<td>170.614, 24.294</td>
<td>103</td>
<td>0.0258</td>
<td>240(^h)</td>
<td>1.05</td>
<td>1.27</td>
<td></td>
</tr>
<tr>
<td>HCG 97</td>
<td>356.844, -2.303</td>
<td>87.2</td>
<td>0.0218</td>
<td>372(^h)</td>
<td>0.62</td>
<td>3.65</td>
<td></td>
</tr>
<tr>
<td>NGC 1132</td>
<td>43.223, -1.275</td>
<td>92.8</td>
<td>0.0232</td>
<td>-</td>
<td>0.47</td>
<td>5.17</td>
<td></td>
</tr>
<tr>
<td>NGC 1399</td>
<td>54.622, -35.450</td>
<td>19.0</td>
<td>0.0048</td>
<td>325(^{fs})</td>
<td>0.45</td>
<td>1.34</td>
<td>Fornax cluster</td>
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<tr>
<td>NGC 1550</td>
<td>64.908, 2.410</td>
<td>49.6</td>
<td>0.0123</td>
<td>-</td>
<td>0.21</td>
<td>11.5</td>
<td>RX J0419.6+0225</td>
</tr>
<tr>
<td>NGC 2563</td>
<td>125.149, 21.068</td>
<td>59.8</td>
<td>0.0149</td>
<td>336(^{±44}_{±40})</td>
<td>0.55</td>
<td>4.23</td>
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<td>185.796, 10.606</td>
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<td>0.0257</td>
<td>265(^{±50}_{±44})</td>
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<td>2.22</td>
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<tr>
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<td>198.859, -16.398</td>
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<td>474(^{fs})</td>
<td>0.73</td>
<td>4.93</td>
<td>WP 23</td>
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<tr>
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<td>20.901, 33.257</td>
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<td>0.0165</td>
<td>595(^w)</td>
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<tr>
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<td>0.86</td>
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<tr>
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<td>0.0276</td>
<td>-</td>
<td>1.03</td>
<td>2.12</td>
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</tr>
<tr>
<td>NGC 6521</td>
<td>268.942, 62.604</td>
<td>111</td>
<td>0.0266</td>
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<tr>
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<td>50.1</td>
<td>0.0125</td>
<td>780(^f)</td>
<td>1.08</td>
<td>0.50</td>
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<td>Pavo</td>
<td>304.628, -70.859</td>
<td>56.0</td>
<td>0.0137</td>
<td>169(^rc)</td>
<td>1.71</td>
<td>7.00</td>
<td></td>
</tr>
<tr>
<td>RGH 80</td>
<td>200.058, 33.146</td>
<td>148</td>
<td>0.0370</td>
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<td>0.32</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>S49-147</td>
<td>5.375, 22.402</td>
<td>76.0</td>
<td>0.0190</td>
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<td>1.13</td>
<td>4.06</td>
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</tr>
<tr>
<td>HCG 62</td>
<td>193.277, -9.209</td>
<td>58.4</td>
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<td>376(^{±52}_{±46})</td>
<td>0.6</td>
<td>3.01</td>
<td>see Chapter 4</td>
</tr>
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<td>NGC 4472</td>
<td>187.445, 8.000</td>
<td>11.6</td>
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<td>0.38</td>
<td>1.66</td>
<td>Elliptical in Virgo</td>
</tr>
<tr>
<td>NGC 4636</td>
<td>190.708, 2.688</td>
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<td>0.0037</td>
<td>-</td>
<td>0.21</td>
<td>1.81</td>
<td>Elliptical in Virgo</td>
</tr>
</tbody>
</table>

(1) Position of the X-ray centroid, from this analysis.
(2) Distance to the group in Mpc, converted from the recession velocity listed in NED database, assuming a Hubble constant of \(H_0 = 75\) km s\(^{-1}\) Mpc\(^{-1}\).
(3) Redshift, from NED database.
(4) Radial velocity dispersion. Groups without index are from Zabludoff and Mulchaey (1998a), “\(h\)” from Hickson et al. (1982), “\(fs\)” from Fargason and Sandage (1990), “\(w\)” from Wegner (1993), “\(f\)” from Fadda et al. (1996), “\(rc\)” from RC3 catalog, “\(r\)” from Ramella (1995), and “\(l\)” from Ledlow et al. (1996).
(5) Optical B-band luminosity of the member galaxies of the group, in \(10^{11}L_\odot\). Obtained from RC3 catalog (de Vaucouleurs et al. 1991).
(6) Galactic absorption column density derived from HI radio emission map by Dickey and Lockmann (1990).
<table>
<thead>
<tr>
<th>target</th>
<th>r(^{(1)})</th>
<th>date(^{(2)})</th>
<th>sequence ID</th>
<th>exposure GIS (ksec)(^{(3)})</th>
<th>SIS (ksec)(^{(3)})</th>
<th>SIS mode(^{(4)})</th>
<th>note</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCG 51</td>
<td>10(^{\prime})</td>
<td>94/06/03</td>
<td>82028000</td>
<td>62</td>
<td>72</td>
<td>1 CCD F/F</td>
<td></td>
</tr>
<tr>
<td>HCG 97</td>
<td>10(^{\prime})</td>
<td>96/06/18</td>
<td>84006000</td>
<td>79</td>
<td>81</td>
<td>1 CCD F</td>
<td></td>
</tr>
<tr>
<td>NGC 1132</td>
<td>10(^{\prime})</td>
<td>97/08/16</td>
<td>65021000</td>
<td>27</td>
<td>20</td>
<td>1 CCD F/B</td>
<td></td>
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<tr>
<td>NGC 1550</td>
<td>15(^{\prime})</td>
<td>99/08/28</td>
<td>87005000(^{(5)})</td>
<td>70</td>
<td>23</td>
<td>1 CCD F</td>
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</tr>
<tr>
<td>NGC 1399</td>
<td>20(^{\prime})</td>
<td>93/07/15</td>
<td>80038000</td>
<td>19</td>
<td>(15)</td>
<td>4 CCD F</td>
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<td>80039000</td>
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<td>81021000</td>
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<td>4 CCD F</td>
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<tr>
<td></td>
<td></td>
<td>99/08/10</td>
<td>87006000(^{(6)})</td>
<td>12</td>
<td>(17)</td>
<td>c4 CCD F/B</td>
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<td></td>
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<td>99/08/10</td>
<td>87006010(^{(6)})</td>
<td>16</td>
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<td>87006020(^{(6)})</td>
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<td>c4 CCD F/B</td>
<td>offset</td>
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<td>99/08/20</td>
<td>87006030(^{(6)})</td>
<td>11</td>
<td>(9)</td>
<td>c4 CCD F/B</td>
<td>offset</td>
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<td>52</td>
<td>1 CCD F</td>
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<tr>
<td>NGC 4325</td>
<td>10(^{\prime})</td>
<td>97/01/05</td>
<td>85066000</td>
<td>27</td>
<td>25</td>
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<td></td>
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<td>NGC 5044</td>
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<td>93/06/20</td>
<td>80026000-10</td>
<td>25</td>
<td>19</td>
<td>4 CCD B</td>
<td></td>
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<tr>
<td></td>
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<td>99/01/14</td>
<td>87002000</td>
<td>22</td>
<td>(15)</td>
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<td>87002010</td>
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<td>1 CCD F/F</td>
<td>offset</td>
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<tr>
<td></td>
<td></td>
<td>99/01/15</td>
<td>87002020</td>
<td>21</td>
<td>(22)</td>
<td>1 CCD F/F</td>
<td>offset</td>
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<td>25(^{(7)})</td>
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<td>62009010</td>
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<td>18(^{(8)})</td>
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<td>61012000</td>
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<td></td>
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<td>97/11/29</td>
<td>85034000</td>
<td>36</td>
<td>19</td>
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<tr>
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<tr>
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<td>95/06/23</td>
<td>83012000</td>
<td>41</td>
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<td>93007040</td>
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</tr>
<tr>
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<td>2 CCD F</td>
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<tr>
<td>NGC 4472</td>
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<td>60029000</td>
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<td>18</td>
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<td>(18)</td>
<td>4 CCD F/B</td>
<td>offset</td>
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<tr>
<td>NGC 4636</td>
<td>8(^{\prime})</td>
<td>93/06/23</td>
<td>60032000</td>
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<td>34</td>
<td>4 CCD F</td>
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<td>64008000</td>
<td>175</td>
<td>(244)</td>
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(1) Radius of the spectral integration region. (2) Observation start date.
(3) The data with the exposure listed with parenthesis are not used in the spectral analysis.
(4) SIS clocking-mode and data-mode.
(7) The data only from the SIS-0 is used. See § 5.2.3.
(8) The SIS data from the first observation is not used. See § 5.2.3.
Figure 5.1: The 0.5–10.0 keV band X-ray contour images of the GIS and the SIS, for (a) the NGC 1399 group, and (b) the RGH 80 group. They are the same as Figs.4.6 (GIS) and 4.7 (SIS), except for the energy band. The contours are logarithmically spaced by factors of 1.7, starting from $5 \times 10^{-5}$ cts s$^{-1}$ arcmin$^{-2}$ for the GIS image of NGC 1399, and from $2.9 \times 10^{-5}$ cts s$^{-1}$ arcmin$^{-2}$ for that of RGH 80. For the SIS images, the first contour shows $1 \times 10^{-4}$ cts s$^{-1}$ arcmin$^{-2}$. The smaller dashed circles represent 3$'$ from the group center, and the larger ones the integration region for spectral analysis, 20$'$ for NGC 1399 and 10$'$ for RGH 80. Open squares indicate the positions of the point sources detected with the PSPC, around 3$'$ of which are excluded from the analysis. See Fig. D.1 for the remaining groups.
~ 1 keV, with clear Fe-L lines that characterize hot plasma with $kT = 0.5 \sim 2$ keV. Some groups, such as the NGC 4325 group and the NGC 5044 group, show a spectral peak below 1 keV and their spectral continua are very soft, while others, such as the NGC 2563 group, show a peak above 1 keV and exhibit relatively hard continua. In addition, several groups, such as RGH 80 and S49-147, simultaneously exhibits the Fe-L peak below 1 keV and hard continua. Their spectra resemble those of HCG 62 (e.g., Fig.4.10).

Table 5.3: Results of the joint fit to the GIS and SIS spectra with a single component vMEKAL model.

<table>
<thead>
<tr>
<th>Target</th>
<th>$kT^{(1)}$ (keV)</th>
<th>$Z_a(Z_{\odot})$</th>
<th>$Z_{Fe}(Z_{\odot})$</th>
<th>$\chi^2/d.o.f$</th>
<th>$kT_H^{(3)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCG 51</td>
<td>1.38$^{+0.03}_{-0.03}$</td>
<td>0.44$^{+0.15}_{-0.13}$</td>
<td>0.38$^{+0.06}_{-0.05}$</td>
<td>97.35/71</td>
<td>0.97$^{+0.44}_{-0.26}$</td>
</tr>
<tr>
<td>HCG 97</td>
<td>1.04$^{+0.03}_{-0.04}$</td>
<td>0.30$^{+0.15}_{-0.12}$</td>
<td>0.18$^{+0.04}_{-0.03}$</td>
<td>81.48/71</td>
<td>1.83$^{+1.00}_{-0.77}$</td>
</tr>
<tr>
<td>NGC 1132</td>
<td>1.09$^{+0.02}_{-0.03}$</td>
<td>0.32$^{+0.15}_{-0.12}$</td>
<td>0.27$^{+0.05}_{-0.04}$</td>
<td>69.41/71</td>
<td>1.14$^{+0.46}_{-0.36}$</td>
</tr>
<tr>
<td>NGC 1399</td>
<td>1.38$^{+0.01}_{-0.01}$</td>
<td>0.46$^{+0.05}_{-0.05}$</td>
<td>0.36$^{+0.03}_{-0.02}$</td>
<td>374.65/69</td>
<td>1.84$^{+0.09}_{-0.12}$</td>
</tr>
<tr>
<td>NGC 1550</td>
<td>1.42$^{+0.02}_{-0.02}$</td>
<td>0.53$^{+0.07}_{-0.06}$</td>
<td>0.40$^{+0.03}_{-0.03}$</td>
<td>164.80/57</td>
<td>1.86$^{+0.68}_{-0.46}$</td>
</tr>
<tr>
<td>NGC 2563</td>
<td>1.36$^{+0.04}_{-0.05}$</td>
<td>0.63$^{+0.27}_{-0.21}$</td>
<td>0.33$^{+0.09}_{-0.07}$</td>
<td>63.52/71</td>
<td>1.63$^{+0.86}_{-0.52}$</td>
</tr>
<tr>
<td>NGC 4325</td>
<td>1.04$^{+0.02}_{-0.02}$</td>
<td>0.42$^{+0.15}_{-0.12}$</td>
<td>0.34$^{+0.06}_{-0.05}$</td>
<td>79.48/67</td>
<td>1.22$^{+0.65}_{-0.41}$</td>
</tr>
<tr>
<td>NGC 5044</td>
<td>1.02$^{+0.01}_{-0.01}$</td>
<td>0.38$^{+0.04}_{-0.04}$</td>
<td>0.27$^{+0.02}_{-0.02}$</td>
<td>312.98/74</td>
<td>1.34$^{+0.11}_{-0.09}$</td>
</tr>
<tr>
<td>NGC 507</td>
<td>1.39$^{+0.02}_{-0.02}$</td>
<td>0.68$^{+0.13}_{-0.11}$</td>
<td>0.43$^{+0.05}_{-0.05}$</td>
<td>192.75/73</td>
<td>1.89$^{+0.21}_{-0.19}$</td>
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<tr>
<td>NGC 533</td>
<td>1.27$^{+0.06}_{-0.06}$</td>
<td>0.49$^{+0.25}_{-0.18}$</td>
<td>0.33$^{+0.11}_{-0.08}$</td>
<td>92.61/69</td>
<td>1.25$^{+0.63}_{-0.40}$</td>
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<tr>
<td>NGC 5846</td>
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<td>0.28$^{+0.12}_{-0.09}$</td>
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<td>150.70/67</td>
<td>2.63$^{+3.77}_{-1.18}$</td>
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<tr>
<td>NGC 6329</td>
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<td>0.27$^{+0.18}_{-0.15}$</td>
<td>0.18$^{+0.06}_{-0.05}$</td>
<td>89.76/71</td>
<td>2.44$^{+1.73}_{-0.87}$</td>
</tr>
<tr>
<td>NGC 6521</td>
<td>1.77$^{+0.31}_{-0.12}$</td>
<td>0.66$^{+0.44}_{-0.32}$</td>
<td>0.39$^{+0.28}_{-0.13}$</td>
<td>57.21/67</td>
<td>1.86$^{+0.68}_{-0.46}$</td>
</tr>
<tr>
<td>NGC 7619</td>
<td>0.97$^{+0.03}_{-0.03}$</td>
<td>0.38$^{+0.14}_{-0.11}$</td>
<td>0.24$^{+0.05}_{-0.04}$</td>
<td>73.35/71</td>
<td>1.33$^{+0.80}_{-0.51}$</td>
</tr>
<tr>
<td>Pavo</td>
<td>0.59$^{+0.04}_{-0.07}$</td>
<td>0.10$^{+0.12}_{-0.08}$</td>
<td>0.08$^{+0.03}_{-0.02}$</td>
<td>104.47/71</td>
<td>0.76$^{+1.09}_{-0.40}$</td>
</tr>
<tr>
<td>RGH 80</td>
<td>1.25$^{+0.05}_{-0.05}$</td>
<td>0.40$^{+0.16}_{-0.13}$</td>
<td>0.21$^{+0.05}_{-0.04}$</td>
<td>130.45/73</td>
<td>2.66$^{+1.07}_{-0.66}$</td>
</tr>
<tr>
<td>S49-147</td>
<td>1.04$^{+0.05}_{-0.05}$</td>
<td>0.12$^{+0.08}_{-0.07}$</td>
<td>0.07$^{+0.02}_{-0.02}$</td>
<td>108.31/71</td>
<td>2.23$^{+1.73}_{-0.82}$</td>
</tr>
<tr>
<td>NGC 4472</td>
<td>1.08$^{+0.01}_{-0.01}$</td>
<td>0.43$^{+0.06}_{-0.06}$</td>
<td>0.28$^{+0.02}_{-0.02}$</td>
<td>381.76/71</td>
<td>2.41$^{+0.42}_{-0.37}$</td>
</tr>
<tr>
<td>NGC 4636</td>
<td>0.70$^{+0.01}_{-0.01}$</td>
<td>0.45$^{+0.07}_{-0.06}$</td>
<td>0.25$^{+0.02}_{-0.02}$</td>
<td>619.20/74</td>
<td>2.48$^{+0.40}_{-0.35}$</td>
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</tbody>
</table>

(1) Best fit temperature in the full-band. (2) Best fit metal abundances in the full-band. (3) Best fit temperature from the hard-band fitting, i.e., above 2.5 keV.

We jointly fitted the GIS and SIS spectra with a vMEKAL model, in which the metal abundances are splitted into the two groups as before, $Z_a$ and $Z_{Fe}$ (see § 4.3.4). The fitting results are listed in Table 5.3, and the best fit model predictions are superposed
on the spectra in Fig.5.2. In the fitting, the redshift and the absorption column are fixed at the values listed in Table 5.2. We examined the SIS data taken after 1997, against the effect of the decreasing quantum efficiency in low-energies (§ 3.4.4), and found it to be generally insignificant, due to the limited photon statistics of the data. Only those of the NGC 1550 group, the second brightest group among the sky, require excess absorption, and we set the value free for its SIS spectra.

The best fit temperature ranges from 0.6 to 1.8 keV. The fits are acceptable for only 6 and 9 groups, in 90% and 99% confidence level, respectively. Some groups show excess hard tails, while the brightest groups show large residuals around the Fe-L line region. The former objects possibly exhibit the excess hard X-ray emission, like HCG 62. To further investigate this possibility, we then fitted the hard-band spectra, above 2.5 keV, using the same model with a fixed metal abundance of $Z_\alpha = Z_{Fe} = 0.3$. The obtained temperatures are also listed in Table 5.3, and are compared with the full-band temperatures in Fig.5.3. Although the error-bars are rather large, the hard-band temperature is significantly higher than the full-band temperature in about half the objects. It sometimes reaches twice the latter value, the ratio similar to that of HCG 62. This may be taken as a possible evidence for the excess hard X-ray emission in at least some targets in our sample.

### 5.2.2 Two component fits

To quantify the amount of the suggested hard excess above the IGM emission, we accordingly added a power law component, with $\Gamma$ fixed at 2.0, to the vMEKAL component (vMEKAL+PL model; see § 4.3.4). The fitting results with this model are summarized in Fig.5.4 and Table 5.4. The best fit temperatures range from 0.4 keV to 1.6 keV, and the fits become acceptable for 9 (additional 3) and 13 (4) groups, in 90% and 99% confidence level, respectively. The $\chi^2$ values of 7 out of 17 groups have decreased by more than 10%; they are generally those groups which exhibit large differences between the hard and full-band temperatures in Fig.5.3. On the other hand, 6 groups require no hard component, and the remaining 4 groups show moderate improvements in $\chi^2$. Here, a reduction in $\chi^2$ by $\Delta \chi^2 \sim 7$ with the introduction of the power law component (1 extra fit parameters) is significant in terms of $F$-test at 99% confidence, for a fit with $\sim 70$ dof and reduced-$\chi^2 \sim 1$. Thus, about a half of the groups show evidence of hard component.

Even employing the vMEKAL+PL model, the five brightest groups, with the 0.5–10 keV fluxes exceeding $\sim 1 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$, exhibit a rather high value of reduced-$\chi^2$, larger than 2.2. It is due to residuals around 0.8–2.0 keV, which is the energy range of the
Figure 5.2: The GIS and SIS spectra of representative object in our sample, jointly fitted with a vMEKAL component. All spectra are plotted to the same scale. The last panel shows the spectra of the elliptical galaxy, NGC 4636. See Fig.D.2 for the remaining targets.
Table 5.4: Results of the joint fit to the GIS and SIS spectra with the two component model.

<table>
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<th>target</th>
<th>$kT^{(1)}$ (keV)</th>
<th>$Z_a(Z_\odot)$</th>
<th>$Z_{Fe}(Z_\odot)$</th>
<th>Soft Flux$^{(3)}$</th>
<th>Hard Flux$^{(4)}$</th>
<th>$\chi^2$/d.o.f</th>
<th>$\Delta \chi^2^{(5)}$</th>
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</thead>
<tbody>
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<td>HCG 51</td>
<td>$1.38^{+0.03}_{-0.03}$</td>
<td>$0.44^{+0.15}_{-0.13}$</td>
<td>$0.38^{+0.06}_{-0.05}$</td>
<td>2.64</td>
<td>0.00$^{+0.05}_{-0.00}$</td>
<td>97.3/70</td>
<td>0.00</td>
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<tr>
<td>HCG 97</td>
<td>$1.02^{+0.03}_{-0.04}$</td>
<td>$0.36^{+0.27}_{-0.17}$</td>
<td>$0.27^{+0.13}_{-0.07}$</td>
<td>1.10</td>
<td>0.23$^{+0.11}_{-0.11}$</td>
<td>68.62/70</td>
<td>−12.86</td>
</tr>
<tr>
<td>NGC 1132</td>
<td>$1.09^{+0.02}_{-0.03}$</td>
<td>$0.39^{+0.15}_{-0.12}$</td>
<td>$0.27^{+0.06}_{-0.04}$</td>
<td>3.46</td>
<td>0.00$^{+0.13}_{-0.00}$</td>
<td>69.41/70</td>
<td>0.00</td>
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<td>$1.33^{+0.02}_{-0.02}$</td>
<td>$0.56^{+0.07}_{-0.06}$</td>
<td>$0.42^{+0.04}_{-0.04}$</td>
<td>19.4</td>
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<td>245.78/68</td>
<td>−128.87</td>
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<td>NGC 1550</td>
<td>$1.41^{+0.02}_{-0.02}$</td>
<td>$0.54^{+0.07}_{-0.06}$</td>
<td>$0.41^{+0.04}_{-0.03}$</td>
<td>25.7</td>
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<td>162.61/56</td>
<td>−2.18</td>
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<td>NGC 2563</td>
<td>$1.33^{+0.05}_{-0.06}$</td>
<td>$0.79^{+0.53}_{-0.30}$</td>
<td>$0.44^{+0.24}_{-0.13}$</td>
<td>2.32</td>
<td>0.41$^{+0.27}_{-0.27}$</td>
<td>57.54/70</td>
<td>−5.98</td>
</tr>
<tr>
<td>NGC 4325</td>
<td>$1.04^{+0.02}_{-0.02}$</td>
<td>$0.42^{+0.15}_{-0.12}$</td>
<td>$0.34^{+0.07}_{-0.05}$</td>
<td>5.84</td>
<td>0.00$^{+0.15}_{-0.00}$</td>
<td>79.48/66</td>
<td>0.00</td>
</tr>
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<td>NGC 5044</td>
<td>$1.00^{+0.01}_{-0.01}$</td>
<td>$0.42^{+0.05}_{-0.04}$</td>
<td>$0.30^{+0.02}_{-0.02}$</td>
<td>29.1</td>
<td>0.99$^{+0.23}_{-0.23}$</td>
<td>262.76/73</td>
<td>−50.22</td>
</tr>
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<td>NGC 507</td>
<td>$1.35^{+0.03}_{-0.03}$</td>
<td>$0.83^{+0.19}_{-0.15}$</td>
<td>$0.52^{+0.09}_{-0.07}$</td>
<td>10.6</td>
<td>0.97$^{+0.25}_{-0.25}$</td>
<td>163.30/72</td>
<td>−29.44</td>
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<td>NGC 533</td>
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<td>$0.49^{+0.25}_{-0.18}$</td>
<td>$0.33^{+0.11}_{-0.11}$</td>
<td>3.60</td>
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<td>0.00</td>
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<td>$0.22^{+0.06}_{-0.04}$</td>
<td>8.61</td>
<td>0.34$^{+0.25}_{-0.25}$</td>
<td>145.67/66</td>
<td>−5.02</td>
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<tr>
<td>NGC 6329</td>
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<td>$0.23^{+0.12}_{-0.08}$</td>
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<td>0.53$^{+0.28}_{-0.29}$</td>
<td>80.86/70</td>
<td>−8.90</td>
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<tr>
<td>NGC 6521</td>
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<td>$0.94^{+1.19}_{-0.50}$</td>
<td>$0.52^{+0.52}_{-0.21}$</td>
<td>2.33</td>
<td>0.66$^{+0.47}_{-0.48}$</td>
<td>51.88/66</td>
<td>−5.01</td>
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<tr>
<td>NGC 7619</td>
<td>$0.97^{+0.03}_{-0.03}$</td>
<td>$0.40^{+0.17}_{-0.12}$</td>
<td>$0.26^{+0.07}_{-0.07}$</td>
<td>3.32</td>
<td>0.13$^{+0.16}_{-0.13}$</td>
<td>71.49/70</td>
<td>−1.86</td>
</tr>
<tr>
<td>Pavo</td>
<td>$0.44^{+0.06}_{-0.04}$</td>
<td>$0.19^{+0.23}_{-0.11}$</td>
<td>$0.07^{+0.06}_{-0.03}$</td>
<td>2.64</td>
<td>0.42$^{+0.10}_{-0.13}$</td>
<td>77.89/70</td>
<td>−26.57</td>
</tr>
<tr>
<td>RGH 80</td>
<td>$1.09^{+0.03}_{-0.04}$</td>
<td>$0.74^{+0.29}_{-0.29}$</td>
<td>$0.36^{+0.18}_{-0.10}$</td>
<td>1.71</td>
<td>0.64$^{+0.12}_{-0.12}$</td>
<td>67.95/72</td>
<td>−62.50</td>
</tr>
<tr>
<td>S49-147</td>
<td>$0.97^{+0.06}_{-0.13}$</td>
<td>$0.12^{+0.11}_{-0.09}$</td>
<td>$0.09^{+0.04}_{-0.03}$</td>
<td>2.89</td>
<td>0.75$^{+0.28}_{-0.28}$</td>
<td>90.11/70</td>
<td>−18.20</td>
</tr>
<tr>
<td>NGC 4472</td>
<td>$1.06^{+0.01}_{-0.01}$</td>
<td>$0.63^{+0.17}_{-0.13}$</td>
<td>$0.46^{+0.08}_{-0.05}$</td>
<td>9.35</td>
<td>$1.77^{+0.24}_{-0.24}$</td>
<td>239.87/70</td>
<td>−141.89</td>
</tr>
<tr>
<td>NGC 4636</td>
<td>$0.68^{+0.01}_{-0.01}$</td>
<td>$0.73^{+0.17}_{-0.12}$</td>
<td>$0.42^{+0.07}_{-0.05}$</td>
<td>9.58</td>
<td>0.73$^{+0.06}_{-0.06}$</td>
<td>259.94/73</td>
<td>−359.26</td>
</tr>
</tbody>
</table>

(1) Best fit temperature from the full-band fitting with a vMEKAL+PL model.
(2) Best fit metal abundances from the full-band fitting with a vMEKAL+PL model.
(3) The 0.5−10 keV flux of the vMEKAL component, in $10^{-12}$ erg s$^{-1}$ cm$^{-2}$.
(4) The 2−10 keV flux of the power-law component, in $10^{-12}$ erg s$^{-1}$ cm$^{-2}$.
(5) The improvement of the $\chi^2$ value by adding a power law component.
Figure 5.3: The best fit temperature from the hard-band fitting, compared to that from the full-band fitting. A diamond represents HCG 62, circles the two ellipticals, and squares the other 17 groups. Solid line indicates equal temperature, dotted line 10% higher and dashed line twice of that of the full-band fitting.

Fe-L line emission. If we introduce another vMEKAL component with a lower temperature (2-vMEKAL+PL model; see § 4.3.4), the $\chi^2$ values further decreases significantly for most of these targets. By doing so, the normalization of the power law component in NGC 1399 and NGC 5044 decreases by $20 \sim 30\%$, while in NGC 507, the hotter component temperature become as high as 6 keV and simply replaces the power law component. In case of NGC 1550 and NGC 5846, the hard fluxes are already insignificant, and the second vMEKAL component just make it even less significant. Thus, the introduction is a second vMEKAL component does not drastically influence our results, and the fit residuals remain significant over the 0.8–2.0 keV regions in some objects. This is supposed to be due to errors in the theoretical calculation of the Fe-L line emission (e.g., Matsushita 1996). Because the precise modeling of the line emission is beyond the scope of this thesis, we do not make further effort to obtain an acceptable fit for these handful of brightest groups. In general, we assume that the model well represents the IGM emission in its averaged feature, which is supported by the existence of five groups requiring no hard component, with their IGM temperature widely distributed from 0.97 keV to 1.41 keV (see § 5.3).
Figure 5.4: The same spectra as shown in Fig.5.2, fitted with a sum of a vMEKAL and a power law components. See Fig.D.3 for the remaining targets.
5.2.3 Comments on individual objects

NGC 1399 group

This object is alternatively called the Fornax cluster, one of the poorest and nearest clusters. This is also one of the X-ray brightest targets in our sample, and a vMEKAL model fit was not acceptable with reduced-\(\chi^2 = 375/69\) (shown as \(\chi^2/\text{dof}\), hereafter \(\chi^2\); see Table 5.3), with prominent hard excess above \(\sim 4\) keV and the residuals around Fe-L line region (Fig.5.2). By adding a power law component (vMEKAL+PL model), the \(\chi^2\) greatly decreased to 246/68 (Table 5.4), while the residuals around Fe-L line region remained unchanged (Fig.5.4). When we employ a 2-vMEKAL model instead of the vMEKAL+PL model, the latter residual decreased and the fit also greatly improved with a \(\chi^2 = 240/68\), while the hard excess is still visible. The derived temperatures are

\[
kT_{\text{cool}} = 0.88^{+0.14}_{-0.04} \text{ keV} \quad \text{and} \quad kT_{\text{hot}} = 1.65^{+0.04}_{-0.04} \text{ keV},
\]

the latter being a little lower than the value of the hard-band fitting, \(kT = 1.84^{+0.09}_{-0.12} \text{ keV}\) (Table 5.3), which should be regarded as a lower limit considering the contribution from the cooler component. Restoring a power law component with \(\Gamma = 2.0\) (2-vMEKAL+PL model), the \(\chi^2\) further decreased to 215/67. The derived temperatures are then \(kT_{\text{cool}} = 0.84^{+0.16}_{-0.10} \text{ keV} \quad \text{and} \quad kT_{\text{hot}} = 1.45^{+0.04}_{-0.04} \text{ keV}\), and the 2–10 keV hard component flux of \(1.59^{+0.32}_{-0.34} \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}\). Although this flux is by \(\sim 20\%\) lower than derived with the vMEKAL+PL model, it still exceeds both the estimated LMXB component (\(\sim 0.4 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}\)) and the CXB fluctuation (\(\sim 0.3 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}\)). All the above results are little affected by setting the column density free, except the parameters for the cooler IGM component. Thus, we conclude that there exists a hard component in NGC 1399, which is either a non-thermal emission or a thermal emission with a temperature higher than \(\sim 2\) keV.

Our results are generally consistent with the previous study by Ikebe (1995) and Ikebe et al. (1996), who fitted the GIS spectra using a vRS model for the IGM emission, and obtained a lower temperature and a more prominent excess hard component (see § 4.5.4). By fitting jointly the GIS and SIS spectra, Boute et al. (1998) and Allen et al. (2000) obtained results similar to ours, although they only used the data from the central \(\sim 4'\) region. The former authors tried only 2-MEKAL model, while the latter authors argued for the existence of additional power law component and attributed it to the possible AGN in the NGC 1399 galaxy. To examine this possibility, we also extracted spectra from the region excluding \(3'\) around NGC 1399. Though less significant, we obtained generally similar results as shown above, where the \(\chi^2\) of 2-vMEKAL and 2-vMEKAL+PL fit being 184.61/68 and 173.01/67, respectively. These results are also consistent with the ROSAT
PSPC results showing a temperature decrease in the group central region, though the
detector has almost no sensitivity to the hard component (e.g., Jones et al. 1997). The
AGN interpretation of the excess hard X-ray emission (Allen et al. 2000) was ruled out
by the latest Chandra observation.

**NGC 5044 group**

This is one of the X-ray brightest groups among the sky, and the vMEKAL model fit
is not acceptable with $\chi^2 = 313/74$ (Table 5.3). With 2-vMEKAL model, we obtain
$kT_{\text{cool}} = 0.79_{-0.05}^{+0.04} \text{ keV}$ and $kT_{\text{hot}} = 1.23_{-0.04}^{+0.05} \text{ keV}$, with $\chi^2 = 210/72$. These are consistent
with the central temperature decrease shown by Fukazawa et al. (1996) using the same
ASCA data, and also the previous ROSAT results (e.g., David et al. 1994). Because the
residual spectra exhibit some hard excess, we employed the 2-vMEKAL+PL model, and
obtained $\chi^2 = 180.90/71$. However, the hard component luminosity is lower than 4% of
the IGM luminosity in both vMEKAL+PL and 2-vMEKAL+PL fitting, making one of
the tightest upper limits in our sample. We think this level is too small to distinguish the
hard component from the possible IGM modeling error. We therefore regard the derived
hard component luminosity as an upper limit.

**NGC 507 group**

The spectrum obtained from the SIS1 is flattened around 1 keV, which is inconsistent
with the SIS1 data from a short supplemental observation performed later (sequence ID
= 61007010). Therefore, we used only the data from the SIS 0 in our analyses. The
group is bright in X-rays, and vMEKAL model fit is not acceptable with $\chi^2 = 193/73$
(Table 5.3). With the 2-vMEKAL model, we obtain $\chi^2 = 164/71$; the temperature of
the hotter component became higher than 6.0 keV, while that of the cooler component
was $kT_{\text{cool}} = 1.35_{-0.08}^{+0.03} \text{ keV}$. The obtained $\chi^2$ and $kT_{\text{cool}}$ are very similar to those from
the vMEKAL+PL fitting (Table 5.4), indicating that the hot component simply replaced
the power law component. The fit does not improve any more by adding a power law
component (2-vMEKAL+PL model). Thus, similar to NGC 1399, the data suggest a
hard component, either thermal or non-thermal.

**NGC 533 group**

The temperature of the SIS detectors was rather high, $T > -60 \text{ C}^\circ$ and $> -59.5 \text{ C}^\circ$ for SIS
0 and 1, respectively, in both of the two observations. This increased the dark current and
the number of the hot and flickering pixels of the detectors, which affected the data taken with long frame interval. Hence, the spectra of the first observation taken with 4 CCD mode, which has the longest frame interval (§ 3.4.2), show strong soft excess below \( \sim 0.8 \) keV, while that of the second observation taken with 2 CCD mode do not. Therefore, we used only data from the second observation, which also has a longer exposure, but a smaller FOV. The fit with the vMEKAL model is almost acceptable (Table 5.3), and there is no evidence for any hard component.

**NGC 6521 group**

The vMEKAL fit is acceptable, while the additional hard component is marginally significant in terms of \( F \)-test. This is due to the rather high IGM temperature, \( \sim 1.64 \) keV, which make it difficult to separate the hard component, if any, from the IGM emission.

**Pavo group**

The IGM temperature derived with the vMEKAL+PL model, \( kT = 0.44 \) keV, may be somewhat too low for the ASCA bandpass to yield an accurate determination. Therefore, the hard component thus obtained is also less reliable. When fitted with a Raymond-Smith model, the best fit temperature is \( kT = 0.77 \) keV, and the hard component becomes less significant with the best fit flux being \( \sim 40\% \) of that of the vMEKAL+PL model.

**RGH 80**

One of the groups with significant hard X-ray emission. It is also the farthest group in our sample and among the most luminous. If we set the photon index of the power law component free in the vMEKAL+PL fitting, it becomes \( \Gamma = 1.61_{-0.86}^{+0.74} \) with \( \chi^2 = 68.03/71 \); this is similar to the case with fixed \( \Gamma \). When fitted with a 2-vMEKAL model, the temperature of the hotter component becomes \( kT_{\text{hot}} = 23.9_{-20.3}^{+\infty} \) keV, and \( \chi^2 = 68.2/71 \). Boute (2000) analyzed the ASCA spectra obtained from the central \( \sim 3.6' \), and reported a rather lower temperature for the hot component, \( kT_{\text{hot}} = 1.64_{-0.17}^{+0.21} \) keV. We confirmed this result by extracting the spectra from a similar region. Therefore, the hard component is inferred to be stronger in the \( 3' < r < 10' \) region.
5.3 General Properties of the Sample Groups

In the last section, evidence for excess hard emission was detected from about half objects in our sample. In this section, we examine their properties as a whole. We compare the significance of the hard component against various parameters, such as the IGM temperature, the observed fluxes, and the X-ray and optical luminosities. Then we examine whether the hard component is extended, by averaging three groups with nearly the same spectra. We compare the results with those from HCG 62.

5.3.1 Comparison with the IGM properties

In Fig.5.5a, the 2–10 keV hard component flux (taken from Table 5.4) derived from the vMEKAL+PL fits is plotted against the 0.5–10 keV flux of the IGM component. There is no correlation visible in the plot, which means that the hard component flux derived is independent of the flux of the IGM component. Thus, it eliminates the possibility that the hard tail is originating from slight errors in the modeling of the hard-band continuum of IGM emission.

![Figure 5.5: (a) The hard component flux plotted against that of the IGM component. Dashed line represents the ratio of 10%, and dotted line 20%. (b) The luminosity ratio of the hard component to the IGM emission, plotted against the IGM temperature. In both panels, symbols are the same as those in Fig.5.3.](image)

In Fig.5.5b, we plot the hard component luminosity \( L_{\text{hard}} \) (derived from Tables 5.4 and 5.1) divided by the IGM luminosity \( L_{\text{IGM}} \) (hereafter, the hard-IGM luminosity ratio) against the fitted IGM temperature. The ratio ranges from < 1% to as high as 40%, and is higher than \( \sim 10\% \) in about half the sample groups. Furthermore, groups with
and without the hard excess coexist at any IGM temperature, and there is no correlation between the two quantities. The lack of correlation in this plot is another evidence that the excess hard X-ray emission from some groups is not an artifact caused by the wrong modeling of the IGM emission, which is mainly defined by its temperature.

Figure 5.6: Spectra of the groups divided with those of the NGC 5044. (a) HCG 62, (b) RGH 80, (c) NGC 4325, and (d) NGC 1550. Black crosses represents the GIS, and gray crosses the SIS.

In Fig.5.5, there are three targets, HCG 97, RGH 80 and S49-147, sharing almost the same position as HCG 62, with the IGM temperature of $kT \sim 1$ keV and the luminosity ratio around $20 \sim 40\%$. In addition, there are another three targets, the NGC 1132, NGC 4325 and NGC 5044 groups, sharing similar temperature but with very low luminosity ratio, below $\sim 5\%$. Because the NGC 5044 group has the best statistics in our sample objects, we divided the spectra of these targets with that of the NGC 5044 group. The derived spectral ratios are presented in Fig.5.6. For the former three targets, the ratio spectra are flat around 1 keV, and rapidly increase in the hard band. On the contrary, those of the NGC 4325 group are almost constant throughout the full energy band. Those of the NGC 1550 group, which has the IGM temperature $\sim 40\%$ higher than that of NGC 5044, show a constant increase; this behavior is different from the steep rising of the
spectra seen in HCG 62. Therefore, the hard component required in the former three
targets is confirmed to be distinct from the hardening due to the high IGM temperature.

In Fig.5.7a, we plot $L_{\text{hard}}$ against $L_{\text{IGM}}$. Unlike the case of the hard component flux
(Fig.5.5a), a clear correlation is visible in this plot; targets with luminous hard component
also are luminous in the IGM emission. There also exist targets which are luminous in the
IGM emission, but not in the hard component. Thus, all the data points are distributed
below the line defining the luminosity ratio of $\sim 30\%$. In Fig.5.7b, we plot $L_{\text{hard}}$ against
the IGM temperature. In contrast to Fig.5.7a, almost no correlation is visible. Therefore,
a necessary condition for a group to have a high hard component luminosity is to have a
high IGM luminosity, while the IGM temperature is irrelevant.

Figure 5.7: (a) The hard component luminosity ($L_{\text{hard}}$) plotted against that of the IGM
($L_{\text{IGM}}$). Dashed line represents the ratio of 10%, and dotted line 20%. (b) The hard
component luminosity ($L_{\text{hard}}$) plotted against the IGM temperature. In both panels,
symbols are the same as those in Fig.5.3.

5.3.2 The CXB fluctuation and the LMXB contribution

The fluctuation of the CXB surface brightness may contribute some amount to the hard
X-ray component (see § 4.5.5). In Fig.5.8a, we plot the hard-IGM luminosity ratio against
the group overall flux observed within the integration region. The CXB fluctuation cal-
culated from equation 4.2 and converted into 2-10 keV flux is $1.7 \sim 3.3 \times 10^{-13}$ erg s$^{-1}$
cm$^{-2}$ for an integration region with $r = 10' \sim 20'$. Although the error bars get larger with
decreasing overall flux, the hard excess emission significantly exceeds the CXB fluctuation
level for most of the objects in our sample. Furthermore, there is no particular correlation
between the two quantities. Thus, our result is little affected by the CXB fluctuation.

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Figure 5.8: (a) The hard vs IGM luminosity ratio plotted against the full-band flux. Dashed line represents the typical fluctuation of the CXB flux, for an integration region with $r = 10^{\prime}$. (b) The hard component luminosity ($L_{\text{hard}}$) plotted against the optical $B$-band luminosity. Dashed line represents the estimated contribution from LMXBs, calculated from equation 2.16. For both panels, symbols are the same as those in Fig.5.3.

In Fig.5.8b, we plot $L_{\text{hard}}$ against the optical $B$-band luminosity of the group member galaxies listed in Table 5.1. We also display there the contribution from LMXBs in the member galaxies estimated using equation 2.16 (see § 2.2.4). Thus, the luminosity of the hard excess emission is about an order of magnitude higher than the LMXB component for most of the groups in our sample, although it is explained by the LMXB contribution in case of the elliptical galaxies and several groups (see also Fig.2.11).

### 5.4 Averaged Properties of HCG 97, RGH 80 and S49-147

Because the objects in our sample generally have poorer data statistics as compared to HCG 62, it is difficult to analyze their properties in further details individually. However, we may sum up data from several objects to improve the data quality. For this purpose, we selected three groups, HCG 97, RGH 80 and S49-147, which have properties similar to those of HCG 62 (see Fig.5.5). These objects have significant hard excess, which is generally well separated from the IGM emission, because of their relatively low temperature.

The summed spectra, with a cumulative exposure of 180 ksec, are presented in Fig.5.9. The fit with a single temperature vMEKAL model is unacceptable with reduced-$\chi^2 =$
164.47/68, which drastically decreases to 91.38/67 by introducing an additional power law component (vMEKAL+PL model). The latter fit results are listed in Table 5.5, and the best fit model is superposed on the spectra in Fig.5.9. Strictly speaking, the fit is not acceptable at 90% confidence, which may be due to the difference of the IGM parameters and redshifts among the three groups. When we set $\Gamma$ free, its acceptance range is less constrained for the same reason, compared to the fit using the RGH 80 data alone (see § 5.2.3). However, in view of $\Delta \chi^2$, the hard component becomes more significant than in the fits to the individual spectra (Table 5.4), and the 2–10 keV hard component flux is determined with a better accuracy, as $31^{+5}_{-3}\%$ of the IGM flux. The hard component is dominant above 4 keV, and the photon counts in the 4–8 keV band is as much as $513.2 \pm 99.6$; this is twice the value from RGH 80 alone, and almost comparable to that of the HCG 62 listed in the last row of Table 4.9.

Table 5.5: Results of the joint fit to the GIS and SIS spectra averaged over HCG 97, RGH 80 and S49-147, with vMEKAL+PL model.

<table>
<thead>
<tr>
<th>$kT$ (keV)</th>
<th>$Z_a(Z_\odot)$</th>
<th>$N_H^{(1)}$</th>
<th>$z^{(2)}$</th>
<th>Soft Flux</th>
<th>Hard Flux</th>
<th>$\chi^2/d.o.f$</th>
<th>$\Delta \chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.03$^{+0.03}_{-0.04}$</td>
<td>0.37$^{+0.09}_{-0.07}$</td>
<td>0.20$^{+0.03}_{-0.01}$</td>
<td>0.019$^{+0.01}_{-0.01}$</td>
<td>1.61</td>
<td>0.50$^{+0.08}_{-0.05}$</td>
<td>91.38/67</td>
<td>−73.09</td>
</tr>
</tbody>
</table>

(1) Fitted column density, in $10^{20}$ cm$^{-2}$. (2) Fitted redshift.

Figure 5.9: The averaged spectra summed over HCG 97, RGH 80 and S49-147, fitted with the vMEKAL+PL model.

Similarly, we have examined the radial profile, summed over the three objects, for
Figure 5.10: The azimuthally averaged radial surface brightness profile, similar to Fig.4.14b of HCG 62. The data from HCG 97, RGH 80 and S49-147 are averaged. The profiles in 4.0–8.0 keV (filled boxes), 0.5–4.0 keV (open circles with histograms), and the PSF of XRT+GIS in the 4.0–8.0 keV band (thick solid histograms) are plotted.

angular extent. The extent of the IGM emission of HCG 97 and RGH 80 is roughly similar, with FWHM of ~ 4′ on the GIS image, while that of S49-147 has a FWHM of ~ 12′. We therefore scaled the latter image by a factor of 1/3, generated radial profiles for all three groups, and then added them. The result is plotted in Fig.5.10. The 4–8 keV band profile is significantly more extended than the PSF of XRT+GIS, and resembles that of the IGM emission. These properties are similar to the results from HCG 62 (see § 4.4.2), supporting that the hard excess emission in these three groups is the same phenomenon as that in HCG 62.

5.5 Brief Summary of the Analysis of 17 Groups

Following the results from HCG 62, we have analyzed additional 17 groups selected from the ASCA data available. About half the selected groups have been shown to host significant hard emission (§ 5.2.2), which cannot be explained by either the LMXB contribution from the group member galaxies or the fluctuation of the CXB surface brightness (§ 5.3.2). It shows little correlation with the IGM temperature or flux, eliminating the possible systematics due to the IGM modeling error. The hard component luminosity ($L_{\text{hard}}$) shows
clear upper-limit defined as $\sim 30\%$ of the IGM luminosity (§ 5.3.1).

We also analyzed the averaged data of the three groups (HCG 97, RGH 80 and S49-147) with spectral properties similar to HCG 62, and showed that the hard component is distinct from the IGM component. Furthermore, we confirmed that the radial extent of the hard component is significantly extended than the XRT+GIS PSF, as much as the IGM emission (§ 5.4). The average properties of these three groups generally resemble those of HCG 62.
Chapter 6

Discussion

6.1 Observed Properties of the Hard X-ray Emission

We detected excess hard X-rays from about half of the 18 selected groups observed with ASCA. Among them, the HCG 62 group exhibits the most statistically significant hard excess emission, which is clearly extended with its radial profile similar to or rather wider than that of the IGM brightness (§ 4.4.2). Assuming a distance of $58.4 h_{75}^{-1}$ Mpc, the 2–10 keV luminosity of the hard emission is $4.18^{+0.70}_{-0.85} \times 10^{41} h_{75}^{-2}$ erg s$^{-1}$, which is $21.4^{+3.8\%}_{-4.1\%}$ of the IGM luminosity in the 0.5–10 keV band (§ 4.3.4). When fitted with a power-law spectra, the photon index $\Gamma$ is not well constrained, $\Gamma = 1.55^{+1.21}_{-0.89}$ (§ 4.3.4). If we adopt a thermal interpretation, the inferred temperature becomes $kT = 32.0^{+\infty}_{-26.3}$ keV, implying a lower limit of 5.7 keV.

Other $\sim 9$ groups also exhibit evidence for a hard emission, with the 2–10 keV luminosity of the hard X-rays being $1 \sim 18 \times 10^{41} h_{75}^{-2}$ erg s$^{-1}$, which is $10 \sim 40\%$ of the IGM luminosity. On the other hand, the remaining 8 groups exhibit little evidence for excess hard emission, with typical upper limit luminosity of $\sim 5\%$ of the IGM component (§ 5.3.1).

6.2 Comparison with Cluster Hard X-ray Emission

In this section, we compare our results with those of the three clusters, Coma, A2256 and A2199, which are reported to host a non-thermal emission (see § 2.4.2).

The spectral shape, i.e., the photon index, of the non-thermal component detected in the three clusters are as poorly constrained as the hard X-ray emission from our group sample, and are generally consistent with $\Gamma = 2.0$, adopted for our analysis. To compare
the luminosities, we must convert the cluster quantities to those in more appropriate energy bands. For the hard component with $\Gamma = 2.0$, the 20–80 keV luminosity is nearly equivalent to that in the 2–10 keV band. For the hot gas component (ICM or IGM), the 0.5–10 keV range adopted for groups is equivalent to an energy range of $(0.5 - 10)kT$, since $kT \sim 1$ keV for most of our sample. We hence adopted this $kT$-dependent energy ranges in calculating the cluster ICM luminosities, and found them similar to the 2–10 keV values for the particular three clusters. We thus simply use the raw values listed in Table 2.4.

In Fig.6.1a, we plot the luminosities of the hard component against those of the hot gas component, including all groups in our sample and the three clusters. The hard-ICM luminosity ratio of the three clusters ranges from 7% to 23%, similar to the values of the groups with hard X-ray emission. In Fig.6.1b, we plot the luminosity of the hard component against the IGM (or ICM) temperature. There, we can see a general correlation between the two quantities, roughly as $L_{\text{hard}} \propto (kT)^3$, which was not obvious without including the clusters. This relation reflects the $kT - L_X$ relation generally found in clusters and groups (§ 2.2.3), combined with the result from Fig.6.1a. From these results, the group hard excess emission and that of the three clusters are considered to be generally similar in view of their luminosity ratio against that of the hot gas component.

![Figure 6.1](image)

Figure 6.1: The hard component luminosity plotted against the (a) luminosity and (b) temperature of the hot gas component. Those plots are the same as Fig.5.7, but includes the three clusters (large circles) with significant excess hard X-ray emission.

In the following sections, we examine several possible mechanisms for the hard X-ray production in groups of galaxies, sometimes in comparison with those from the three clusters. We constrain relevant physical quantities involved in each mechanism, based on
the observed properties of our sample groups, in particular, HCG 62.

6.3 Inverse Compton Scattering

6.3.1 Derived parameters

One possible interpretation of the hard X-rays is to assume that relativistic electrons are scattering off some soft seed photons via IC process and boost them into hard X-rays (see § 2.3.3). The seed photons are considered to be supplied by the CMB, because the energy density of the CMB photons, $U_{\text{CMB}} = 4.2 \times 10^{-13} (1+z)^4 \text{ erg cm}^{-3}$, is more than an order of magnitude higher than that of the star-light, except at the very center ($R \sim 10$ kpc) of HCG 62. Because the representative CMB photon energy is $\sim 7 \times 10^{-4}$ eV, the Lorentz factor of the electrons required to generate 10 keV IC photons is $\gamma \sim 3.4 \times 10^3$ from equation 2.21. This implies a cooling time of $\tau_{\text{cool}} \sim 7 \times 10^8$ yr, considering only the energy loss due to the IC scattering.

The hard component in HCG 62 and other groups is well fitted by a power law with a photon index of $\Gamma = 2.0$, or an energy index of $\alpha = \Gamma - 1 = 1.0$. This value is generally consistent with the radio halo spectra (§ 2.4.1). The implied electron number index (equation 2.17) of $\mu = 2\alpha + 1 = 3.0$ (see § 2.3.3), is comparable to the cosmic ray electron spectrum at the top of the earth’s atmosphere. For these reasons, we adopt $\alpha = 1.0$ and $\mu = 3.0$ for the moment.

Then, equation 2.23 is re-written as

$$\frac{dL_{\text{IC}}}{d\nu} = 5.55 \times 10^{-27} \frac{N_0}{\nu} \text{ [erg s}^{-1} \text{ Hz}^{-1}] \quad . \quad (6.1)$$

As the hard component luminosity in the 2–10 keV band is $4.2 \times 10^{41}$ erg s$^{-1}$ for HCG 62, we obtain $N_0 = 4.72 \times 10^6$ in number.

The relativistic electrons produce at the same time synchrotron emission by interacting with a magnetic field (§ 2.3.2). From equation 2.18, the Lorentz factor of the electron required to generate 1.4 GHz radio emission is $\gamma = 1.8 \times 10^4 \left( \frac{B}{\mu G} \right)^{1/2}$. This in turn implies a cooling time of $\tau_{\text{cool}} \sim 1 \times 10^8 (\frac{B}{\mu G})^{1/2}$ yr, which is also defined mainly by the IC scattering process (see Fig.2.12).

From $\mu = 3.0$, $\nu = 1.4$ GHz and $N_0 = 4.72 \times 10^6$, the synchrotron luminosity is derived as $2.65 \times 10^{31} (\frac{B}{\mu G})^2$ erg s$^{-1}$, using equation 2.20. At the distance of 58.4 $h_{75}^{-1}$ Mpc, its flux at 1.4 GHz is thus estimated as

$$f(1.4 \text{ GHz}) = 6.85 \left( \frac{B}{\mu G} \right)^2 \text{ [Jy]} \quad . \quad (6.2)$$
Here, $1 \text{ Jy} = 1 \times 10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$.

### 6.3.2 Comparison with radio observations

The synchrotron flux predicted by equation 6.2 is rather high (see Table 2.2): the most crucial test of the IC scenario is whether this prediction is consistent with radio observations. We accordingly examined the radio all sky maps and catalogs for the possible radio halo around HCG 62.

We first used the NRAO VLA Sky Survey (NVSS), which presents the sky image in 1.4 GHz radio band, and a catalog of sources brighter than $\sim 2.5$ mJy detected in the image (Condon et al. 1998, http://www.nrao.edu). As the synchrotron emission should be as extended as the hard X-rays, it will have a size of $\sim 15'$. We present the NVSS image of HCG 62 in Fig.6.2. There are 10 sources within $15'$ from HCG 62 in the NVSS catalog, all of which are discrete sources. The integrated flux within $r = 15'$ is $\sim 83.5$ mJy, while the sum of fluxes of the 10 sources is 118 mJy. Therefore, no diffuse emission is detected by NVSS.

<table>
<thead>
<tr>
<th>name</th>
<th>$\nu^{(1)}$</th>
<th>beam size</th>
<th>halo flux$^{(2)}$</th>
<th>halo flux in 1.4 GHz$^{(3)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NVSS</td>
<td>1.4 GHz</td>
<td>45$''$</td>
<td>$\sim 0$ (no detection)</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>PMN</td>
<td>4.85 GHz</td>
<td>4'.2</td>
<td>$&lt; 40$ (no detection)</td>
<td>$&lt; 138$</td>
</tr>
<tr>
<td>Texas</td>
<td>365 MHz</td>
<td>4' $\sim 7'$</td>
<td>$&lt; 250$ (no detection)</td>
<td>$&lt; 66$</td>
</tr>
</tbody>
</table>

(1) Observation frequency.
(2) Observed (upper limit) flux at the observation frequency in mJy.
(3) Observed (upper limit) flux converted to 1.4 GHz assuming $\alpha = 1.0$, in mJy.

NVSS is not sensitive to sources extended more than a few times the $\theta = 45''$ (FWHM) beam-width (Condon et al. 1998). For example, Coma-C is not visible in the NVSS image. Therefore, we searched two other catalogs, the Parkes-MIT-NRAO (PMN) Surveys at 4.85 GHz (e.g., Griffith and Wright 1993), and the Texas Survey at 365 MHz (Douglas et al. 1996), for emission from HCG 62. The former has a beam size of 4'.2 (FWHM) and a flux limit of $\sim 40$ mJy, which corresponds to $\sim 138$ mJy at 1.4 GHz assuming $\alpha = 1.0$. The latter has a beam size of 4' $\sim 7'$ and a flux limit of $\sim 250$ mJy, which corresponds to $\sim 66$ mJy at 1.4 GHz. Parameters of these catalogs are summarized in Table 6.1. We found no counterpart of HCG 62 in either catalog.
Figure 6.2: The 1.4 GHz radio image of HCG 62 from NVSS. The scale levels are shown in the right side, in units of mJy arcmin$^{-2}$. Solid circle represents $r = 15'$ from the group center.

As these two surveys have a relatively wide beam-size, in contrast to the NVSS, a halo with $r \sim 15'$ should have been detected, if its flux level exceeds the survey limits. The latter survey with lower frequency provides the most strict constraints. Thus, we found no signature of a synchrotron halo in HCG 62, and quote here a conservative upper-limit of 100 mJy at 1.4 GHz. From equation 6.2, the upper limit of the group averaged magnetic field is derived to be

$$ B < 0.12 \ [\mu G] , $$

assuming that the IC interpretation is correct.

### 6.3.3 Total energies and energy densities

As we have derived the number density of relativistic electrons (§ 6.3.1) and the upper-limit of the magnetic field (§ 6.3.2), we can estimate the total energy of these non-thermal components, and compare them with that of the thermal component.

The total energy of the thermal component can be estimated from the mass and temperature of the IGM. From the IGM surface brightness profile of HCG 62, the total number of thermal proton is derived to be $N_{\text{th}} = 5.9 \times 10^{68}$ within $R = 250$ kpc. Here, 250 kpc corresponds to 15' for HCG 62. This gives the average proton density of $3.0 \times 10^{-4}$
cm$^{-3}$. The total thermal energy of the hot plasma is then

$$E_{\text{tot}}^{\text{th}} \sim \frac{3}{2} \left( 2 \times N_{\text{tot}}^{\text{th}} \times kT \right) = 2.8 \times 10^{60} \text{ [erg]} \quad (6.4)$$

Assuming a sphere of radius $R = 250$ kpc, the average thermal energy density becomes $U_{\text{th}} = 1.4 \times 10^{-12}$ erg cm$^{-3}$.

The total energy of the relativistic electron can be derived by integrating equation 2.17 multiplied by $\gamma m_c c^2$, as

$$E_{\text{tot}}^{\text{CR}} = \int_{\gamma_{\text{min}}}^{\infty} N_0 \frac{\gamma m_c c^2}{\gamma^3} d\gamma = 3.86 \times 10^{58} \left( \frac{1000}{\gamma_{\text{min}}} \right) \text{ [erg]} \quad (6.5)$$

Assuming the same sphere, the average relativistic electron energy density becomes $U_{\text{CR}} = 2.0 \times 10^{-14} \left( \frac{1000}{\gamma_{\text{min}}} \right)$ erg cm$^{-3}$. For the magnetic field, the energy density is derived as

$$U^B = \frac{1}{8\pi} B^2 = 5.7 \times 10^{-16} \left( \frac{B}{0.12 \mu G} \right)^2 \text{ [erg cm}^{-3}] \quad (6.6)$$

Thus the total magnetic energy in the same sphere is $E_{\text{tot}}^B = 1.1 \times 10^{57} \left( \frac{B}{0.12 \mu G} \right)$ erg, if the IC interpretation is true. We summarized all these results in Table 6.2.

Table 6.2: The energy density of the thermal and non-thermal components in HCG 62, derived from the IC model.

<table>
<thead>
<tr>
<th>Component</th>
<th>Total energy [erg]</th>
<th>Energy density [erg cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>thermal</td>
<td>$2.8 \times 10^{60}$</td>
<td>$1.4 \times 10^{-12}$</td>
</tr>
<tr>
<td>relativistic electron</td>
<td>$3.9 \times 10^{58} \left( \frac{1000}{\gamma_{\text{min}}} \right)$</td>
<td>$2.0 \times 10^{-14} \left( \frac{1000}{\gamma_{\text{min}}} \right)$</td>
</tr>
<tr>
<td>magnetic field</td>
<td>$1.1 \times 10^{57} \left( \frac{B}{0.12 \mu G} \right)$</td>
<td>$5.7 \times 10^{-16} \left( \frac{B}{0.12 \mu G} \right)$</td>
</tr>
</tbody>
</table>

(1) Energy density averaged in a sphere of $R = 250$ kpc.

In Table 6.3 and Fig.6.3, we compare energetics of HCG 62 and the three clusters, assuming that the IC interpretation is correct. The non-thermal energy is dominated by the relativistic electrons. The ratio of the non-thermal energy to the thermal one is similar in all four objects, which is $\sim 0.4 \left( \frac{1000}{\gamma_{\text{min}}} \right)$%. Here, we take $\gamma_{\text{min}} = 1000$, because it is generally used in the cluster analysis (e.g. Fusco-Femiano et al. 2000). However, we notice that the $\gamma_{\text{min}}$ may be smaller. From the average hot gas density of $3.0 \times 10^{-4}$ cm$^{-3}$, and the magnetic strength of $B < 0.12 \mu G$, the cooling time of the relativistic electrons in HCG 62 is longest at $\gamma = 100$ (see Fig.2.12b). Therefore, $\gamma_{\text{min}}$ may well be as low as $\sim 100$, and consequently, the non-thermal energy may be an order of magnitude higher.
Table 6.3: The total energy of the thermal and non-thermal components in HCG 62 and the three clusters, derived from the IC model.

<table>
<thead>
<tr>
<th>name</th>
<th>integration(1)</th>
<th>$E_{\text{tot}}^{\text{th}}$ (2)</th>
<th>$E_{\text{tot}}^{\text{CR}}$ (3)</th>
<th>$E_{\text{tot}}^{B}$ (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>radius [Mpc]</td>
<td>[erg]</td>
<td>$(\frac{1000}{\text{[erg]}})$</td>
<td>[erg]</td>
</tr>
<tr>
<td>Coma</td>
<td>2.1</td>
<td>$9.4 \times 10^{63}$</td>
<td>$5.8 \times 10^{60}$</td>
<td>$8.4 \times 10^{59} (\frac{B}{0.14 \mu G})^2$</td>
</tr>
<tr>
<td>A2256</td>
<td>2.1</td>
<td>$9.4 \times 10^{63}$</td>
<td>$1.9 \times 10^{61}$</td>
<td>$3.7 \times 10^{59} (\frac{B}{0.05 \mu G})^2$</td>
</tr>
<tr>
<td>A2199</td>
<td>1.5</td>
<td>$1.7 \times 10^{63}$</td>
<td>$4.3 \times 10^{60}$</td>
<td>$8.8 \times 10^{58} (\frac{B}{0.075 \mu G})^2$</td>
</tr>
<tr>
<td>HCG 62</td>
<td>0.50</td>
<td>$1.1 \times 10^{61}$</td>
<td>$3.9 \times 10^{58}$</td>
<td>$8.8 \times 10^{57} (\frac{B}{0.12 \mu G})^2$</td>
</tr>
<tr>
<td>(r=15')</td>
<td>0.25</td>
<td>$2.8 \times 10^{60}$</td>
<td>$3.9 \times 10^{58}$</td>
<td>$1.1 \times 10^{57} (\frac{B}{0.12 \mu G})^2$</td>
</tr>
</tbody>
</table>

(1) Integration radius defined as $r = 1.58 h_{75}^{-1}$ Mpc $(\frac{kT}{10 \text{ keV}})^{1/2}$ (Mohr et al. 1999). For HCG 62, the radius of the analysis region $\sim 250$ kpc is also used.

(2) The total thermal energy within the integration radius, derived by converting the parameters listed in Mohr et al. (1999).

(3) Relativistic electron energy derived from the hard component luminosity (Table 2.4), assuming an electron number index $\mu = 3$.

(4) Magnetic field energy within the integration radius. Field strength derived by comparing the hard X-ray emission and the radio halo, taken from; Fusco-Femiano et al. (1999) for Coma, Fusco-Femiano et al. (2000) for A2256, and Kempner and Sarazin (2000) for A2199.

Figure 6.3: The total non-thermal energy plotted against that of the thermal component. Dotted line represents a ratio of $1(\frac{1000}{\text{[erg]}})\%$. 

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6.3.4 Examination of the model

The IC interpretation provides a reasonable account of the observed excess hard X-ray emission from groups of galaxies, at least in terms of the implied non-thermal energy content, and various similarities to the hard X-ray emission from the three clusters. However, the scenario involves a serious problem, that the inferred upper limit on the magnetic field, \( B = 0.12 \ \mu \text{G} \) derived in § 6.3.2, clearly contradicts the generally accepted values of the intra-cluster magnetic fields. For example, observations of Faraday rotation of radio sources inside or behind clusters yield the line-averaged intra-cluster magnetic field intensity of

\[
B = (1 \sim 10) \times \left( \frac{l}{10 \ \text{kpc}} \right)^{-1/2} \ h_7^{1/2} \ \mu \text{G} ,
\]

where \( l = 1 \sim 10 \ \text{kpc} \) is the field correlation length (e.g. Kim et al. 1991, Clarke et al. 2000). The IC hypothesis of the cluster hard X-rays leads essentially to the same discrepancy (Coma, Fusco-Femiano et al. 1999: A2245, Fusco-Femiano et al. 2000: A2199, Kempner and Sarazin 2000).

Strictly speaking, no Faraday-rotation measurements are yet available for HCG 62. In fact, clusters with the observed Faraday rotation are limited to the brightest ones with the ICM temperature ranging \( 2.3 \sim 10 \ \text{keV} \) (Kim et al. 1991). No correlation between the ICM temperature and the magnetic field strength has so far been reported. Therefore, we do not have any independent information on the magnetic field in HCG 62, and the inferred low values of \( B < 0.1 \mu \text{G} \) may not be a problem in itself. Nevertheless, the implied magnetic pressure in HCG 62 falls by more than three orders of magnitude below the IGM gas pressure (Table 6.2). It would be extremely difficult to suppress the magnetic pressure to such an extremely low level, since the member galaxies are moving with trans-sonic speed in the intra-groups space and must be continuously exciting the plasma turbulence (Makishima 2000).

Then, can we somehow avoid this difficulty? If we increased the electron number index \( \mu \) from 3 to 4, the estimated flux of synchrotron emission would decrease by a factor of \( \sim 5 \) at \( 365 \ \text{MHz} \), and the magnetic field upper limit would increase to \( 0.27 \ \mu \text{G} \). This is however still insufficient. A more promising way is to give up the homogeneous picture which we have implicitly assumed (e.g. Fusco-Femiano et al. 1999). We may presume that the magnetic field forms a number of compressed thin flux tubes where the field strengths reach micro-Gauss level, while the field may be relatively weak (e.g., sub-micro-Gauss level) outside them. Since the IGM will permeate both inside and outside the flux tubes, a strong Faraday rotation can be produced inside them. If furthermore the relativistic
electrons are somehow kept outside the flux tubes, they will not emit strong synchrotron emission while producing significant IC emission. Such condition may be realized if the electrons are accelerated by magnetic reconnection that takes place near magnetic neutral sheets. Quantitatively, a magnetic-field segregation by a factor of $10 \sim 100$ may be able to solve the problem. This may not be unrealistic, since a similar condition is clearly realized in the solar corona.

We further examined whether the radial profile of the hard component observed with the GIS can constrain the emission mechanisms. If the non-thermal electron has a distribution similar to that of the IGM, the IC emissivity will be proportional to the IGM density itself, because the energy density of the CMB photon is constant. This is in contrast to the IGM emission profile which is proportional to the square of its density. In Fig.6.4, we plot the observed 4–8 keV radial profile of HCG 62 divided by that of the simulated hard component which has the same radial profile as the IGM emission. The dot-dashed line represents the predicted ratio when the emissivity is proportional to the gas density. The prediction is generally consistent with the data profile, except at the innermost region of $r < 2'$.

Thus the both possibilities remain.

![Figure 6.4: The ratio of the observed 4–8 keV radial profile and that of the simulation. See text for details.](Image)

In summary, the IC interpretation, otherwise reasonable, requires unrealistically low magnetic fields of $\sim 0.1 \mu\text{G}$. In order for the IC interpretation to be the right answer, a highly inhomogeneous magnetic field may be required. The energy density of the relativistic electrons amount to $0.4 \sim 4\%$ of that of the thermal component, depending on the lower cut off energy of the electrons.
6.4 Non Thermal Bremsstrahlung

An alternative interpretation of the hard X-rays is the non-thermal bremsstrahlung (NTB) emission from suprathermal electrons (see § 2.3.4). In this case, we do not need to worry about the magnetic field, since such electrons do not produce synchrotron radio emission.

Here again we take a model with \( \alpha = 1 \), which implies the electron number index in momentum of \( \mu = 2 \) (see equation 2.25). From the average hot gas density of \( 3.0 \times 10^{-4} \) cm\(^{-3} \), equation 2.27 gives

\[
\frac{dL_e}{d\epsilon} = 1.13 \times 10^{-26} N_0 \left( \frac{1}{\epsilon} \right) \quad \text{[erg s}^{-1} \text{ cm}^{-2} \text{ erg}^{-1} \] . \quad (6.7)

Then, for the HCG 62 parameters, this gives \( N_0 = 2.31 \times 10^{67} \). As we have mentioned in § 2.3.4, this value is an overestimate by a factor of \( \sim 2 \), due to the trans-relativistic effects (Sarazin and Kempner 2000). Thus, the corrected value becomes \( N_0 = 1.15 \times 10^{67} \).

Following Sarazin and Kempner (2000), we took the lower cut off energy of the suprathermal electron to be \( 3kT = 3 \) keV, which gives \( p = \sqrt{(1 + (3kT)/(m_e c^2))^2 - 1} = 0.11 \). If we integrate the energy of these electrons up to 100 keV (\( p = 0.65 \)), their total energy is derived to be

\[
E_{\text{tot}}^\text{NTB} = \int_{0.11}^{0.65} N_0 m_e c^2 \frac{\sqrt{p^2 + 1} - 1}{p^2} dp = 3.2 \times 10^{60} \quad \text{[erg]} . \quad (6.8)
\]

This value is comparable to that of the thermal component (see equation 6.4). If we substitute \( \mu = 2 \) with \( \mu = 3 \), the total energy becomes \( 2.6 \times 10^{60} \) erg, which is almost unchanged. Thus, the non-thermal bremsstrahlung interpretation leads to a rather high non-thermal energy density. The non-thermal pressure will greatly affect the mass estimate relying only on the IGM profile, and the total gravitating mass \( M_{\text{tot}} \) will increase by a factor of \( \sim 2 \). In this case, the velocity dispersion of the member galaxies (376 km s\(^{-1} \); see § 4.1.1) is \( 1/\sqrt{2} \) times short of the required value, which is still within the scatter of the \( kT - \sigma \) relation (§ 2.2.3).

The biggest difficulty with the NTB scenario is that the suprathermal electrons suffer a great amount of Coulomb loss due to electron-electron encounter in the thermal plasma (§ 2.3.5). For a 100 keV electron, the Coulomb loss rate is \( \sim 10^4 \) times higher than the bremsstrahlung loss rate. Accordingly, the cooling time of such an electron becomes as short as \( \sim 1 \times 10^8 \) yr when we include the Coulomb interactions, while it was \( \sim 1 \times 10^{12} \) yr when considering the NTB only. In other words, most of the energy input will eventually be used to heat up the IGM, rather than in radiating NTB photons (e.g. Petrosian 2000). Because the radiative cooling time of the IGM is generally longer than \( \sim 10^{10} \) yr,
the IGM temperature will increase by 1 keV within $\sim 10^9$ yr. The groups with excess hard emission would then exhibit systematically higher temperature than those without it, leading to a difference in $\beta_{\text{sp.e.}}$ (equation 2.15). However, within the available rather limited information, we find no such a systematic difference between the two types of groups. Even if this theoretical prediction is somehow reconciled with the observation, a still more serious problem is how to supply such a large amount of heating/acceleration energy. Since the NTB loss and the Coulomb loss are both directly proportional to the IGM density, the problem cannot be avoided by changing the IGM density.

In summary, the NTB interpretation requires the total energy of the suprathermal electron to be comparable to the thermal energy, together with relatively short ($\sim 10^8$ yr) cooling time. Because most of the electron energy is dissipated by Coulomb collision rather than the bremsstrahlung emission, the IGM must be significantly heated, which is not observed. Furthermore, the energy source would become a serious problem. Therefore, the NTB interpretation seems to be rather implausible, though not completely impossible.

6.5 Thermal Interpretation

Although we have so far considered non-thermal interpretations of the excess hard X-ray emission, its observed properties also allow an interpretation in terms of a thermal emission with high temperature, $kT = 2 \sim 10$ keV. The normalization of a thermal emission is given in terms of emission integral ($EI$), which is expressed as a volume integration of proton density multiplied with that of electron. When we fit the spectra of HCG 62 with a sum of a $kT \sim 1$ keV vMEKAL component and a $kT = 10$ keV bremsstrahlung component, the relative emission integral of the two components is derived to be $EI_{\text{hard}}/EI_{\text{IGM}} = 0.12$. In an isothermal and uniform hot plasma, the emission integral is given by $EI = (N_{\text{proton}} \times N_e)/V$, where $N_{\text{proton}}$ and $N_e$ is the total proton and electron number in the volume $V$, respectively. Assuming a pure hydrogen plasma, the ratio of the emission integral can be re-written as

$$\kappa \equiv \frac{(N_{\text{hard}}^2/V_{\text{hard}})}{(N_{\text{IGM}}^2/V_{\text{IGM}})} = 0.12.
\quad (6.9)$$

Here, $N_{\text{IGM}}$ and $N_{\text{hard}}$ are the total electron (=proton) number of the soft and hard components, respectively, and $V_{\text{IGM}}$ and $V_{\text{hard}}$ is the volume filled with the corresponding component.

When we assume a pressure balance between the two components, the condition is expressed as $N_{\text{hard}}/T_{\text{hard}} = N_{\text{IGM}}/T_{\text{IGM}}$. Then, the filling factor of the hot (hard)
component, defined as $\eta = V_{\text{hard}}/V_{\text{IGM}}$, can be described as

$$\eta = \kappa \times \left( \frac{T_{\text{hard}}}{T_{\text{IGM}}} \right)^2 \sim 10 .$$

(6.10)

This means that the hard component dominates the whole volume. In other words, the plasma emitting the $kT \sim 1$ keV component is not the “real” IGM, and the $kT \sim 10$ keV component instead traces the gravitational potential. However, this clearly contradicts the optical velocity dispersion measurements, as already mentioned in § 4.3.2. Therefore, in case of HCG 62, the thermal interpretation under the pressure balance assumption is not realistic. When $T_{\text{hard}}$ is as low as $\sim 3$ keV, and $\kappa$ is relatively small, this interpretation may work.

When we alternatively assume that the hard component is confined in some small regions by a magnetic field, what is the required field strength? Here, we take the filling factor $\eta$ to be 0.1, as a tentative value. Because the total number of the IGM particle is derived as $N_{\text{IGM}} = 5.85 \times 10^{68}$ (§ 6.3.3), equation 6.9 gives $N_{\text{hard}} \sim 6.5 \times 10^{67} (\frac{\eta}{0.1})^{-1/2}$. Then the total energy of the hard component becomes $E_{\text{tot}}^{\text{hard}} = 3.1 \times 10^{60} (\frac{\eta}{0.1})^{-1/2}$ erg, which implies the energy density of $U_{\text{hard}} = 1.6 \times 10^{-11} (\frac{\eta}{0.1})^{-1/2}$ erg cm$^{-3}$. Thus, the required magnetic field strength is about $20 (\frac{\eta}{0.1})^{-1/4} \mu$G. This value seems to be rather high, although there are no observational results contradicting it.

In summary, the thermal interpretation does not work under the assumption of pressure balance, at least for the groups of which the hard emission is relatively luminous and requires a high ($\sim 10$ keV) temperature, such as the HCG 62 group. The three clusters are in the same situation. It may work, however, for the groups of which the hard emission is relatively weak and allows a relatively lower ($\sim 3$ keV) temperature, such as the NGC 1399 group. As an alternative to the pressure balance assumption, we may speculate that magnetic fields of $20 \mu$G or higher confine the hard component. This scenario might work, depending on the required filling factor.
6.6 Candidates for Acceleration and Heating Mechanisms

Since every emission mechanism discussed so far requires the presence of either relativistic or semi-relativistic particles, a significant particle acceleration or heating must be in progress in some, if not all, groups of galaxies. Our final task in the present thesis is to discuss possible acceleration/heating mechanisms and the available energy source. For the IC and thermal interpretation, the required energy input rate (luminosity) is comparable to the observed hard X-ray luminosity, although it must actually be $2 \sim 10$ times higher due to the limited energy range (2–10 keV) of our analysis. On the other hand, for the NTB interpretation, the actual energy loss rate must be about four orders of magnitude higher than the observed hard X-ray luminosity, due to the Coulomb loss. Therefore, we need $\sim 10^{42}$ erg s$^{-1}$ as a minimum energy input rate for the IC and thermal interpretations, whereas $\sim 10^{45–46}$ erg s$^{-1}$ for the NTB interpretation. Below we briefly review several candidates for the acceleration or heating source, including: the supernova (SN), the active galactic nucleus (AGN), kinetic energy of the group member galaxies, and group merger events. Here again, we mainly take HCG 62 as a template.

6.6.1 Super novae

A supernova (SN) produces an explosion energy of $\sim 10^{51}$ erg, and can accelerate cosmic rays up to $\sim 100$ TeV, as observed in SN 1006 ($\S$ 2.5.1). Therefore, it may be the origin of the hard component. To account for a luminosity of $\sim 10^{42}$ erg s$^{-1}$, we need a SN rate of $0.3(\frac{f_c}{0.1})^{-1}$ SNe yr$^{-1}$. Here, $f_c$ is the average conversion efficiency of the SN explosion energy to the particle acceleration, which ranges from a few % up to $\sim 50\%$, depending on the models (e.g., Berezinsky et al. 1997, Ellison et al. 2000). From the optical luminosity of the member galaxies in HCG 62 ($L_B = 6.0 \times 10^{10}L_\odot$; Carvalho et al. 1997), the SN rate is estimated to be relatively low, 0.06 SNe yr$^{-1}$ (e.g., van-den-Berg and Tanman 1991), since there is no evidence for ongoing rapid star formation activity in HCG 62 (e.g. Verdes-Montenegro et al. 1998). Therefore, the SN scenario can marginally explain the energy input required by HCG 62, on condition that $f_c$ is relatively high.

The hard component luminosity ($L_{\text{hard}}$) in fact varies among the groups by an order of magnitude, with no correlation to the their optical luminosities (see Fig.5.8b). This leaves a room for the possibility that the phenomenon is transient rather than steady, and we are observing an after effect of a strong star forming activity in the past. In order
for this scenario to be valid, the putative star forming activity should have taken place within $\sim 10^9$ yr, considering the cooling time of $\tau_{\text{cool}} = 7 \times 10^8$ yr estimated for electrons with $\gamma = 3.4 \times 10^3$ (§ 6.3.1). There is yet another possibility that the SN rate significantly differs among the groups.

In short, the SN origin may work for the IC and thermal scenarios. However, for the NTB interpretation, the required SN rate, $300 \left( \frac{r}{61} \right)^{-1}$ SNe yr$^{-1}$, is too high to be realistic.

### 6.6.2 Active galactic nucleus

Another possibility is the active galactic nucleus (AGNs) hosted in the member galaxies (see § 2.2.4). It can produce a radio lobe filled with $\sim 10$ GeV electrons, as observed in Fornax-A (§2.5.3). When matter accretes onto a massive black hole that is thought to be the nature of the AGN, $\sim 10\%$ of the rest mass energy of the accreting matter will be converted into heating or acceleration of particles (Ensslin et al. 1998). This is sometimes observed as jets and halos of the AGNs. The scenario works even though we do not see obvious AGNs at present in these groups, on condition that the past AGN activity was sufficiently high. Specifically, a black hole with a typical mass of $10^7 M_\odot$ can generate a high energy particles with a total energy of $\sim 2 \times 10^{61}$ erg, over its typical formation epoch of $\sim 10^8$ yr (e.g. Valagas and Silk 1999). This value is sufficient for all three emission models discussed in § 6.3~6.5.

While the AGN scenario is thus promising from the energetics viewpoint, problems remain as to the actual energy transfer from the AGNs to the intra-group space. In the case of the Fornax-A radio lobes, the emission mechanism of the hard X-rays is the IC process. From its radio and X-ray luminosity, Kaneda et al. (1995) found that the magnetic filed is as strong as $\sim 3 \mu$G, which is an order of magnitude higher than those estimated from HCG 62 and the three clusters (see Table 6.3). This cannot be explained by the decay of the magnetic field, because its life time is sufficiently long (e.g. Tribble 1993). Moreover, the size of a radio lobe is $\sim 100$ kpc, which is an order of magnitude smaller than the radio halo, such as Coma-C. As the electron dissipation within the ICM is quite limited (e.g. Sarazin 1988), the lobe remnant cannot by itself form a cluster-wide halo. From these reasons, for the AGN to be the origin of the hard component, we need some mechanisms other than those working in the radio lobes.
6.6.3 Galaxy motion

Yet another candidate for the origin of the hard component is the huge kinetic energy contained in the groups and clusters, in the form of random motion of galaxies.

Galaxies with a total luminosity of $L_B = 6 \times 10^{10} L_\odot$ have a total stellar component mass of $M_{\text{star}}^{\text{gal}} = 5 \times 10^{11} M_\odot$, assuming $M_{\text{star}}/L_\odot = 8$ in solar units. When these galaxies are moving in the intra-group space with a line-of sight velocity dispersion of 400 km s$^{-1}$, they have three dimensional velocity of $v \sim 700$ km s$^{-1}$. Thus, their kinetic energy becomes as much as $\frac{1}{2} M_{\text{star}}^{\text{gal}} \times (700 \text{ km s}^{-1})^2 = 2.5 \times 10^{60}$ erg. This is taken as a typical value for the member galaxies in HCG 62. If $\sim 10\%$ of this energy is converted into particle acceleration, it is sufficient to supply $1 \times 10^{42}$ erg s$^{-1}$ for as long as the Hubble time. Therefore, this picture may potentially be successful for the IC and thermal scenarios.

If we include the possible dark-halo component associated with each galaxy, the estimated heating luminosity further increases. However, even this increased kinetic energy must be dissipated within $\sim 10^{7-8}$ yr, in order to sustain the NTB mechanism. This seems to be too short, compared with the crossing time of these galaxies of $\sim 10^9$ yr. Therefore, the NTB scenario is again unlikely.

A practical problem associated with this galaxy-motion picture is how the kinetic energy is efficiently dissipated. A drag force exerted onto a galaxy moving through the ICM can be written as $\frac{dE}{dt} \sim -\pi \rho_{\text{ICM}} \times v^3 \times R_D^2$. Here $\rho_{\text{ICM}}$ is the ICM density, $v$ is the galaxy velocity, and $R_D$ is the effective radius of the galaxy (e.g. Sarazin 1988). The force will lead to an acceleration or heating of the hot plasma, while a deceleration of the galaxy motion. For the galaxies shown above, the total drag force is given as $1.7 \times 10^{41} N_{\text{gal}} \left( \frac{R_D}{10 \text{ kpc}} \right)^2 \text{ erg s}^{-1}$, where $N_{\text{gal}}$ is the number of the galaxies and $R_D$ is the average effective radius. Therefore, the energy dissipation rate may be sufficient depending on $R_D$. Unfortunately, the actual value of $R_D$ is not well understood. It strongly depends on the model of the galaxy: a galaxy with neither the inter-stellar gas nor the magnetic field will be virtually transparent against the ICM. If, on the other hand, the inter-stellar plasma and the inter-stellar magnetic field of each galaxy is fully taken into account, $R_D$ may be as large as 10 kpc as employed in the above estimate (e.g. Makishima 1999). In any way, the conversion mechanism and efficiency of the kinetic energy of a galaxy, through its interaction with the plasma, is an important subject of future study, particularly from the viewpoint of plasma astrophysics.

Then, are there any observational results which favor this model? In view of our group sample, the HCG 62 and RGH 80 groups, which show strong excess hard X-rays,
Table 6.4: Criteria for dividing the group sample into three sub-categories.

<table>
<thead>
<tr>
<th></th>
<th>$L_{\text{hard}}$ is consistent with being larger than 10% of $L_{\text{IGM}}$, while its 3.3$\sigma$ error (two times that of the 90% error) does not cross with zero.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible hard</td>
<td>similar to the above groups, while its 3.3$\sigma$ error do cross with zero.</td>
</tr>
<tr>
<td>No hard</td>
<td>$L_{\text{hard}}$ is well below 10% of that of $L_{\text{IGM}}$.</td>
</tr>
</tbody>
</table>

Table 6.5: Galaxy number counts within $50h_{75}^{-1}$ kpc of the group center.

<table>
<thead>
<tr>
<th>hard</th>
<th>$N_{50 \text{ kpc}}^{\text{gal}}$</th>
<th>possible hard</th>
<th>$N_{50 \text{ kpc}}^{\text{gal}}$</th>
<th>no hard</th>
<th>$N_{50 \text{ kpc}}^{\text{gal}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCG 62</td>
<td>4</td>
<td>NGC 2563</td>
<td>1</td>
<td>HCG 51</td>
<td>4</td>
</tr>
<tr>
<td>HCG 97</td>
<td>2</td>
<td>NGC 6329</td>
<td>1</td>
<td>NGC 1132</td>
<td>1</td>
</tr>
<tr>
<td>NGC 1399</td>
<td>2</td>
<td>NGC 6521</td>
<td>1</td>
<td>NGC 1550</td>
<td>1</td>
</tr>
<tr>
<td>NGC 507</td>
<td>2</td>
<td>Pavo$^{(1)}$</td>
<td>2</td>
<td>NGC 4325</td>
<td>1</td>
</tr>
<tr>
<td>RGH 80</td>
<td>2</td>
<td></td>
<td></td>
<td>NGC 5044</td>
<td>1</td>
</tr>
<tr>
<td>S49-147</td>
<td>1</td>
<td></td>
<td></td>
<td>NGC 533</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>See § 5.2.3.</td>
<td>NGC 5846</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NGC 7619</td>
<td>1</td>
</tr>
</tbody>
</table>

---

Page 139
host several galaxies in their central regions. In contrast, the NGC 5044 and NGC 4325 groups, which show little evidence for excess hard X-rays, have a single, relatively isolated central galaxy in the center (see Appendix D.3). To quantify this possible difference, we accordingly divide our group sample into 3 sub-categories using the results of spectral analysis listed in Table 5.4: groups with strong hard excess (“hard groups”), those with possible hard excess (“possible hard groups”), and those with little (limited) hard excess (“no hard groups”). The classification criteria are summarized in Table 6.4. We then count the number of bright galaxies within 50h75 kpc (N^gal_{50 kpc}) of the X-ray centroid by eye. Here, 50 kpc is taken to be two times the typical galaxy diameter. The results are summarized in Table 6.5 and Fig.6.5. A clear tendency is visible: most of the groups with little signature of hard X-rays have a single isolated galaxy in its center, while those with significant hard X-rays seems to have more than two galaxies. The average galaxy count is 2.2 ± 0.6, 1.3 ± 0.6 and 1.4 ± 0.4 for the “hard groups”, the “possible hard groups”, and the “no hard groups”, respectively. The errors are poisson error of the total galaxy counts in the sub-categories. Although this result is not statistically significant, and our sample is far from being complete, it fits in the current model: a dominant galaxy sitting at the center of the group potential does not move, hence do not dissipate any kinetic energy into the intra-group space. If, in contrast, multiple galaxies reside in the central group region, they must be continuously moving around one another, possibly leading to an efficient IGM heating.

In summary, the galaxy motion will be a reasonable candidate as an origin for the hard component, though its acceleration (or heating) mechanisms is poorly understood.

![Figure 6.5: Histogram of the groups sorted with the galaxy count within 50h75 kpc of the group center. Open squares represent the “hard groups”, open triangle the “possible hard group”, and filled circles the “no hard groups”.

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6.6.4 Group merger

A galaxy group with a bulk velocity of 1000 km s$^{-1}$ has a kinetic energy of $10^{62}$ erg, assuming a group mass of $10^{13}M_\odot$. Thus, a group merger event can generate sufficient energy for all the three emission models discussed above. Because it is intrinsically a temporal phenomenon, the group merger can explain the variation in the hard component luminosities among the groups, and it is also in principle consistent with the correlation between the central galaxy number and the hard component. However, the merging events are not observationally confirmed to be a common feature among the groups, in contrast to the case of clusters (e.g. Sarazin et al. 1999, Honda et al. 1996, Markevitch et al 1998). Thus we will just refer to it as a candidate of the acceleration source.
Chapter 7

Conclusion

From our study of excess hard X-ray emission from groups of galaxies with ASCA, we have arrived at following conclusions.

- The existence of an excess hard X-ray emission is confirmed in about half of the 18 galaxy groups selected from the ASCA data. The emission cannot be explained by either the point sources (LMXBs or AGNs) in the member galaxies, or the fluctuation in the CXB brightness. In several groups, in particular HCG 62, the hard X-rays are confirmed to be extended, with its radial profile similar to or rather wider than that of the IGM brightness. Therefore the hard component is suggested to be truly of diffuse nature.

- The spectra of the hard component is described by a power law with $\Gamma \sim 2$. It is also consistent with a thermal origin. In the groups with strong hard excess, the inferred temperature becomes as high as $\sim 10$ keV. When the hard component is weak, rather lower temperature ($2 \sim 3$ keV) is obtained.

- The observed hard component luminosity varies considerably among the group sample. In the most convincing cases, it amounts to $1 \sim 18 \times 10^{41} h_{75}^{-2}$ erg s$^{-1}$, or $10 \sim 40\%$ of that of the IGM luminosity. In the least significant cases, the upper-limit becomes $\sim 5\%$ of that of the IGM component.

- The luminosity ratio between the hard component and the IGM, obtained from the groups with significant hard excess, is similar to those obtained from the three clusters from which the hard excess emission are reported.

- As the emission mechanisms of the hard X-rays, the non-thermal bremsstrahlung (NTB) interpretation is unrealistic, due to the huge Coulomb loss. The inverse
Compton (IC) interpretation predicts very low magnetic field strength, of $\sim 0.1\mu G$, requiring an inhomogeneity of the magnetic field. The thermal interpretation under pressure equilibrium assumption is not applicable to at least several groups and all the clusters, while magnetic confinement picture requires a large field strength of $\sim 20\mu G$. The non-thermal pressure associated with the hard component remains a few percent of that of the hot gas component for the IC interpretation.

- The acceleration or heating mechanism for the hard component is not well constrained from current data. However, we found that most of the groups with significant hard excess emission host a few bright galaxies in their central regions, while those without predominantly host a single dominant galaxy. We propose that the member galaxies moving in a plasma may be supplying their kinetic energy to the hard component.
Appendix A

Individual Properties of the Five Observations of HCG 62

A.1 Ratio of the spectra

Figure A.1: The raw GIS spectra from the five pointings obtained within 15' from the group center (Fig.4.8), divided by the averaged spectra (Fig.4.9) after the correction for the difference in the detector effective area.
Figure A.2: The same as Fig.4.15a, but for each observation.
Appendix B

Detailed Analysis of the 4.0–8.0 keV Band Image of HCG 62

B.1 Image clumpiness

In §4.4.2, we analytically estimated the CXB fluctuation to be $\sim 0.5 \times 10^{-5} \text{ cts s}^{-1} \text{ arcmin}^{-2}$ at 1σ level in the 4.0–8.0 keV band. To verify this estimation by the actual data, we also analyzed blank sky data in the same manner as for HCG 62. In Fig.B.1, we show the resulting 4–8 keV image obtained from the sky region SA-57 (observation ID = 91001040), which is one of the blank sky data sets used in the CXB template (§3.3.5). It has an exposure of 105 ksec, which is comparable to the sum of the five observations of the HCG 62 group. By comparing this image with Fig.4.14a, we can see that the fluctuation level is very similar between the two images.

We also quantified the clumpiness of the 4.0–8.0 keV band image of HCG 62 (Fig.4.14a) and SA-57 (Fig.B.1). The average signal brightness and the 1σ fluctuation in the $4.5 < r < 15\arcmin$ region of HCG 62 are both derived to be $0.44 \times 10^{-5} \text{ cts s}^{-1} \text{ arcmin}^{-2}$. On the other hand, those of SA-57 are 0.0 and $0.42 \times 10^{-5} \text{ cts s}^{-1} \text{ arcmin}^{-2}$. Thus, the fluctuation level is in good agreement with the analytically estimated value for both cases, while HCG 62 shows a systematic excess in this energy band.

B.2 Correlation with the galaxies

If the hard X-rays are emitted from galaxies located within the integration regions, the distribution of the hard X-rays and those of the galaxies will show a correlation. To examine this effect, we made a radial profile in the 4.0–8.0 keV band centered on each
Figure B.1: The 4.0–8.0 keV GIS gray scale image of the SA-57 region, which is similar to Fig.4.14a for the HCG 62 group. The contour is linearly spaced with distances of $0.5 \times 10^{-5}$ cts s$^{-1}$ arcmin$^{-2}$. A supplemental contour of $-0.5 \times 10^{-4}$ cts s$^{-1}$ arcmin$^{-2}$ is also plotted (dotted lines).

galaxy, and averaged the obtained profiles. For simplicity, we excluded the central $4'.5$ of the group, because the region is very crowded, and used the 9 galaxies within $4'.5 < r < 15'$ of the integration region. The background profiles were made by the same manner using the template CXB and NXB, in which the CXB fluctuation calculated from equation 4.2 was included as a systematic error. The results are plotted in Fig.B.2. We also show the radial profile expected when all the hard X-rays ($\sim 500$ photons) are emitted from these 9 galaxies. The profile shows no enhancement around the galaxies, and clearly differs from the expected profile. Thus, the galaxy contribution to the hard X-rays is concluded to be insignificant.

B.3 Azimuthal dependence

In Fig.4.14a, there is a tendency that the hard emission is brighter in the northern half of HCG 62 than in the southern half. If this tendency is significant, it may contain some information about the origin of the hard X-rays. To examine this possibility, we divided the spectrum integration region into 8 sectors, each having $45^\circ$ angular scale, where the central $r < 3'$ is excluded. The count rate of these 8 sectors obtained after subtracting the background are plotted in Fig.B.3. Thus, the surface brightness of the southern regions is about half that of the northern regions. However, the CXB fluctuation expected in
Figure B.2: Averaged 4–8 keV radial profile centered on 9 galaxies in the HCG 62 field (black crosses), and that of the background (gray crosses), in cts s\(^{-1}\) arcmin\(^{-2}\). Error bars are in 1\(\sigma\), which are averaged over the 9 galaxies. The background error includes the CXB fluctuation. Thin histograms show what is expected if the hard component is entirely emitted from these 9 galaxies.

these integration regions is \(\sim 4 \times 10^{-6}\) cts s\(^{-1}\) arcmin\(^{-2}\), and the profile is statistically consistent with being flat when we consider this effect. Thus, we found no evidence for azimuthal variation in the hard component distribution.

Figure B.3: Azimuthal profile of the 4–8 keV image of HCG 62, in cts s\(^{-1}\) arcmin\(^{-2}\). The angle is defined clockwisely, the north being the origin. Thin line represents the 1\(\sigma\) level of the estimated CXB fluctuation. Errors are 1\(\sigma\) statistical.
Appendix C

Calculation of the CXB Fluctuation

We present here a brief summary of the calculation we used in estimating the CXB fluctuation. See Ishisaki (1996) for detail.

C.1 Formulation of the CXB fluctuation

Condon (1974) estimated the CXB fluctuation level, and we below introduce her results briefly.

Let \( n(S) \) denote the differential source number density with the flux \( S \) (erg cm\(^{-2}\) s\(^{-1}\)). This \( n(S) \) represents the log \( N \)-log \( S \) relation, usually expressed by

\[
n(S) = k S^{-\gamma} \quad (\gamma = 2.5 \text{ for the Euclidian universe}).
\] (C.1)

We next define the transmission function \( f(\theta, \phi) \) for the detector, which relates the observed counting rate \( x \) (c s\(^{-1}\) cm\(^{-2}\)) for the detector to the flux \( S \) from the source locating at \( \Omega = (\theta, \phi) \) on the sky as:

\[
x = A f(\Omega) S,
\] (C.2)

where \( A \) is a constant which normalizes \( f(\theta, \phi) \) to be 1.0 at the peak, i.e., \( f(0, 0) = 1 \). Then, the expectation \( d\overline{m}(x) \) of the source number with the counting rate in the range \( x \sim x + dx \) can be estimated as

\[
d\overline{m}(x) d\Omega = n(S) dS d\Omega = n \left( \frac{x}{A f(\Omega)} \right) \frac{dx}{A f(\Omega)} d\Omega,
\] (C.3)

since \( dx = A f(\Omega) d\Omega \). Assuming equation (C.1), we derive

\[
d\overline{m}(x) = k A^{\gamma-1} x^{-\gamma} \Omega_e \, dx,
\] (C.4)
where
\[
\Omega_e \equiv \int [f(\Omega)]^{\gamma-1} d\Omega.
\]  \hspace{1cm} (C.5)

This \( \Omega_e \) is called “effective beam size” and represents the response of the detector to the source confusion.

Utilizing equation (C.4), we can calculate the expectation \( \bar{D} \) of the observed counting rate \( D \) (c s\(^{-1}\) cm\(^{-2}\)) as:
\[
\bar{D} = \int_{D_0}^{\infty} x \, d\bar{n} = k A^{\gamma-1} \Omega_e \int_{D_0}^{\infty} x^{-\gamma+1} dx = \frac{k A^{\gamma-1} \Omega_e}{2 - \gamma} \; D_0^{2-\gamma}, \hspace{1cm} (C.6)
\]

where \( D_0 \) is a lower cut-off of \( x \), which is introduced to avoid the divergence of the integral. Physically, this means that the log \( N \)-log \( S \) relation should flatten below some flux. Since \( d\bar{n} \) should be subject to the Poisson distribution, i.e., \( \delta(dn)^2 = d\bar{n} \), we can also calculate the standard deviation \( \sigma_D \) of the observed counting rate \( D \) as:
\[
\sigma_D^2 = \int_0^{D_c} \frac{[x \, \delta(dn)]^2}{dx} dx = \int_0^{D_c} x^2 d\bar{n} = \frac{k A^{\gamma-1} \Omega_e}{3 - \gamma} \; D_c^{3-\gamma}, \hspace{1cm} (C.7)
\]

where \( D_c \) is an upper cut-off of \( x \), i.e. we discard the data brighter than \( D_c \) regarding not a blank sky. Therefore, the fraction of the CXB fluctuation is
\[
\sigma_D/\bar{D} = \frac{(k A^{\gamma-1} \Omega_e \; D_c^{3-\gamma})^{1/2} \; (2 - \gamma)}{(3 - \gamma)^{1/2} k A^{\gamma-1} \Omega_e \; D_0^{2-\gamma}} = \frac{2 - \gamma}{\sqrt{(3 - \gamma) k \Omega_e}} \left( \frac{D_c}{A} \right)^{3-\gamma/2} \left( \frac{D_0}{A} \right)^{\gamma-2} . \hspace{1cm} (C.8)
\]

for the Euclidian universe, i.e., \( \gamma = 2.5 \), this becomes
\[
\sigma_D/\bar{D} \propto \Omega_e^{-0.5} \; S_c^{0.25} \hspace{0.5cm} (S_c \equiv D_c/A). \hspace{1cm} (C.9)
\]

**C.2 Effective beam size for the XRT+GIS**

Taking into account both vignetting and stray-light effects, we calculate \( \Omega_e \) for the XRT+GIS when we use inside 20 mm from the optical axis as the data integration region. Fig.C.1 shows the dependence of the Crab counting rate on the offset angle \( \theta \) from the XRT optical axis. As seen in the figure, we approximate the counting rate as:

\[
f(\theta) = \begin{cases} 
\frac{710}{1 + (x/13)^2} & \cdots (\theta < 18') \\
-51.6 (\theta - 22) + 20 & \cdots (18' \leq \theta < 22') \\
\frac{20}{1 + 0.5 \exp[(\theta - 60)/9]} & \cdots (22' \leq \theta) 
\end{cases} \hspace{1cm} (C.10)
\]
Figure C.1: (a) The observed Crab counting rate in the 0.7–10 keV energy band plotted against the offset angle from the XRT optical axis. Filled circles represent GIS2 and open circles GIS3. (b) Same as panel (a) but for the larger $\theta$. Solid line represents equation (C.10).

If we ignore the azimuth angle dependence, we can calculate $\Omega_c$ as:

$$\Omega_c = 2\pi \int_0^\infty [f(\theta)/f(0)]^{\gamma-1} \sin \theta \, d\theta.$$  \hspace{1cm} (C.11)

In figure C.2, we show

$$\Omega_c(\theta_c) = 2\pi \int_0^{\theta_c} [f(\theta)/f(0)]^{1.5} \sin \theta \, d\theta.$$  \hspace{1cm} (C.12)

Therefore, $\Omega_c$ for the XRT+GIS is 0.142 deg$^2$. Contribution of the stray light to $\Omega_c$ is $\sim 0.01$ deg$^2$ and almost negligible.
Figure C.2: Calculation of $\Omega_e$ for the XRT+GIS.
Appendix D

Analysis Results of All Groups

D.1 Images and integration regions

Figure D.1: The full band X-ray contour images of the GIS and the SIS, similar to Fig.5.1, but for the other groups. In most of the GIS images and all the SIS images, background is not subtracted. The contours are logarithmically spaced by factors of 1.7, starting from $5 \times 10^{-5}$ cts s$^{-1}$ arcmin$^{-2}$ for the GIS ($2.9 \times 10^{-5}$ cts s$^{-1}$ arcmin$^{-2}$ for NGC 507), and $1 \times 10^{-4}$ cts s$^{-1}$ arcmin$^{-2}$ for the SIS. Spectral integration region and positions of the point sources are shown only in the GIS image.

(a) HCG 51 GIS (bgd inclusive)
(e) NGC 4325 GIS (bgd inclusive)

(f) NGC 5044 GIS (bgd subtracted)

(g) NGC 507 GIS (bgd subtracted)
(h) NGC 533 GIS (bgd inclusive)

(i) NGC 5846 GIS (bgd inclusive)

(j) NGC 6329 GIS (bgd inclusive)
D.2 Spectra

D.2.1 Single component fits

Figure D.2: The same as Fig.5.2, plotted for the remaining targets.
D.2.2 Two component fits

Figure D.3: The same as Fig.5.4, plotted for the remaining targets.
D.3 Optical images of central $300 \, h_{75}^{-1}$ kpc.

Figure D.4: Optical images of the central $300 h_{75}^{-1}$ kpc region of the groups. “H” indicates the “hard groups”, “P” the “possible hard groups”, and “N” the “no hard groups” (see Table 6.5).

HCG 51  (N)

HCG 62  (H)

HCG 97  (H)

NGC 1132 (N)
NGC 533 (N)

NGC 5846 (N)

NGC 6329 (P)

NGC 6521 (P)

NGC 7619 (N)

Pavo (P)
RGH 80  (H)

NGC 4636 (not used in Fig.6.5)

S49-147  (H)

NGC 4472 (not used in Fig.6.5)
Abbreviation

GIS: gas imaging spectrometer (onboard ASCA)
SIS: solid-state imaging spectrometer (onboard ASCA)
XRT: X-ray telescope (onboard ASCA)
PSPC: position sensitive proportional counter (onboard ROSAT)
HPGSPC: high pressure gas scintillator proportional counter (onboard Beppo-SAX)
PDS: phoswitch detector system (onboard Beppo-SAX)
MECS: medium energy counter system (onboard Beppo-SAX)
UV: ultra violet
EUV: extreme ultra violet
AGN: active galactic nuclei
LLAGN: low luminosity AGN
SN: supernova
SNR: supernova remnant
LMXB: low-mass X-ray binary
HCG: Hickson’s compact groups
IC: inverse compton
NTB: non-thermal bremsstrahlung
CMB: cosmic microwave background
CXB: cosmic X-ray background
NXB: non X-ray background
ICM: intra-cluster matter
IGM: intra-group matter
ISM: interstellar matter
CDM: cold dark matter
FWHM: full width half maximum
IPMT: imaging photo-multiplier tube
RT: rise time
RTD: rise time discriminator
PH: pulse height
COR: cut off rigidity
CCD: charge coupled device
PSF: point spread function
FOV: field of view
PI: principal investigator
EI: emission integral
NGC: new galaxy catalog
KSC: Kagoshima Space Center
ISAS: Institute for Space and Astronautical Science
GSFC: Goddard space flight center
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