CENTRAL ELEMENTAL ABUNDANCE RATIOS IN THE PERSEUS CLUSTER: RESONANT SCATTERING OR SN Ia ENRICHMENT?

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ABSTRACT

We have determined abundance ratios in the core of the Perseus Cluster for several elements. These ratios indicate a central dominance of Type Ia supernova (SN Ia) ejecta similar to that found for A496, A2199, and A3571. Simultaneous analysis of ASCA spectra from SIS1, GIS2, and GIS3 shows that the ratio of Ni to Fe abundances is ~3.4 ± 1.1 times solar within the central 4′. This ratio is consistent with (and more precise than) that observed in other clusters whose central regions are dominated by SN Ia ejecta. Such a large Ni overabundance is predicted by “convective deflagration” explosion models for SNe Ia such as W7 but is inconsistent with delayed detonation models. We note that with current instrumentation the Ni Kα line is confused with Fe Kβ and that the Ni overabundance we observe has been interpreted as an anomalously large ratio of Fe Kβ to Fe Kα caused by resonant scattering in the Fe Kα line. We argue that a central enhancement of SN Ia ejecta and hence a high ratio of Ni to Fe abundances are naturally explained by scenarios that include the generation of chemical gradients by suppressed SN Ia winds or ram pressure stripping of cluster galaxies. It is not necessary to suppose that the intracluster gas is optically thick to resonant scattering of the Fe Kα line.

Subject headings: galaxies: abundances — galaxies: clusters: individual (Perseus) — supernovae: general — X-rays: galaxies

On-line material: machine-readable table

1. INTRODUCTION

The existence of heavy elements in the intracluster medium (ICM) has been known since the discovery of the ~6.7 keV Fe Kα line in the Perseus Cluster (Mitchell et al. 1976) and indicates that part of the intracluster gas is not primordial, i.e., was processed in stars and injected into the ICM. If the emitting plasma is assumed to be optically thin, then the iron line flux can be converted into an elemental abundance. When this is done, the inferred ICM iron abundances are typically in the range 0.3–0.4 solar (Mushotzky & Loewenstein 1997). The measurements of abundances of iron and other elements are key data used in constraining models of the formation and evolution of the ICM. Therefore, it is important to check that line fluxes can be unambiguously converted to elemental abundances.

A key assumption is that the plasma is optically thin. However, Gilfanov, Sunyaev, & Churazov (1987) pointed out that this may not always be true for the Fe Kα line. Resonant scattering (the absorption and immediate reemission of an Fe Kα line photon by an Fe ion) could be significant in the cores of clusters. If so, the line emission from the cluster core would be reduced because of photons being scattered out of the line of sight, and the measured Fe abundance would be an underestimate of the true intracluster gas abundance. The simplest test for resonant scattering in the Fe Kα line is to compare its line flux with that from the Fe Kβ line. The optical depth in the Fe Kβ line is ~20% of the Fe Kα so that if the Fe Kβ/Fe Kα ratio is anomalously high then resonant scattering must be taken into account.

Such anomalous ratios have been observed with low significance in data from the HEAO 1 (Mitchell & Mushotzky 1980) and Tenma (Okumura et al. 1988) satellites. Recently, these results have been placed on a much firmer basis using observations of several clusters using ASCA (Akimoto et al. 1997; Yamashita et al. 19991) and of the Perseus Cluster using BeppoSAX (Molendi et al. 1998). The best data are from Molendi et al. (1998), who show that the Fe Kβ/Fe Kα ratio is anomalously high for the inner 6′ of the Perseus Cluster. Outside that radius the ratio decreases to the expected value for an optically thin plasma. They deduce from this that the Fe abundance is underestimated by about a factor of 2 in the center of the Perseus Cluster.

However, at the resolution of current X-ray spectrometers the Fe Kβ line is confused with the Ni Kα line so that a measurement of the Fe Kβ/Fe Kα ratio requires an assumed flux in the Ni Kα line. The results reported above assumed that the ratio of Ni and Fe abundances is similar to the solar value (0.038 by number, photospheric value; Anders & Grevesse 1989). To make the Fe Kβ/Fe Kα ratio consistent with the optically thin case requires an Ni/Fe abundance ratio several times that of solar. To see whether this is reasonable, it is necessary to consider how heavy elements arrived in the ICM.

Einstein FPCS spectroscopy (Canizares et al. 1982) and more recent ASCA spectroscopy (Mushotzky & Loewenstein 1997; Mushotzky et al. 1996) suggest that global intracluster metal abundances are consistent with ejecta from Type II supernovae (SNe II). This implies that the bulk of the heavy elements were injected into the ICM by protogalactic winds. This is further supported by analysis of ICM energetics (White 1991). Since SNe II do not produce much

1 astro.estec.esa.nl/XMM/news/wsl/procs/yamashitak.ps.gz.
As mentioned above, SN Ia metal injection mechanisms such as ram pressure stripping or protogalactic suppressed SN Ia winds may contribute significantly to ICM enrichment. SNe Ia can generate large amounts of Ni. “Convective deflagration” models such as W7 (Nomoto, Thielemann, & Yokoi 1984; Thielemann, Nomoto, & Yokoi 1986) predict an Ni/Fe number abundance ratio ~ 5 times solar. Alternative slow flame speed (delayed detonation) models produce a lower Ni/Fe abundance ratio closer to that from SNe II (~1.6). Recently, Dupke & White (2000a) and Dupke (1998) have found evidence that in the central regions of A496, A2199, and A3571 the ICM is enriched predominantly by SN Ia ejecta. In these objects the ratio of Fe abundance to that of α-process elements increases with decreasing radius from the cluster center. These results suggest that, in clusters for which the abundance profile is centrally enhanced, SN Ia ejecta provide most of the total iron mass in the central regions (see also Allen et al. 2000). In the outer regions the SN Ia contribution is smaller than in the cluster’s center but not negligible (e.g., Nagataki & Sato 1998). In A496 the excess iron that generates the central abundance gradient is fully accounted for by the excess SN Ia ejecta that produce a chemical gradient (Dupke & White 2000b). In all three clusters mentioned above the Ni/Fe abundance ratio is consistent with that predicted by the SN Ia “convective deflagration” W7 model, i.e., the Ni/Fe ratio is several times solar (assuming that the Fe Kβ/Fe Kα ratio takes its optically thin value). The analysis of A1060 (the only cluster with flat abundance distribution in the sample of Dupke 1998) shows no significant abundance ratio trend in its radial distribution (including the Ni/Fe ratio). However, since the number of clusters with detailed measured abundance ratio distributions is relatively small, it is not clear whether this “chemical gradient” is always true for clusters with central abundance gradients.

This work extends the analysis of Dupke & White (2000a) to the Perseus Cluster. This cluster is closer and brighter than A496, A2199, and A3571, so we can determine elemental abundance ratios with higher precision. The Fe abundance is known to be centrally enhanced in Perseus (Ulmer et al. 1987; Ponman et al. 1990; Kowalski et al. 1993; Arnaud et al. 1994; Ikebe et al. 1997; Ezawa et al. 1997; Xu et al. 1997; Pišlar et al. 1997; Dupke 1998; Dupke & White 2000a, 2000b; Irwin & Bregman 2001; Finoguenov, David, & Ponman 2000; White 2000; Allen et al. 2000). There are several mechanisms that may cause central abundance enhancements in the ICM, including (1) the radial profile of intracluster gas density is shallower than that of metal-injecting galaxies, i.e., if metals trace the galaxies that injected them into the ICM and these galaxies are more concentrated in the center than the intracluster gas, one would expect to find a general abundance enhancement toward the clusters central regions; (2) mass loss from the stars in central dominant galaxies may accumulate near the cluster center; (3) ram pressure stripping of the metal-rich gas in cluster galaxies by intracluster gas is more effective at the center, where the intracluster gas density is highest; and (4) secular SN Ia winds in central dominant galaxies are partially suppressed because of the galaxy location at the bottom of the cluster gravitational potential, where the intracluster gas density is highest (Dupke & White 2000b).

Some of the above-mentioned mechanisms could deposit substantial amounts of SN Ia enriched material near the clusters’ center, therefore creating a “chemical gradient.” Since SNe Ia and SNe II have different elemental mass yields, analysis of the elemental abundance ratios provides information on the fractional contribution of gas enriched by SNe Ia and SNe II. The analysis of abundance ratios in the central regions of clusters having abundance gradients indeed indicates a central dominance of SN Ia ejecta (Dupke & White 2000a, 2000b; see below).

As mentioned above, SN Ia metal injection mechanisms such as ram pressure stripping or protogalactic suppressed SN Ia winds may contribute significantly to ICM enrichment. SNe Ia can generate large amounts of Ni.

The Perseus Cluster is one of the closest, X-ray–bright, rich clusters of galaxies. Its X-ray emission has been the object of many studies since its discovery as an X-ray source by Fritz et al. (1971). It is a nearby cluster (at a redshift of 0.0183) and Bautz-Morgan type II–III. The cluster is elongated, and the ratio of its minor to major axis is 0.83 at radii greater than 20'. (Snyder et al. 1990). The radiative cooling time of the X-ray-emitting gas in the central regions of Perseus is less than a Hubble time, so the cluster has a cooling flow with a mass deposition rate of about (1–5) × 10^2 M⊙ yr⁻¹ (Fabian et al. 1981; Allen et al. 1992; Peres et al. 1998). The centroid of the cluster emission is offset by ~2' to the east of NGC 1275 (Snyder et al. 1990; Branduardi-Raymond et al. 1981), which has a Seyfert nucleus and shows signs of nonthermal emission with a power-law spectrum (Rothschild et al. 1981; Primini et al. 1981; Branduardi-Raymond et al. 1981; Ulmer et al. 1987; Kowalski et al. 1993; Allen et al. 2000). The average temperature of the X-ray–emitting gas is approximately 6.5 keV (Eyles et al. 1991), and the average abundance is 0.27 solar in the central 1' (Arnaud et al. 1994). There are significant signs of both temperature and abundance substructure (Schwarz et al. 1992; Arnaud et al. 1994) in the gas distribution.
The existence of an iron abundance gradient in Perseus was first suggested by Ulmer et al. (1987) using data from SPARTAN I. They found that the inner (0'–5') region has an abundance of ~0.81 solar and a temperature of ~4.2 keV, while an outer region (6'–20') has an abundance of ~0.41 solar and a temperature of ~7.1 keV. Further observations of Perseus have confirmed the gradient. Pomman et al. (1990), analyzing data from Spacelab 2, found an abundance value of ~0.75 solar in the central 3' that decreases to ~0.25 solar in the outer regions. Kowalski et al. (1993), also using SPARTAN I data, have measured a central abundance enhancement with a central value of ~0.77 solar. ASCA analysis of GIS data (Arnaud et al. 1994; see also Fabian et al. 1994 for SIS data from the central region) has corroborated the existence of a global abundance gradient (with local nonaxisymmetric variations), where the abundance values ranged from ~0.4 solar in the central regions to ~0.2 solar in the outer regions, over a region of ~1° around the cluster center.

3. DATA REDUCTION, TEMPERATURE, AND ABUNDANCE PROFILES

ASCA carries four large-area X-ray telescopes, each with its own detector: two Gas Imaging Spectrometers (GISs) and two Solid-State Imaging Spectrometers (SISs). Each GIS has a 50' diameter circular field of view and a usable energy range of 0.8–10 keV; each SIS has a 22' square field of view and a usable energy range of 0.4–10 keV.

Two pointings of the Perseus Cluster were analyzed in this work. Perseus was observed for 20 ks by ASCA in 1993 August (central pointing) and 1993 September (outer pointing). We selected data taken with high and medium bit rates, with cosmic-ray rigidity values ≥6 GeV/c, with elevation angles from the bright Earth of ≥20° and from the Earth’s limb of ≥5° (GIS) or 10° (SIS); we also excluded times when the satellite was affected by the South Atlantic Anomaly. Rise-time rejection of particle events was performed on GIS data, and hot and flickering pixels were removed from SIS data. The resulting effective exposure times for each instrument are shown in Table 1. We estimated the background from blank-sky files provided by the ASCA Guest Observer Facility. The ASCA point-spread function (PSF) mostly scatters high-energy photons from internal regions outward. The scattering from outside inward is negligible and should not affect our results. The two extraction regions chosen for the central pointing (0°–4° and 0°–20°) are centered on the contaminating source, i.e., the X-ray center. The gas temperature in the very central region (0°–4°) is relatively low (~4.5 keV). Therefore, the effect of high-energy photon depletion in that region due to the PSF is negligible (Takahashi et al. 1995).

Furthermore, the best-fit temperature for that region agrees very well with that of White (2000), who did correct for the PSF, when the same spectral models are used in the fittings (see below). Therefore, we do not worry about ASCA PSF scattering. We also include the analysis of a 0°–20° region centered in the X-ray peak, which is more than 3 times larger than that where Molendi et al. (1998) detected resonant scattering. We analyzed this larger region for the purposes of (1) measuring the elemental abundances in a region large enough so that resonant scattering is not effective, (2) discriminating between different delayed detonation SN Ia explosion models with better photon statistics, and (3) giving a better idea of the uncertainties involved when a power-law spectral component is introduced.

We used XSPEC v10.0 (Arnaud 1996) to analyze the SIS and GIS spectra separately and jointly. The spectra were fitted using the mekal and smekal thermal emission models, which are based on the emissivity calculations of Mewe, Gronenschild, & van den Oord (1985), Mewe, Lemen, & van den Oord (1986), and Kaastra (1992), with Fe L calculations by Liedahl, Osterheld, & Goldstein (1995). Abundances were measured relative to the solar photospheric values of Anders & Grevesse (1989), in which Fe/H = 4.68 × 10⁻⁵ by number. Galactic photoelectric absorption was incorporated using the wabs model (Morrison & McCammon 1983). Spectral channels were grouped to have at least 25 counts per channel. Energy ranges were restricted to 0.8–10 keV for the GIS and 0.4–10 keV for the SIS. We show here the results of the spectral analysis for three spatial regions. The first is a circular region of 4° radius around the cluster’s X-ray center, chosen for comparison to the analysis of spatially equivalent regions in A496, A2199, and A3371. The second is a region of 10° radius centered 35' from the center (outer pointing), selected to provide a measurement of abundances well outside the core. The third is a circular region of 20° radius around the cluster’s X-ray center (basically covering the whole effective field of view of the central pointing).

Since there is a moderate cooling flow in the center of the Perseus Cluster, we added a cooling flow component to the mekal isothermal emission model in the central region. We adopted the emission measure temperature distribution that corresponds to an isobaric cooling flow. We tied the maximum temperature of the cooling flow to the temperature of the isothermal component, and we fixed the minimum temperature at 0.1 keV. The abundances of the two emission components (mekal and cflow) were tied together. We also applied a single (but variable) Galactic absorption to both spectral components wabs and a variable extra absorption zwabs to the cooling flow component.

We fitted spectra from the two SISs and two GISs independently and then from all four instruments together. The spectral fits of SISO data for the central pointing had unusually high reduced χ² and showed spurious spectral features. In particular, the width of the Fe K complex is 50% larger in SISO than in SIS1. We have no explanation for this discrepancy. Nevertheless, the SISO best fits for the interesting parameters agreed well with those obtained with SIS1 and the two GISs. Since the inclusion of the SISO data did not alter the results significantly and made the χ² significantly worse, we excluded the instrument from our analysis.

When performing joint fits, the redshift parameters corresponding to spectral models applied to the GISs and SISO1 were set free to vary to compensate for possible gain differences between different instruments. The individual and joint SISO, GIS2, and GIS3 fits achieved χ² close to 1 and produced consistent estimates of temperatures and metal abundances. The best-fit values for the temperatures and abundances for the central 4° and for the external pointing are shown in Table 2. It can be seen from Table 2 that there is a positive temperature gradient. The best-fit temperature found for the outer region is 7.24 ± 0.4 keV, and it declines to 4.43 ± 0.08 keV in the inner 4°, which is consistent with

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2 http://heasarc.gsfc.nasa.gov/Images/asca/newsletters/ext_src_analysis3.gif.
the presence of a central cooling flow. There is a significant (>90% confidence) central abundance enhancement. The abundance in the center is 0.50 ± 0.03 solar declining to 0.25 ± 0.05 solar at ~35' from the center.

3.1. Individual Elemental Abundances

We determined the abundances of individual elements using a fitting procedure similar to that used for determining general abundances, but with the *vmekal* spectral model in XSPEC. Since the global abundance is mainly driven by Fe, the cooling flow abundance was tied to the Fe abundance of the *vmekal* component. We adopt as a basis for comparison the following theoretical elemental abundance

(by number) ratios relative to solar values: for SNe Ia (Nomoto et al. 1984, 1997b),

\[
\begin{align*}
O & \approx 0.35 \text{Fe}, \\
\text{Ne} & \approx 0.006 \text{Fe}, \\
\text{Si} & \approx \text{Ar} \approx \text{Ca} \approx 0.5 \text{Fe}, \\
\text{Ni} & \approx 4.8 \text{Fe},
\end{align*}
\]

and for SNe II (Nomoto et al. 1997a),

\[
\begin{align*}
O & \approx 0.14 \text{Si} \approx 3.7 \text{Fe}, \\
\text{Ne} & \approx 0.3 \approx 2.5 \text{Fe}, \\
\text{Ar} & \approx \text{Ca} \approx \text{Ni} \approx 1.7 \text{Fe}.
\end{align*}
\]

In our spectral model fits, the He abundance was fixed at the solar value, while C and N were fixed at 0.3 solar (the derived abundances of other elements are not affected by the particular choice of C and N abundances). In order to test the statistical significance of the spectral fittings where individual elemental abundances are free to vary, we used the $F$-test. Initially, all the individual abundances were tied. Then we systematically untied the abundance of each interesting element and refitted, and a new $\chi^2$ was found. The difference between the $\chi^2$ of these two fits must follow a $\chi^2$ distribution with 1 degree of freedom (dof) (Bevington 1969). Based on the $\chi^2$ differences for each spectral fitting, the $F$-test shows significant differences at the greater than 99.5%, greater than 99.9%, greater than 99%, greater than 99.9%, greater than 97.5%, and greater than 95% confidence levels for letting Fe, Ni, Si, Ne, O, and S free to vary, respectively. The significance is less than 90% for Mg, Ar, and Ca, and therefore they are tied together. We used in our analysis only those abundances that were reasonably well constrained, namely, O, Ne, Si, S, Fe, and Ni. The observed individual abundances are shown in Table 3 for the central 0'-4' and for an outer circular region centered at ~35' away from the center with a radius of 10'. The individual elemental abundances in the outer parts were not constrained enough to determine spatial variations of abundance ratios within the cluster. Therefore, we could only set upper limits for most individual elemental abundances other than Fe in the outer region.

We also determined the central Fe abundance from the Fe L lines alone. The abundance found when the Fe K lines are ignored is 0.62 ± 0.12 and is also shown in Table 3. This value is consistent with the abundance determined from the Fe K complex. The Ni abundance determined from the L-shell lines is not well constrained (1.3 ± 1.6) but is consistent with that determined from the K-shell complex. The best constrained individual abundances are Fe, Si, and Ni.

3 Ni abundances based on L-shell lines are likely to be unreliable for the following two reasons. First, the Ni L lines are interspersed among the Fe L lines, so an accurate measurement of the Ni L line fluxes requires a good model for the Fe L lines. Second, even if the Ni L line fluxes are correct, turning these into an Ni abundance depends on accurate Ni L-shell atomic physics. The corrections to the Fe L-shell physics of Liedahl et al. (1995) have not yet been applied to Ni, so any conclusions based on Ni L lines should be considered very preliminary.

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**Table 1**

| SPECTROMETER | EXPOSURE TIME |
|--------------|---------------|
|               | Central Pointing | Outer Pointing |
|----------------|------------------|
| SISO ................ | 18               | 18             |
| SIS1 ............. | 18               | 19             |
| GIS2 ............. | 12               | 17             |
| GIS3 ............. | 12               | 17             |

**Table 2**

| Region | $kT$ (keV) | Abundance (solar) | $\chi^2$ |
|--------|------------|-------------------|----------|
| 0'-4'  | 4.43 ± 0.08 | 0.50 ± 0.03      | 1.29     |
| 25'-45' | 7.24 ± 0.44 | 0.25 ± 0.05      | 1.05     |

* Errors are 90% confidence limits.

**Table 3**

| ELEMENT | ABUNDANCE (INNER) | ABUNDANCE (OUTER) |
|---------|-------------------|-------------------|
|          | (solar)            | (solar)            |
| O .......... | 0.87 ± 0.53        | ≤0.95             |
| Ne .......... | 1.19 ± 0.57        | ≤2.01             |
| Si .......... | 0.71 ± 0.14        | ≤0.83             |
| S .......... | 0.32 ± 0.16        | ≤0.11             |
| Fe L ....... | 0.57 ± 0.25        | 0.25 ± 0.05       |
| Fe K .......... | 0.67 ± 0.14        | 0.12              |
| Fe Ksh, d .. | 0.59 ± 0.13        | ...               |
| Fe Kax, d .... | 0.49 ± 0.01        | ...               |
| Ni .......... | 0.79 ± 0.57        | ≤0.56             |
| Nax, d .. | 1.17 ± 0.29        | ≥3.5              |
| Nax, e .... | 1.47 ± 0.48        | ...               |

* Errors are 90% confidence level limits.

* Simultaneous ASCA spectral fittings using GIS2, GIS3, and SISO spectrometers for an absorbed *vmekal + cflow* model ($\chi_{\nu}^2 = 1.12$).

* Abundance determined from spectral fits of the Fe L line complex.

* Abundance determined from simultaneous spectral fits of MECS 1, 2, and 3, for a simple *vmekal* model.

* Abundance determined from simultaneous spectral fits of MECS 1, 2, and 3, for a simple *vmekal + cflow* model.
We also consider abundances of other elements when determining the SN Ia Fe mass fraction in the next section.

4. ABUNDANCE RATIOS AND THE SN Ia AND SN II FRACTIONS

Discriminating between the products of SNe Ia and SNe II requires the determination of the abundances and abundance ratios of Z-elements and comparison to SN models. The determination of the relative contributions of the two SN types is complicated by the theoretical uncertainties in the elemental mass yields for different SN models, especially for SNe II (e.g., Gibson, Loewenstein, & Mushotzky 1997). In general, SN Ia models show far better agreement on elemental mass yields than SN II models. However, discrepancies between some SN Ia explosion models still exist. For example, the Ni mass yields for models with fast Ne speed are like W7 (Nomoto et al. 1984; Thielemann et al. 1986) are such that if multiplied by the SN II mass yields of Ne or S would bring the SN Ia mass fraction to the average of the two models. This value is consistent with the SN Ia Fe mass fraction derived from the Ni/Fe abundance ratio alone (0.57 ± 0.10). The total weighted average of the SN Ia Fe mass fractions based on ratios involving only the abundances of Ni, O, Si, and Fe is 0.67 ± 0.06. The observed Ni/Fe ratio is inconsistent with either (1) pure SN II ejecta or (2) a combination of SN II and SN Ia ejecta as predicted by delayed detonation models.

To determine the SN Ia Fe mass fraction contribution, we considered several abundance ratios involving the elements described in the previous paragraph. The abundance ratios used are shown in Table 4, along with the expected theoretical abundance ratios (by number, normalized by the solar photospheric values) for pure SN Ia (for both W7 and delayed detonation explosion model WDD2 of Nomoto et al. 1997b) and SN II ejecta. All the errors associated with the observed abundance ratios are the propagated 90% confidence errors. The derived SN Ia Fe mass fractions for the inner region (0'–4') are also listed in Table 4. It can be seen that most abundance ratios show, within the 90% confidence errors, a combination of SN Ia and SN II ejecta. Some abundance ratios, however, are observed to be completely out of the predicted theoretical range for SNe Ia and SNe II, e.g., Ne/S and Ne/Si. These measurements are consistent with the results of Mushotzky et al. (1996), who also found that S is observed to be underabundant and Ne overabundant relative to several different theoretical SN II models. Based on a detailed analysis of A496, Dupke & White (2000b) proposed correcting the theoretical SN II sulfur yields by 0.25–0.5. To be conservative, we avoid including abundance ratios involving these two elements in the calculation of the SN Ia iron mass fraction.

From the abundance ratios involving O, Si, and Fe, we derived the fraction of the iron mass from SNe Ia. The Fe mass fraction estimates are also listed in Table 4. The average SN Ia Fe mass fraction based on ratios involving the above-mentioned three elements is 0.69 ± 0.08. This value is consistent with the SN Ia Fe mass fraction derived from the Ni/Fe abundance ratio alone (0.60 ± 0.35). The total weighted average of the SN Ia Fe mass fractions based on ratios involving only the abundances of Ni, O, Si, and Fe is 0.67 ± 0.06. The observed Ni/Fe ratio is inconsistent with either (1) pure SN II ejecta or (2) a combination of SN II and SN Ia ejecta as predicted by delayed detonation models. The mutual consistency of the derived SN Ia Fe mass fractions derived from different abundance ratios suggests that the Ni/Fe ratio is a robust indicator of SN Ia contamination.

It should be noticed that the Si/Fe ratio measured in the center (0'–4') of Perseus (1.37 ± 0.28) is completely out of the range allowed by the delayed detonation model WDD1 (Si/Fe > 1.69). Furthermore, if WDD2 is assumed, there is a contradiction between the predicted SN Ia Fe mass fractions derived from Si/Fe (0.86 ± 0.1) and O/Si (<0.73). However, the only abundance ratio that is systematically in contradiction with all three delayed detonation models is Ni/Fe. Figure 1 shows that the Ni/Fe abundance ratio derived in this work is consistent with the values found for other clusters that show central SN Ia contamination. Figure 1 also shows the theoretical predictions of the Ni/Fe

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**TABLE 4**

| ABUNDANCE RATIO | REGION 0'–4' | THEORYb | SN Ia Fe MASS FRACTION 0'–4' | CORRECTIONc |
|-----------------|-------------|---------|-----------------|-------------|
| O/Fe            | 1.67 ± 0.16 | 0.037   | 3.82            | 0.57 ± 0.21 |
| Si/Fe           | 1.37 ± 0.28 | 0.538   | 5.35            | 0.72 ± 0.09 |
| Si/Ni           | 0.40 ± 0.15 | 0.113   | 2.14            | 0.68 ± 0.15 |
| Ni/Fe           | 3.44 ± 1.1  | 4.758   | 1.65            | 0.60 ± 0.35 |
| Ni/Fe L         | 2.89 ± 1.14 | 4.758   | 1.65            | 0.43 ± 0.36 |
| O/Si            | 1.23 ± 0.1  | 0.068   | 0.72            | <0.84       |
| O/Ni            | 0.49 ± 0.27 | 0.008   | 2.32            | 0.57 ± 0.15 |
| O/S              | 2.72 ± 1.83 | 0.092   | 1.54            | <0.8        |
| Si/S             | 2.22 ± 1.19 | 0.063   | 1.67            | <0.95       |
| S/Fe             | 0.62 ± 0.31 | 0.585   | 2.29            | 0.98 ± 0.18 |
| S/Ni             | 0.18 ± 0.11 | 0.123   | 1.39            | 0.88 ± 0.18 |
| Ne/S             | 3.72 ± 2.26 | 0.011   | 1.18            | ...         |
| Ne/Fe            | 2.29 ± 0.76 | 0.006   | 2.69            | 0.15 ± 0.15 |
| Ne/Si            | 1.68 ± 0.64 | 0.012   | 0.76            | ...         |
| Ne/Ni            | 0.67 ± 0.30 | 0.001   | 1.63            | 0.33 ± 0.21 |

**Note.** This table is also available in machine-readable form in the electronic edition of the Journal.

b SNe Ia: Nomoto et al. 1997b; SNe II: Nomoto et al. 1997a.
c Errors are propagated 90% errors.
from all three MECSs using only the channels correspond-
into position-dependent PSF and vignetting which convolves a given surface brightness profile with the effective area. Files were generated using "EFFAREA,Ï which is recommended by the data for Perseus. We used standard reduction procedures as their results with ours, we have reanalyzed the trader Spectrometer (MECS) data. In order to compare those involving other elements (from abundance ratios involving Ne and S to agree with models such as W7.

It is clear from Figure 1 that delayed detonation models for SN II and for three different SN Ia delayed detonation models. It is clear from Figure 1 that delayed detonation explosion models are not preferred over the standard models such as W7.

In order to have the SN Ia iron mass fractions derived from abundance ratios involving Ne and S to agree with those involving other elements (\textasciitilde0.67), one would have to multiply systematically the theoretical SN II mass yields of S by \sim0.34 and of Ne by \sim2.7. These suggested corrections for Ne and S are also listed in Table 4.

\section{Comparison with BeppoSAX Results}

Molendi et al. (1998) reported the detection of resonant scattering in the central regions of the Perseus Cluster based on the analysis of the BeppoSAX Medium Energy Concentrator Spectrometer (MECS) data. In order to compare their results with ours, we have reanalyzed the BeppoSAX data for Perseus. We used standard reduction procedures as recommended by the BeppoSAX Science Data Center. The effective area files were generated using "EFFAREA," which convolves a given surface brightness profile with the MECS energy/position-dependent PSF and vignetting functions.

Following Molendi et al. (1998), we analyzed spectra from all three MECSs using only the channels corresponding to the 3–10 keV energy range. Background spectra were extracted from blank-sky event files using the same extraction regions as those for the source. The spectral fitting procedure was analogous to that used with ASCA as described in § 3. We were unable to find reasonably good fits with the redshift constrained to the optical value. This is probably due to a known MECS gain calibration problem, and the recommended solution is to allow the redshift to be a free parameter (F. Fiore 1999, private communication). We found a best-fit redshift of 0.011. Because of the limited safe energy range of the MECS (3–10 keV), the comparison of line strengths between BeppoSAX and ASCA is limited to the best constrained Fe and Ni lines. To compare with ASCA, we extracted spectra from the 0–4′ region. The results are shown in Table 3. The reduced $\chi^2$ is significantly worse than that obtained with ASCA ($\chi^2 \approx 1.25$ for a vmekal+cflow model) even with the cluster redshift set as a free parameter in the spectral fittings.

The discrepancy of our best-fit values of Fe and Ni abundances with those of Molendi et al. (1998) is most likely due to the difference in dealing with the MECS gain calibration problem and to the insensitivity of the MECS spectra to the cooling flow within the energy range considered (3–10 keV). If we add a cooling flow component with the best-fit normalization (300 M$_\odot$ yr$^{-1}$) obtained from the ASCA spectral fittings, the best-fit Ni and Fe abundances are found to be 1.47 ± 0.48 and 0.49 ± 0.01, respectively, with $\chi^2$ of \sim1.19.

We also extracted spectra from a central region with a radius of 6′ for the purpose of direct comparison with the Molendi et al. (1998) best-fit values. Our results are similar to those obtained for the 0′–4′ region. The Ni abundance is 1.34$^{+0.26}_{-0.44}$ solar and the Fe abundance is 0.47 ± 0.012 solar with $\chi^2 \approx 1.23$ for a vmekal+cflow model. As can be seen in Table 3, the Fe and Ni abundance measurements in the central regions obtained with ASCA and BeppoSAX for the same spectral models agree very well.

\subsection{4.2. Influence of the Power-Law Component}

Since the cD galaxy in Perseus, NGC 1275, has a Seyfert-like spectrum (Rubin et al. 1977), we added a power-law component to the absorbed vmekal+cflow spectral model. The addition of the power-law component to the simultaneous GIS2, GIS3, and SIS1 fittings has a general effect of decreasing the temperature of the hot component (of the cflow model) and does not improve the spectral fittings ($\chi^2 \sim 1.12$ or $\chi^2 \sim 1495$ for 1333 dof). However, the inclusion of the power-law component introduces large uncertainties in the determination of Ni and Fe abundances and especially the power-law slope, which are found to be 1.5 ± 0.7 solar, 0.47 ± 0.05 solar, and 2.6$^{+2.6}_{-0.5}$, respectively. In order to understand the reasons for the high uncertainties in these parameters introduced by the power-law component, we fitted the spectra obtained with the GISs and SIS1 separately. The individual spectral fittings indicated that GIS2 and GIS3 are insensitive to the inclusion of the power law. Furthermore, the introduction of the power-law component increases the uncertainties of the Ni abundance determination very strongly (90% confidence range.

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\footnote{This gain problem has been observed to be significant in 80% of the clusters observed by BeppoSAX and gives a redshift discrepancy of \sim0.009 when compared to optical redshifts (J. Irwin 1999, private communication).}
for Ni is 0.1–2.8). The SISs, on the other hand, are less sensitive to the cflow model than to the power-law component. There is a significant improvement in the spectral fittings with the addition of the power-law component. However, the Ni abundance (~1.6) as well as the other individual abundances are similar to those obtained without the power-law model.

The allowed low Ni abundance is a consequence of the inclusion of the power-law component in the joint spectral fittings and seems to be due to different instrumental sensitivities in the spectral fittings to the combination cflow + power models, i.e., an artifact of the spectral fittings, which also generates large uncertainties in the best-fit values of the power-law slope (varying from 0.9 to 3). Since the introduction of the power-law component does not improve significantly the simultaneous GIS + SIS1 spectral fittings and introduces large artificial uncertainties on the determination of the best-fit Ni abundances, we do not include the power-law component when determining the SN Ia Fe mass fraction. However, since the power-law component poses a new undesired uncertainty to both mechanisms (resonant scattering and W7 SN Ia enrichment) proposed to explain the excess flux at ~8 keV in the cluster central regions we will consider its possible effects on the Ni and Ni/Fe measurements when checking the validity of the delayed detonation models (below).

In order to compare the two above-mentioned competing mechanisms and to estimate the effect that a power-law component would have on the abundance ratios involving Ni, we extracted spectra from a large region (radius of 20") around NGC 1275 in the central pointing. The size of the region is large enough so that the directional number of Fe Kα photons is conserved, and resonant scattering should have no effect on the Fe Kβ/Fe Kα ratio. The abundance ratios derived from this region, however, are emission measure–weighted averages and are highly biased toward the values of the abundance ratios in the cluster central regions. The best-fit values of Si, Fe, and Ni and their ratios obtained from the spectral fittings of the 0"–20" region are shown in Table 5. The spectral fittings are significantly worse ($\chi^2 = 1.79$) than those for the central 4". The observed Ni/Fe ratio (3.9 ± 0.2) corresponds to an SN Ia Fe mass fraction of 0.73 ± 0.13, which is consistent with that derived from the central 4". This high value for the Ni/Fe ratio is inconsistent with all delayed detonation models, independently of resonant scattering effects. The inclusion of a power-law component (with a best-fit slope of ~1.2) improves significantly the spectral fittings ($\chi^2 = 1.55$) and has the effect of lowering somewhat the Ni abundance, therefore lowering the Ni/Fe ratio to 2.9 ± 0.9, which is consistent with a radial decline in SN Ia Fe mass fraction (Fig. 1).

However, even the lower Ni/Fe ratio obtained with the addition of the power-law component is in contradiction with the delayed detonation models. If the power-law slope is fixed at higher values, the Ni/Fe ratios measured are even higher. Thus, the average Ni/Fe ratio is inconsistent with the delayed detonation SN Ia explosion models independently of the resonant scattering effect and also of the inclusion of a power-law component in the spectral fittings.

5. DISCUSSION

5.1. Abundance and Chemical Gradients

The comparative spectral analysis of the large region versus the central region clarifies the question of whether a chemical gradient exists in the Perseus Cluster. The average (0"–20") Si/Fe ratio measured is 1.83 ± 0.16 (implying an emission measure–weighted average SN Ia Fe mass fraction of 0.57 ± 0.05). This value is significantly (≥90% confidence) higher than that obtained in the central regions (Si/Fe = 1.37 ± 0.28), indicating the presence of a chemical gradient in the intracluster gas of Perseus, where SN Ia ejecta are more concentrated toward the central regions of the cluster. Some of the possible scenarios, proposed to explain the abundance and chemical gradient could be better constrained by determining the abundance radial profiles for different elements and analyzing the SN Ia and SN II Fe mass-to-light ratio distribution for the cluster. This is beyond the scope of this work. Nevertheless, at least two difficulties are apparent if stripping models are used to explain the central abundance and chemical gradients (Dupke & White 2000b). First, the Fe abundances measured in most early-type galaxies by ASCA (Loewenstein et al. 1994; Matsumoto et al. 1997) and ROSAT (Davis & White 1996) are lower (0.2–0.4 solar) than the abundance observed at the cluster center (~0.5 solar). Furthermore, there is evidence of abundance gradients in elliptical galaxies themselves (e.g., in NGC 4636; Matsuishi et al. 1997), so that most stripped gas will have even lower abundances than indicated by the global X-ray Fe abundances of elliptical galaxies. Second, the efficiency of ram pressure stripping is dependent on the ICM density, which rises strongly toward the central regions. The difference in Fe abundances measured in inner and outer regions is mild (a factor of ~2) and might be expected to be larger if stripping were important.

5.2. Resonance Scattering or SN Ia Convective Deflagration Models?

We have shown above that the high Fe Kβ/Fe Kα ratio observed in Perseus, which has been attributed to resonant scattering of the Fe Kα, can also be explained by a super-

| Element | Abundance or Abundance Ratio (Average) |
|---------|---------------------------------------|
| Si      | 0.88 ± 0.13                          |
| Fe      | 0.48 ± 0.012                         |
| Fe$^{\text{power}}$ | 0.5 ± 0.02               |
| Ni      | 1.87 ± 0.13                          |
| Ni$^{\text{power}}$ | 1.46 ± 0.14               |
| Ni/Fe   | 3.9 ± 0.6                             |
| Ni/Fe$^{\text{power}}$ | 2.92 ± 0.7                |

$^a$ Errors are 90% confidence level limits or propagated 90% confidence level.

$^b$ Abundance determined with the addition of a power-law model to smekal + cflow.

$^c$ However, there is evidence that the Fe abundance in ellipticals can be significantly higher when multiphase spectral models are used in the X-ray spectral fittings (Buote & Fabian 1998).
solar Ni/Fe abundance ratio due to the products of SNe Ia. In this section we consider the arguments for and against these two explanations. The first point to make is that this is independent of the question of whether there is a significant contribution from SN Ia products. The abundance ratios of elements other than Ni can be used to measure the relative contributions from SNe Ia and SNe II. So, the basic choice lies between (1) resonance scattering and delayed detonation SN Ia explosion models and (2) no resonance scattering and convective deflagration SN Ia explosion models.

Delayed detonation SN Ia explosion models (and alternatives that have low Ni production) have certainly been espoused by SN theorists. However, recent treatment of turbulence effects in subsonic flames in delayed detonation models shows that the transition to detonation requires unusually high turbulent velocity fluctuations (Lisewski, Hillebrandt, & Woosley 1999). Resonant scattering optical depth is a function of the gas density and therefore should fall to the optical thin value at regions away from the cluster's center. Observations of the radial distribution of the SN Ia gas contamination in other clusters also show a decrease in SN Ia Fe mass fraction as the distance from the center increases (Dupke 1998; Dupke & White 2000b; Finoguenov et al. 2000). This seems also to be the case for Perseus as indicated by the significantly lower Si/Fe values in the central 4' when compared to the average value observed for the (0'-20') region. This "chemical gradient" is expected from models proposed to explain the central SN Ia ejecta excess (e.g., suppressed SN Ia winds, ram pressure stripping, cD stellar mass loss). Therefore, if one assumes the classical W7 SN Ia model, both scenarios, SN Ia enrichment and resonant scattering, predict that, observationally, the excess flux in the Fe Kβ–Ni Kα line complex should decrease radially.

Against the resonance scattering scenario is the fact that simulations of its expected effect on clusters (where Ni abundances are set to solar) show that resonant scattering alone cannot explain the high Fe Kβ/Fe Kα ratio observed (Tawara et al. 1997; Furuzawa et al. 1997), particularly in Perseus (Akimoto et al. 1997, 1999). Furthermore, if the X-ray-emitting gas has turbulent velocities of a few hundred kilometers per second, then any resonance scattering will be totally suppressed (Gilfanov et al. 1987).

If we use Fe, Si, and O alone to set the relative fractions of SN II and SN Ia products and then use these relative fractions to predict Ni relative abundances, we obtain a very good match to what is observed if the W7 model for SNe Ia is assumed. Therefore, resonant scattering can contribute significantly to the relative enhancement of the Fe Kβ–Ni Kz line complex only if delayed detonations are assumed. Chemically, W7 and WDD models differ in the ejected mass yields of some elements. In particular, WDDs produce more Ni than W7 and, in a smaller degree, more Si. If resonant scattering were the mechanism responsible for the apparent high Ni abundances in the central cluster regions and therefore WDD models were preferred, then we should expect that if we extracted spectrum from a region large enough, such as to be immune to resonant scattering, the observed Ni/Fe abundance ratio would be smaller and necessarily consistent with WDD models. In the previous paragraph we showed that the Ni/Fe ratio measured within the 0'-20' region is not consistent with any WDD model, even when the uncertainties from the power-law component are incorporated. This shows that delayed detonation models are not preferred over the W7 model and strongly suggests that resonant scattering has a much smaller contribution (if any) to the observed Fe abundance measurements than that claimed by Molendi et al. (1998).

The Molendi et al. (1998) determination of the resonant scattering in Perseus was based on spectral fittings of a blend of Fe and Ni lines, assuming the contribution of the Ni Kα line to this blend to be small, therefore requiring a priori a specific SN enrichment type (either SNe II or delayed detonation SNe Ia). One of the goals of our analysis is to determine the very SN type contamination of the ICM. We showed that the delayed detonation SN Ia explosion models are not adequate to explain the observations while the "classical" W7 SN Ia model can explain what we observe without the need to invoke resonant scattering.

6. CONCLUSIONS

In this work we have shown the following:

1. The central region (0'-4') of the Perseus Cluster is significantly enriched with ejecta from SNe Ia, which produce more than half (~67%) of the total iron.
2. The observed Ni/Fe ratio is in excellent agreement with the observed ratios of other elements involving Fe, Si, Ni, and O in predicting the SN Ia Fe mass fraction in the central regions of Perseus. The Ni/Fe ratio observed is ~3.4.
3. The Ni/Fe ratio is consistent with the theoretically predicted values for SN Ia models with fast flame speed (W7) but not with delayed detonation explosion models.
4. The average Si/Fe ratio in Perseus is significantly (>90% confidence) higher than in the central regions, which indicates that the central Fe abundance gradient is accompanied by a chemical gradient, i.e., the SN Ia contamination has a radial decline in Perseus.
5. It is not necessary to invoke resonant scattering in the Fe Kα line since the high Fe Kβ/Fe Kα ratio can be totally attributed to substantial ICM contamination from SN Ia ejecta.

Although the high central Ni abundances can be fully explained by SN Ia enrichment, the current data do not allow a precise quantification of the relative contribution of resonant scattering, which can be done only with very high resolution X-ray spectroscopy. If resonance scattering is important, it will always provide the largest effect at the peak density of the cluster. Therefore, clusters with high resonant scattering optical depth should show, observationally, an Ni abundance profile decreasing with radius (within the resolution of current X-ray spectrometers). Therefore, additional discriminating evidence between the two scenarios can be provided by observation of other clusters that show no central SN Ia ejecta dominance and, at the same time, have large resonant scattering optical depth.

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[7] Actually, the intensity ratio Fe Kα/(Fe Kβ + Ni Kα) for the central regions of 78 clusters (Fig. 1 of Akimoto et al. 1999) can be well described by an optically thin plasma with a central Ni/Fe ratio greater than 2.
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