TEMPERATURE AND HEAVY-ELEMENT ABUNDANCE PROFILES OF COOL CLUSTERS OF GALAXIES FROM ASCA

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ABSTRACT

We perform a spatially resolved X-ray spectroscopic study of a set of 18 relaxed clusters of galaxies with gas temperatures below 4 keV. Spectral analysis was done using ASCA/SIS data coupled with the spatial information contained in ROSAT/PSPC and Einstein/IPC observations. We derive the temperature profiles using single-temperature fits and also correct for the presence of cold gas at the cluster centers. For all of the clusters in the sample, we derive Si and Fe abundance profiles. For a few of the clusters, we also derive Ne and S abundance profiles. We present a comparison of the elemental abundances derived at similar overdensities as well as element mass-to-light ratios. We conclude that the preferential accretion of low-entropy, low-abundance gas into the potentials of groups and cold clusters can explain most of the observed trends in metallicity. In addition, we discuss the importance of energy input from Type II supernovae on cluster scaling relations and on the relation between the observed scatter in the retention of Type Ia supernova products with differences between the epoch of cluster formation.

Subject headings: galaxies: abundances — galaxies: clusters: general — galaxies: evolution — intergalactic medium — supernovae: general — X-rays: galaxies

1. INTRODUCTION

The intracluster medium (ICM) has long been a subject of research for analyzing elements produced and lost by galaxies. By determining the total mass in metals produced by the stellar population of a cluster, one can place constraints on the population of massive stars, or equivalently, the initial mass function (IMF) and the integrated Type Ia supernova (SNe Ia) rate. In addition, the abundance and distribution of heavy elements in the ICM are sensitive to the processes of hierarchical clustering and therefore provide a unique tool for accessing the details of how present-day clusters evolve.

In Finoguenov, David, & Ponman (2000, hereafter FDP), we presented an extensive study of the distribution of heavy elements in groups and clusters and discussed the implications regarding the chemical enrichment of the ICM. For clusters with the best photon statistics, we found that the Fe abundance decreases significantly with radius, while the Si abundance is either flat or decreases slightly. This results in an increasing Si/Fe ratio with radius and implies a radially increasing abundance distribution of Fe and Si. For clusters with good photon statistics we can also constrain the distribution of Ne and S. We present new spectroscopic results for A262, A2197 (subclusters E and W), A539, MKW 3S, MKW 4S, MKW 9, AWM 4, HCG 94, A779, A400, A2052, A2634, A4038 (Klemola 44), 2A 0335+096, A2063, and A194. We also include an analysis of the Centaurus Cluster to compare with the method of Ikebe et al. (1999). This paper is organized as follows: in §2 we describe our analysis technique; temperature profiles are discussed in §3; in §4 we present the radial abundance profiles of Fe, Si, Ne and S; in §5 we analyze the elemental abundances derived at similar overdensities and their corresponding mass-to-light ratios with a further discussion of the roles of SNe II in §5.1 and 5.2 and SNe Ia in §5.3. Our main results are summarized in §6. We assume $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, $q = 0.5$ throughout the paper.

2. DATA REDUCTION

A detailed description of the ASCA observatory as well as the SIS detectors can be found in Tanaka, Inoue, & Holt (1994) and Burke et al. (1991). All observations are screened using FTOOLS version 4.2 with standard screening criteria. The effect of the broad ASCA point-spread function (PSF) is treated as described in Finoguenov et al. (1999) including the geometrical projection of the three-dimensional distribution of X-ray-emitting gas. Our minimization routines are based on the $\chi^2$ criterion. No energy binning is done, but a special error calculation is introduced, as in Churazov et al. (1996), to properly account for small number statistics. Model fits to ROSAT (Trümper 1982) surface brightness...
profiles are used as input to the ASCA data modeling. The details of our minimization procedure for ASCA spectral analysis are described in Finoguenov & Ponman (1999). We adapted the XSPEC analysis package to perform the actual fitting and error estimation. The spatially resolved spectral characteristics are quoted as the best-fit solution plus an estimate of the 90% confidence area of possible parameter variation based on the regularization technique (Press et al. 1992; Finoguenov & Ponman 1999). To study the systematic errors related to the spatially resolved spectroscopic analysis of the ASCA data, we follow the approach described in FDP. For all ROSAT imaging analysis we use the software described in Snowden et al. (1994) and references therein.

We use the MEKAL plasma code (Mewe, Gronenschild, & Oort 1985; Mewe & Kaasstra 1995; Liedahl, Osterheld, & Goldstein 1995) in all of our spectral analysis. All abundances are given relative to the photospheric solar values in Anders & Grevesse (1989). The abundances of He and C are fixed to their solar value. The remaining elements are combined into five groups for fitting: Ne; Mg; Si; and Ar; and Ca, Fe, and Ni. We restrict our analysis to the energy range 0.8–7.0 keV to avoid the large systematic uncertainties at low energies, which prevent us from determining the O abundance. We do not report the Mg abundance because of the proximity of the Mg K lines with the poorly understood transition lines of iron, which are strongest at temperatures of 2–4 keV (see Fabian et al. 1994 and Mushotzky et al. 1996).

Table 1 contains the optical and X-ray properties of our sample. Column (1) identifies the system, column (2) the adopted luminosity distance, column (3) the corresponding scale length, column (4) the total blue light along with a reference, column (5) the corresponding radius of the optical measurement, column (6) the B luminosity of the dE galaxy from NASA Extragalactic Database, column (7) the core radius of the galaxy distribution, and column (8) the slope $\alpha$ of the modified King profile $[1 + (r/R_c)^2]^{-\frac{1}{2}}$. Columns (9) and (10) give the results of the cluster surface brightness fitting outside the central region using a $\beta$ model. Since the outer region chosen for the spatial analysis corresponds only to a part of the cluster owing to, e.g., the number of CCDs read-out, in column (11) we denote the position of the observed region relative to the cluster center with NW $\Rightarrow$ E denoting an area extending from the northwest to the east in a counterclockwise direction. Column (12) gives the best-fit cluster emission-weighted temperature, (13) the corresponding 90% error, (14) the best-fit cluster emission-weighted hotter temperature in a two-temperature fit (data for the colder component are listed in Table 2), (15) the corresponding 90% error, and (16) an estimate of the virial radius of the system $(r_{180} = 1.23T^{0.5} h_{50}^{-2} Mpc)$; Evrard, Metzler, & Navarro (1996) using $kT_e$. Estimates of the virial radii using X-ray observations carried out in Finoguenov, Reiprich, & Boehringer (2001) show that the actual virial radii are 20% lower than Evrard’s value.

### 2.1. Optical Data Reduction

A modified King profile was assumed for the galaxy distribution. The core radius and slope were taken from the literature when available (the references are given in Table 1), otherwise we assumed average values of $R_c = 0.25$ Mpc and $\alpha = 1$. For A779, A2197 (E, W), and Centaurus, we fitted the cumulative galaxy distribution derived from the galaxy catalog of Trèvese et al. (1997), Dixon, Godwin, & Peach (1989), and Jerjen & Dressler (1997), respectively. Only galaxies brighter than the catalog completeness limit were considered. The corresponding background counts were estimated as described in Trèvese, Cirimele, & App noticing (1996) for A779 and from the deep counts of the ESO–Sculptor Redshift Survey (Arnouts et al. 1997) for A2197. They are negligible in the latter case. No background correction was applied for Centaurus; cluster members and background objects are distinguished in the catalog on the basis of morphological criteria, and we considered only definite cluster members. A2197 is a double cluster, as revealed by the X-ray morphology; one subcluster is centered on NGC 6160 (A2197W) and the other on NGC 6173 (A2197E). To limit confusion between the two components, we considered only the central region of each subcluster within 6′ (~300 kpc) from its central galaxy. The galaxy distribution parameters of A4038 were derived from a fit to the surface density of galaxies published in Green, Godwin, & Peach (1990, Table 4).

The total blue light of each cluster within a given projected radius is listed in Table 1. Some processing was required to obtain a set of homogeneous values from the published data (see the references in Table 1). The published luminosities of A194 and A262 were corrected for the faint end of the luminosity function (LF). We used a Schechter LF with $M^* = -20.6$ and $\alpha = -1.25$ and converted the published limiting magnitudes to limiting luminosities, taking into account interstellar absorption. The correction is negligible in our redshift range. The luminosities of A2052, A2063, and A2634 within 1.5 Mpc were computed using a Schechter LF and a modified King galaxy distribution with the parameters published in Cirimele, Nesci, & Trèvese (1997, 1998). The luminosity of A779 within 2.85 Mpc was computed from the LF determined by Trèvese, Cirimele, & App noticing (1996) in that region. The normalization of the LF was deduced from the published galaxy counts within the completeness limit. For these four clusters and A400, the luminosity in the $V$ band was converted into a $B$-band luminosity assuming $L_V = 1.3L_B$. The luminosity of the Centaurus Cluster was estimated using the catalog of Jerjen & Dressler (1997). We summed the luminosities of all possible cluster members within 1.5 Mpc from the cluster center and down to the catalog completeness limit ($M_b = -15.3$). The error induced by the uncertainty on cluster membership is small. The luminosity is only 20% less if only definitive cluster members are considered. The correction for the faint end of the LF, estimated from the Schechter LF given in Jerjen & Tammann (1997), was found negligible. A similar procedure was performed for A2197W and A2197E using the galaxy catalog of Dixon et al. (1989), down to its completeness limit. The background correction, estimated statistically from the deep counts in each magnitude bin (Arnouts et al. 1997), is negligible (at the few percent level), as well as the correction for incompleteness.

### 2.2. Details of X-Ray Data Reduction

Although the analysis technique was intended to be similar for all of the clusters, some corrections were individually made, which we describe in this section.

A194, A2063, AWM 4, and A539 have bright pointlike sources in the field of view. In these cases we extract the spectra of point sources with both ROSAT/Position Sensitive Proportional Counter and ASCA/SIS, subtract the
| Name     | $D$ (Mpc) | arcmin | $L_B \times 10^{13}$ $L_\odot$ | $R_{\text{arcmin}}$ (Mpc) | $L_{\text{B,50}} \times 10^{13}$ $L_\odot$ | $R_{\text{50}}$ (Mpc) | $a$ | $b$ | $r_e$ (kpc) | Position | $kT_{\text{arcmin}}$ (keV) | $\delta kT_{\text{arcmin}}$ (keV) | $kT_e$ (keV) | $\delta kT_e$ (keV) | $R_e$ (Mpc) |
|----------|-----------|--------|---------------------------------|---------------------------|---------------------------------|----------------|-----|-----|----------|-----------|----------------------|----------------|-------------|----------------|---------------|
| A2197E   | 177       | 49     | 4.25$^a$                        | 0.29                      | 2.7                             | 0.38           | 0.89| 0.35| 17      |           | 1.10                 | 0.07            | 1.10        | 0.07            | 1.29          |
| A400     | 145       | 40     | 21.$^b$                         | 3.0                       | 0.8                             | 0.08           | 0.83| 0.56| 180     | SE W      | 1.83                 | 0.16            | 1.83        | 0.16            | 1.67          |
| A194     | 107       | 30     | 5.1$^c$                         | 0.8                       | 0.00                            | 0.267          | 0.925| 0.60| 26      | NE SW     | 2.12                 | 0.43            | 2.12        | 0.43            | 1.79          |
| A262     | 97        | 27     | 10.$^d$                         | 0.82                      | 0.55                            | 0.02           | 0.59| 0.46| 58      | SE $\Rightarrow$ W | 2.18                 | 0.21        | 2.26            | 0.23          | 1.85          |
| MKW 4S   | 171       | 47     | 6.3$^e$                         | 0.5                       | 2.62                            | 0.25           | 1.0 | 0.51| 124     | SE        | 2.13                 | 0.64            | 2.29        | 0.26            | 1.87          |
| A539     | 174       | 48     | 38.$^f$                         | 2.0                       | 0.79                            | 0.04           | 0.78| 0.69| 250     | E         | 2.81                 | 0.34            | 2.81        | 0.34            | 2.07          |
| AWM 4    | 195       | 57     | 6.4$^g$                         | 0.5                       | 1.09                            | 0.25           | 1.0 | 0.62| 110     |           | 2.92                 | 0.39            | 2.92        | 0.39            | 2.11          |
| MKW 9    | 240       | 65     | 6.7$^h$                         | 0.5                       | 1.46                            | 0.25           | 1.0 | 0.52| 54      | E W       | 2.66                 | 0.57            | 2.92        | 0.43            | 2.11          |
| A2197    | 183       | 50     | 3.0$^i$                         | 0.31                      | 1.90                            | 0.185          | 0.94| 0.43| 53      |           | 2.21                 | 0.49            | 3.05        | 0.82            | 2.15          |
| A2634    | 189       | 52     | 70.$^j$                         | 1.5                       | 1.57                            | 0.324          | 0.47| 0.69| 448     | SW        | 3.06                 | 0.35            | 3.06        | 0.35            | 2.16          |
| A4038    | 171       | 47     | 15.$^k$                         | 1.2                       | 1.04                            | 0.043          | 0.86| 0.61| 160     | NW $\Rightarrow$ E | 3.31                 | 0.25        | 3.31            | 0.25          | 2.24          |
| 2A 0335  | 211       | 57     | 7.3$^l$                         | 0.5                       | 0.71                            | 0.25           | 1.0 | 0.65| 80      |           | 3.07                 | 0.27            | 3.40        | 0.39            | 2.27          |
| HCG 94   | 253       | 68     | 7.0$^m$                         | 0.5                       | 0.29                            | 0.25           | 1.0 | 0.48| 75      | NE SE     | 2.94                 | 0.45            | 3.45        | 0.50            | 2.29          |
| A2052    | 210       | 57     | 26.$^n$                         | 1.5                       | 1.10                            | 0.139          | 0.7  | 0.64| 100     |           | 3.24                 | 0.32            | 3.46        | 0.39            | 2.29          |
| A779     | 136       | 38     | 13.1$^o$                        | 2.9                       | 2.11                            | 0.525          | 0.95| 0.34| 54      | N S       | 2.97                 | 0.39            | 3.56        | 0.53            | 2.33          |
| MKW 3S   | 273       | 73     | 9.4$^p$                         | 0.5                       | 1.67                            | 0.25           | 1.0 | 0.71| 300     | SE $\Rightarrow$ NW | 3.45                 | 0.47        | 3.79            | 0.53            | 2.40          |
| Cen      | 63        | 18     | 48.$^q$                         | 1.0                       | 1.40                            | 0.230          | 0.88| 0.44| 28      | N         | 3.56                 | 0.28            | 3.82        | 0.29            | 2.41          |
| A2063    | 214       | 58     | 12.$^r$                         | 0.5                       | 1.91                            | 0.253          | 0.94| 0.69| 220     | N $\Rightarrow$ E | 3.83                 | 0.39        | 3.86            | 0.24          | 2.42          |

$^a$ Present work.
$^b$ Arnaud et al. 1992.
$^c$ Nikogossyan et al. 1999.
$^d$ Sakai, Giovanelli, & Wagner 1994.
$^e$ Interpolated value using eq. (1) from FDP.
$^f$ Ostriker et al. 1988.
$^g$ Cirimele et al. 1998.
$^h$ Green et al. 1990.
$^i$ Trevese et al. 1996.
$^j$ Jerjen & Tammann 1997.
cluster background, analyze the spectra, and then, based on the ASCA response matrix, estimate the contribution from these point sources to the regions selected for analysis of the diffuse cluster emission. For A194 the contribution of the point sources was severe at the center, and we omit the central region of A194 from further discussion.

The observation of A400 was performed in 4-CCD mode, which, at the time of observation, (1996) had significant SIS calibration problems, so we omit the SIS1 data from further analysis.

The observation of MKW 9 has a high background, which is noticeable at the edges of the detector (owing to warm CCDs as pointed out by Buote 2000). This background dominates the spectrum below 1 keV. We analyze and subtract the excess background and fit only the source spectrum in the 0.9–3.5 keV energy band. Thus, the Fe abundance for this cluster is derived from the L-shell line complex. Buote (2000) claims that the derived Fe abundance in MKW 9 increases from 0.4 to 0.7 solar when adding a second temperature component. We find that this conclusion depends on whether the high-energy part of the spectrum is included in the spectral fitting and does not depend on the inclusion of the second temperature component as advocated by Buote (2000). While we attribute this effect to uncertainties in the subtraction of the background, our error bars allow for both Fe abundance values.

The spatial modeling of MKW 9 was taken from an ground, our error bars allow for both Fe abundance values. We correct for the lower ASCA SIS normalizations relative to ASCA Gas Imaging Spectrometer (GIS) following Iwasawa, Fabian, & Nandra (1999). This increases our gas mass estimates by approximately 10%.

### 3. TEMPERATURE PROFILES

We present the derived temperature distributions using single-temperature fits in Figure 1 and the temperature profiles of the hotter component in the two-temperature fits in Figure 2. In the central spatial bins of the clusters exhibiting a presence of a colder temperature component, we also attempt the two-temperature fits. The single-temperature fits are used to calculate \( kT_{\text{unc}} \) in Table 1, while the temperature of the hot component in the two-temperature fits is used to calculate \( kT_c \). One can see from the table that there is no difference for A400, A194 (however, for this cluster the center is excluded anyway), A539, AWM 4, and A2634, while changes in the weighted temperature for other clusters appear not to be very significant. In the single-temperature fits, the temperature appears to drop significantly with radius in A400, A2634, HCG 94, in the outskirts of MKW 3S, and also marginally in Cen. Adding a second temperature in the fits adds A2063 and, marginally, MKW 4S to the list of clusters with declining temperature profiles. More evident is the removal of rising temperature profiles in A262, 2A 0335 + 096, A2052, A779, Cen and, marginally, in MKW 3S. The hot component is rather faint in the center and, as was shown in the case of M87, may be spatially distinct from a cold component (Finoguenov & Jones 2000). However, the use of a two-temperature model mimics the cooling-flow model of Johnstone et al. (1992; see Buote 2000). To quantify the characteristics of the cold component, we present in Table 2 the temperature, emissivity, and gas mass of this component. The corresponding cooling rates can then be derived from these values. It was pointed out by Fukazawa (1997) that the cold component of a two-temperature fit in the range between 1 and 2 keV may reflect the potential of the central cD rather than being an indication of a cooling flow. While we cannot distinguish between these two possibilities with our present sample, in the FDP sample our fits to A2029, A3112, and the A780 spectra resulted in temperatures for the cold components of ~ 5, 3, and 3 keV, respectively. It is therefore more likely that these clusters have cooling flows.

Most of the clusters in our sample have temperature profiles similar to the universal temperature profile of Markevitch et al. (1998). Only 2A 0335 + 096 can be considered as discrepant, similar to findings of Kikuchi et al. (1999). However, our conclusion regarding MKW 3S favors the results of Markevitch et al. (1998). In MKW 3S we detect a lower temperature in the outer annulus even with the single-temperature models. However, at the radius in question, the SIS data do not cover the northeastern part of the cluster.
The presence of high-temperature gas in this region would account for our discrepancies with Kikuchi et al. (1999). Some of the clusters in this sample (A194, A539, AWM 4, MKW 9, A4038, A2052, and A779) suggest an isothermal temperature distribution. The implications of this result on the $M-T$ relation are further discussed in Finoguenov, Reiprich, & Boehringer (2001). Modeling of ASCA data is especially complicated in the presence of strong cooling flows (M. Markevitch 2000, private communication). Therefore, our observation of the apparent temperature declines in the noncooling flow clusters A400 and A2634 is particularly important for confirmation of temperature gradients.

The steep rise in the central gas temperature we detect in the Centaurus Cluster mimics the presence of the non-thermal component reported in Allen et al. (2001). Owing to the limitations of the SIS data, i.e., the complex PSF and low sensitivity at high energies, a more detailed study must await XMM and Chandra observations.

Temperature and iron-abundance profiles for the clusters reported in this paper were also analyzed by White (2000) using GIS data. A comparison of our temperature profiles with those in White shows remarkable agreement for single-temperature fitting (our Fig. 1), while our results on the iron abundance supersede in quality the White (2000) results because of the greater spectral resolution and sensitivity of the SIS compared to the GIS. For hotter clusters, the GIS iron abundance results have a similar quality with the SIS results of FDP. Given the differences in White's method for
Fig. 2.—Corrected temperature profiles, derived considering a two-phase model for the center to fit the data. The solid lines correspond to the best fit with filled circles indicating the spatial binning used in the analysis. Dark and light shaded zones around the best-fit curves denote the 68% and 90% confidence areas. Contours denote the range of temperatures found in Markevitch et al. (1998), scaled according to the luminosity-weighted temperature of the cluster, $kT_e$ (col. [14] in Table 1) using virial units for radii (col. [16] in Table 1).

4. RADIAL DISTRIBUTION OF HEAVY ELEMENTS

4.1. Iron

With a statistical threshold of 90%, an iron-abundance gradient is observed in A400, A262, MKW 4S, 2A 0335+096, HCG 94, MKW 3S, and Cen (Fig. 3). Among these clusters, an Fe gradient outside the central 100 kpc is seen in A400, 2A 0335+096, and Cen. A comparison with other ASCA measurements produces good agreement, except possibly for AWM 4, where the presence of a strong point source complicates the analysis. The analytical fit of the Fe abundance in Cen from Ikebe et al. (1999) appears to be slightly more centrally concentrated. However, one should take into account the spatial width of our bins. We ascribe the abundance values to the center of the spatial bin, but the abundance values in each bin are dominated by the emission closer to the cluster center, which can explain our broader Fe distribution. Overall, good agreement between
Fig. 3.—Derived Fe abundances (in units of $4.68 \times 10^{-5}$ for iron number abundances relative to H). The solid lines correspond to the best-fit Fe abundances derived from the ASCA data. The filled circles indicate the spatial binning used in the analysis. Dark and light shaded zones around the best-fit curves denote the 68% and 90% confidence areas. Crosses on A400, A194, A262, MKW 4S, A539, AWM 4, MKW 9, A2634, and A2063 panels show the results from Fukazawa et al. (1998) with radii of measurement from Y. Fukazawa (2000, private communication). Crosses on the 2A 0335 and MKW 3S plots denote the results of modeling of GIS data from Kikuchi et al. (1999) and similarly lines on the Cen plot from Ikebe et al. (1999).

our results and Ikebe et al. (1999) serves as an argument against the suggestion of Buote (2000) about the underestimation of elemental abundances in the center of clusters owing to “over-regularization.”

4.2. Silicon, Neon, and Sulfur

With a statistical threshold of 90%, Si abundance gradients are observed in A400, A262, and Cen. Only in A400 is there a significant decrease in the Si abundance beyond the central 100 kpc. A comparison with the results of Fukazawa et al. (1998) shows very good agreement (see Fig. 4), except possibly for AWM 4 (our value is 2 $\sigma$ higher).

No Ne abundance gradients are detected in this sample. Ne abundance are significantly constrained in only A262, MKW 4S, MKW 3S, and Cen (see Fig. 5). A sulfur abundance gradient is detected in Cen excluding the central 100 kpc from consideration. The S/Fe ratio changes by much less than the Si/Fe ratio with radius, which was also noted.
Fig. 4.—Derived Si abundances. The solid lines correspond to the best-fit Si abundances derived from the ASCA data. The filled circles indicate the spatial binning used in the analysis. Dark and light shaded zones around the best-fit curves denote the 68% and 90% confidence areas. Crosses on A400, A194, A262, MKW 4S, A539, AWM 4, MKW 9, A2634, Cen, and A2063 panels show the results from Fukazawa et al. (1998) with radii of measurement from Y. Fukazawa (2000, private communication).

Fig. 5.—Derived Ne abundances. The solid lines correspond to the best-fit Ne abundances derived from the ASCA data. The filled circles indicate the spatial binning used in the analysis. Dark and light shaded zones around the best-fit curves denote the 68% and 90% confidence areas.
by Fukazawa (1997). Central enhancements of sulfur are marginally seen in 2A 0335+096 and MKW 4S, and sulfur abundance is constrained at any radius in A2197E, A400, A262, MKW 9, A4038, and A2052 (see Fig. 6).

5. HEAVY ELEMENTS AT SIMILAR OVERDENSITY
The derived elemental abundances in our sample of groups and clusters of galaxies span the range from 1/10 to a few times solar, even within a single system (e.g., Cen cluster). To compare the results between different systems, we need to choose an appropriate physical scale. The natural physical scale of a cluster is its virial radius, and we thus compare data at given fractions of $r_{180}$. This is equivalent to comparing data at similar overdensity.

It is worth noting that the overdensity does appear to be a fundamental parameter for the metal enrichment, as indicated by the simulations of Cen & Ostriker (1999). Furthermore, the cluster morphological content, another potentially important factor for chemical enrichment, should be the same at the radius of comparison since it depends on the local galaxy density (Dressler 1980).

In Table 1 we show $r_{180}$ for all the systems in our sample. Comparisons between systems are made at $\frac{1}{2}$ and $\frac{2}{3}$ of $r_{180}$ (corresponding to overdensities of 8600 and 1600). We choose an outer radius of $0.4r_{180}$ because of the limited extent of our observations. The inner radius of $\frac{1}{3}r_{180}$ is chosen to avoid the central 200 kpc. Among the elements presented in Figure 7, Ne and S do not reveal any distinct trend because of large measurement errors.

A major difference between our work and some earlier results (e.g., Renzini et al. 1993) is the dependence of the Fe abundance on gas temperature at lower temperatures. We do not find an increase in the Fe abundance near 1 keV as previously reported. Instead, the Fe abundances at $0.2r_{180}$...
are similar among groups and clusters with a tendency for the Fe abundance to decrease at lower overdensities (compare the values at 0.2r_{180} and 0.4r_{180}). The average trends in the Fe abundance at 0.2r_{180} with temperature plotted in Figure 7 are in good agreement with the findings of Fukazawa et al. (1998). There is a peak in the Fe abundance of 0.3 solar for cool clusters, with hotter clusters having average iron abundances of 0.2 solar.

In contrast, the Si abundances increase strongly with gas temperature, starting from 1/3 solar in groups and reaching solar values in hot clusters. This agrees with the previous findings of Fukazawa et al. (1998). This drastic difference between the Si and Fe abundances reflects the equal role of SNe Ia in groups and clusters of galaxies (e.g., FDP). To determine the relative enrichment from different supernovae types, we adopt the yields in FDP, given by $y_{\text{Si}}/M_{\text{SN II}} = 0.133 M_\odot$ and $y_{\text{Fe}}/M_{\text{SN II}} = 0.07$ for SN II yields, and $y_{\text{Si}}/M_{\text{SN Ia}} = 0.158 M_\odot$ and $y_{\text{Fe}}/M_{\text{SN Ia}} = 0.744 M_\odot$ for SN Ia.

In Figure 8 we show the Fe and Si mass accumulated within $r_{0.2}$ expressed in a form useful for the study of element production, i.e., the $M_{\text{ICM}}/L_B$ ratio. The light and gas within the central 200 kpc are not included in this calculation for systems with cD galaxies. In Figure 8 we also show the IMLR for each SN type. As can be seen in Figure 8, both the Si $M_{\text{ICM}}/L_B$ and the SN II Fe $M_{\text{ICM}}/L_B$ increase by a factor of 10 between groups and clusters of galaxies. In contrast, the difference in Fe $M_{\text{ICM}}/L_B$ and SN Ia Fe $M_{\text{ICM}}/L_B$ is less prominent, especially at 0.4r_{180}. For comparison, we also plot in Figure 8 the corresponding gas mass fractions. Between 0.2r_{180} and 0.4r_{180} there is a significant change in $f_{\text{gas}}$, with clusters tending to have similar gaseous fractions at large radii. These results can be compared with the low scatter in gas fractions found at smaller overdensities by Ettori & Fabian (1999) and Vikhlinin, Forman, & Jones (1999).

5.1. SNe II and the Preferential Infall Scenario

The main goal of this section is to explain the different observed Si abundances in these systems. In particular, we are interested in the dependence of the Si abundance on the gas retention (or accretion) in these systems. To illustrate this idea, consider an outflow of material from a group caused by some form of heating. Such a scenario can explain the reduced gas fractions and mass in elements inside groups, but such a scenario cannot change the Si abundance.

In FDP, we proposed that the absence of strong gradients in α-elements implies that SN II enrichment occurred prior to cluster collapse. We also note that the Si abundance does not vary significantly between 0.2r_{180} and 0.4r_{180} (see Figs. 7 and 8) even though there is a significant change in $f_{\text{gas}}$ between these radii. This result also requires that the enrichment of the ICM with Si occurs before the gas distribution in these systems has been established. Thus, we propose a preferential infall scenario to explain the different levels of α-elements in these systems. In this scenario, intergalactic gas, after being enriched with SN II ejecta, becomes too hot (or has too high an entropy) to accrete into the shallow potential wells of cold systems, so only the low-entropy metal-poor gas is accreted onto groups. The more strongly enriched, higher entropy gas can be accreted onto only rich clusters.

In order for this scenario to work, the excess entropy of the SN-preheated gas should exceed the entropy increase produced during the accretion and shock heating of the gas in groups. It is worth noting that the entropy increase owing to shocks and the entropy increase owing to preheating exhibit different scaling relations depending on the cluster formation redshift, e.g., Ponman, Cannon, & Navarro (1999). This provides a possible test of the above
scenario through future observations of the Si abundance levels in a large sample of groups. A large scatter in formation epochs for groups, as suggested by simulations, may be a reflection of the relative importance of preheating versus accretion shock heating and may allow a more precise determination of the actual energy released by SNe II in the form of preheating.

Since between 0.2$r_{180}$ and 0.4$r_{180}$ the Si abundance is constant, as well as the $M_{col}/L_B$ ratio, the observed differences in SN II Fe $M/L$ ratio at the 0.2$r_{180}$ and 0.4$r_{180}$ simply follow the changes in $f_{gas}$.

One possible explanation for the reduced gas fractions in cold clusters is that the baryons are contained in the form of stars, and the baryon fraction is actually a constant. However, such a scenario cannot reproduce the observed behavior in the Si abundance, since the consumption of any gas will change the mass of elements in the ICM but will not alter the abundances.

In the scenario presented above, we propose that the trend in the observed Si abundance is produced by varying degrees of SN II refection. In the following, we discuss an alternative “closed-box” scenario, in which the increase in the Si abundance with gas temperature results from a dependence of the star formation on the gravitational potential of the system. This requires that SNe II are more common in hotter clusters, because either their galaxies are more massive (Diaferio 2000) and more metals per given light are released into the ICM, or the IMF is top-heavy in the host galaxies of hotter clusters (Larson 1998). In such a case, SNe II are favored in massive systems, resulting in higher [Si/H] and Si $M/L$ ratios. In terms of the slope of the IMF, the observed Si abundances require an IMF slightly steeper than the Scalo IMF for systems cooler than 3 keV, and an IMF that is slightly more top-heavy than a Salpeter IMF in hot clusters (using the calculations of the SN II contribution to the IMLR from Renzini et al. 1993, who adopt $\nu_{Fe}$ from SNe II consistent with our definition; IMLR($x = 1.7$) = 0.003 = IMLR($x = 1.35$) = 0.009 = IMLR($x = 0.9$) = 0.035). We note that only the measurement for A2029 at $\frac{r}{r_{180}}$ exceeds the amount of IMLR predicted for a Salpeter IMF. A precise estimation of the IMF, however, requires determination of the disk/bulge fractions, which we defer to a future work.

5.2. SN Energy Input and the Scaling Relations

Preheating of the intergalactic medium by supernovae has long been considered a possible explanation for the observed deviation of cluster scaling laws from theoretical expectations based on simple gravitational collapse. More recently, the amount of preheating was estimated to be 1–3 keV per particle in order to explain the entropy floor in cool systems (Ponman et al. 1999; Loewenstein 2000; Wu, Fabian, & Nulsen 1999). This amount of energy has been considered too high to be produced by SN heating alone, and heating by active galactic nuclei (AGNs) has been suggested as an alternative solution to the problem (Wu et al. 1999).

Our observations provide for the possibility of determining the amount of energy associated with SNe in a robust way using the measured Si abundances. The advantage of this method consists in the similar Si yields for different SN types, so a separation between SNe Ia and SNe II is not required to calculate the energy released.
that at $0.4r_{180}$ the observed entropy in groups begins to exceed the adopted preheating level, but there is no drastic difference in the gas fraction among these systems (see Fig. 8). Yet the Si abundance does not increase in groups, which implies that there is no substantial enrichment at later times and that previously enriched gas escaped the group's surroundings. This escaped gas can enrich a cluster of galaxies sitting on the same filament and create enhanced Si abundance. Fukugita, Hogan, & Peebles (1998) estimated the total amount of baryons in groups maybe similar to that in clusters. Therefore, hot clusters may accrete a substantial amount of $\alpha$-elements (up to 50%) but not (yet?) the galaxies.

The largest uncertainty in estimating the mechanical heating from SNe comes from radiative losses. Under the assumption of a thermal wind, where the wind velocity is equal to the escape velocity of a galaxy, Renzini (2000) obtained a value for SN energy input that is 10% of the initial energy released. We argue that this is a lower limit on the escape velocity of a galaxy, Renzini et al. (1993), we assume a power-law dependence of the SN Ia rate. Soon (with the advent of the Next Generation Space Telescope) this will be a nicely determined function; the rising $Fe/M/L$ ratios detected in compact groups (FDP) can be understood within the context of this scenario if the galaxies have collapsed only recently onto the center of groups (in agreement with a statement that compact groups are dynamically young). Second, the $Fe/M/L$ ratio should be correlated with the formation of the galactic components of clusters since clusters that form earlier will retain more ejecta. Within this scenario, we can easily explain the scatter in the $Fe/M/L$ as well as the peak in $Fe/M/L$ for cold clusters in view of direct similarity to the Butcher-Oemler effect (e.g., Kauffmann 1995). We can therefore test our scenario by comparing it with simulations of large-scale structure.

To derive the redshift of cluster formation from the observed mass of heavy elements, we have to assume a present-day SN Ia rate and the redshift dependence of the SN Ia rate. Soon (with the advent of the Next Generation Space Telescope) this will be a nicely determined function; at present, in addition to the local measurements (Cappellaro et al. 1997), there is only one point at $z = 0.4$ from the SN Ia Cosmology Project (Pain et al. 1996) obtained for field galaxies. Following a suggestion made by Renzini et al. (1993), we assume a power-law dependence of SN Ia rate with time, using the two measured points. We adopt for this calculation $h = 0.75$ (and rescale our IMLRs), local $R_{SN,Ia} = 0.2$ SNe (1 SN per century per $10^{10}L_{B}$); adopting this value we consider all the galaxies as SN Ia...
producers), and $s = 2$ (see eq. [7] in Renzini et al. 1993). The use of $s = 2$ (which implies a greater SN Ia rate in the past) is also justified by the large amount of Fe attributed to SNe Ia in our measurements. For example, a time-independent rate of SNe Ia can provide only about $\sim 10\%$ of the measured value (this consideration is similar to the estimate of Renzini et al. 1993). We also consider two different cosmologies: $\Omega = 1$ and $\Lambda$CDM with $\Omega_m = 0.3$.

The calculation itself could be expressed as

$$M_{\text{Fe, SN Ia}} = \int_{t(\theta = 0)}^{t(\theta = \infty)} L_{z=0} \theta(t - t_{\text{formation}}) A(t) dt,$$

where $A(t)$ is the SN Ia metal production rate per unit luminosity. We approximate the evolution of the galactic components of clusters by $L_{z=0} \theta(t - t_{\text{formation}})$, i.e., by observing the present-day light for some period of time ($\theta$ is equal to 1 after cluster collapse epoch and 0 before). The results of this calculation are shown in Figure 10. We choose a redshift binning of 0.5 to improve the statistical significance of the points and yet retain the most useful information. Every cluster is added as a Gaussian of width corresponding to the uncertainty of the measurement. In order for these plots to be directly compared with observations, we should correct for the incompleteness of our sample. To accomplish this we used the cluster number function from Henry & Arnaud (1991), counting systems colder then 2 keV as 2 keV clusters.

In the plot we also show the analytical and numerical results on the formation of clusters (Lacey & Cole 1993), following the formulae presented in Balogh, Babul, & Patton (1999) for $\Omega_m = 0.3$. We set the mass fraction of clusters whose formation we want to trace to 40%, representing the ratio of the mass at $\frac{1}{2}$ of virial radius (chosen for comparison with the SN Ia products) to the total virialized mass of the cluster and do the calculation for two masses ($2$ and $5 \times 10^{14} M_\odot$), characterizing two subsamples, shown in Figure 10. In making comparisons with the simulations, we implicitly assume that there is no segregation between the clustering of mass and light. As can be seen from the figure, formation of the central 40% of the mass in the nearby clusters is shifted to earlier epochs.

The remarkable similarity between the distribution of formation redshifts derived here with the calculations of Lacey & Cole (1993) lends support to our explanation for the observed scatter in SN Ia Fe $M/L$ ratio being due to differences in the epoch of cluster formation. The exact meaning of Figure 10 is the formation of a certain part of the studied clusters ($0.2r_{180}$). Similar plots can be done for any overdensity and can thus provide an effective mechanism for tracing the formation of large-scale structure.

### 6. Conclusions

By combining a new analysis of 18 cool clusters with our previous work we have a sample of clusters that span a factor of 10 in temperature. We derive the following conclusions on the basis of abundance measurements at $0.2r_{180}$ and $0.4r_{180}$.

1. Groups and cool clusters preferentially accreted low-entropy, low-abundance gas, as best illustrated by the strong correlation between Si abundance and emission-weighted gas temperature of clusters. This supports the claim that energetic SN II winds, driven at earlier epochs by starburst galaxies, are responsible for preheating the gas.

2. We detect a drastic change in the behavior of the gas mass fractions between $0.2r_{180}$ and $0.4r_{180}$ that is not accompanied by changes in the Si abundance. This requires that the enrichment by Si (SN II) occurs before the observed gas distribution was formed. Lower Fe abundances at higher gas mass fractions suggests that the SN Ia enrichment also occurred after gas density distribution was established. Accounting for the baryons in stars cannot solve the problem of the low gas mass fractions in low-mass systems.

3. The energy per particle associated with SN explosions, when plotted against the emission-weighted system temperature, exhibits a break at 3 keV. At comparable temperatures many cluster scaling relation start to deviate from self-similarity (e.g., Ponman et al. 1999). This proves the importance of SN feedback on the formation of the gaseous component of clusters.

4. We observe a significant scatter in the amount of SN Ia products between systems, with cool clusters among the most SN Ia–rich systems. We propose an explanation on the basis of the distribution of cluster formation redshifts. A comparison of the predicted distribution of formation redshifts of our sample with analytical formulation by Lacey & Cole (1993) for $\Omega_m = 0.3$ demonstrates good agreement.

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Note added in proof.—The estimation of contribution to the metal enrichment from SN types Ia and II discussed in this paper rely on the W7 (convective deflagration) SN Ia model yields of K. Nomoto et al. (ApJ, 286, 644 [1984]). Consideration of the WDD1 (delayed detonation) SN Ia model yields of Nomoto et al. (1984), favored by recent XMM data, has a moderate effect and actually reaffirms both the separation of groups from clusters in terms of the SN II ejecta and our conclusion on the cold systems being SN Ia-rich.