HOW ABUNDANT IS IRON IN THE CORE OF THE PERSEUS CLUSTER?

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ABSTRACT

The analysis of Perseus data collected with the Medium-Energy Concentrator Spectrometer (MECS) on board BeppoSAX shows that the ratio of the flux of the 8 keV line complex (dominated by Fe Kβ emission) to the 6.8 keV line complex (dominated by Fe Kα emission) is significantly larger than predicted by standard thermal emission codes. Moreover, the analysis of spatially resolved spectra shows that the above ratio decreases with increasing cluster radius. We find that, among the various explanations that we consider, the most likely requires the plasma to be optically thick for resonant scattering at the energy of the Fe Kα line. We argue that if this is the case, then measures of the iron abundance made using standard thermal emission model codes that assume optically thin emission may significantly underestimate the true iron abundance. In the case of the core of Perseus, we estimate the true abundance to be ~0.9 solar in a circular region with a radius of ~60 kpc and centered on NGC 1275. Finally, we speculate that similar results may hold for the core of other rich clusters.

Subject headings: galaxies: abundances — galaxies: clusters: individual (Perseus) — intergalactic medium — scattering — X-rays: galaxies

1. INTRODUCTION

The X-ray emission from clusters is due to a diffuse thermal plasma permeating the intracluster space. The plasma is tenuous (with typical densities of 10⁻⁴–10⁻² cm⁻³), hot (with temperatures in the range 10⁷–10⁸ K), and optically thin at almost all energies. Under these conditions the plasma is so inefficient in radiating its thermal energy that it cools down on timescales comparable to the age of the universe. Thus, it is quite plausible that a large fraction of the emitting gas in clusters is of primordial origin, in the sense that it has never been cycled through stars. Such a possibility is actually corroborated by measurements of the heavy-element abundances, principally iron, in galaxy clusters. Indeed, Fe abundances typically range between 0.3 and 0.4 solar. Estimates of iron abundance are mostly derived from measurements of the equivalent width of the prominent Fe Kα line complex at ~6.8 keV. It can be easily shown (e.g., Sarazin 1988) that, assuming the gas is optically thin, the equivalent width of an emission line is directly proportional to the abundance of the element responsible for the line emission.

However, as pointed out by Gilfanov, Syunyaev, & Churazov (1986, hereafter G86), emission at the Fe Kα line energy may not be always optically thin. Resonant scattering, i.e., the process describing the absorption of an Fe Kα line photon by an iron ion followed by immediate re-emission, can be quite effective for typical cluster gas densities and temperatures. The above authors have shown that the cores of rich clusters, such as Perseus and Virgo, should have optical depths, for the resonant scattering process, on the order of a few. Indeed, if the gas is optically thick to resonant scattering, the line emission coming from the core of the cluster will be attenuated because of the photons that are scattered out of the line of sight. If this is the case, then the abundances measured using standard thermal emission codes that assume optically thin thermal emission may be significantly underestimated.

The attenuation of the line intensity cannot be directly measured using the Fe Kα line only, at least not with current instrumentation. An alternative method to estimate the attenuation from resonant scattering is to measure the Fe Kα line and the Fe Kβ line. Since the Fe Kβ line is expected to have an optical depth smaller than 1, the ratio of the Fe Kβ to Fe Kα equivalent widths can lead to an estimate of the attenuation of the Fe Kα equivalent width and therefore of the real iron abundance. The measurement of the Fe Kβ/Fe Kα line ratio relies critically on the measurement of the weaker of the two lines, i.e., the Fe Kβ line. The Medium-Energy Concentrator Spectrometer (MECS) on board BeppoSAX is the first imaging X-ray experiment to have both sufficiently large effective areas at 8 keV to measure the line and sufficiently good spatial resolution in the 6–9 keV band to perform the measurement in the core of a nearby cluster such as Perseus. In this paper, we present the measurement of the Fe Kβ/Fe Kα line ratio for the Perseus Cluster.

Measurements of the Fe Kβ/Fe Kα line ratio have been performed in the past with various experiments. Mitchell & Mushotzky (1980), using HEAO 1 A-2 data, measured a ratio larger than would have been expected for an optically

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thin single-temperature thermal plasma in the Centaurus Cluster. Okumura et al. (1988), using Tenma data, found anomalous line ratios in the Coma and Ophiuchus Clusters. An observation of Perseus, presented in the same paper, lacked the necessary signal-to-noise ratio (S/N) to derive a significant measure of the Fe Kβ/Fe Kα ratio. Akimoto et al. (1997) have used ASCA data to analyze the Fe Kβ/Fe Kα line ratios for a few nearby clusters, namely, Abell 664, Virgo, Perseus, Abell 496, and Abell 3266. They find that the Fe Kβ/Fe Kα ratios measured from their data are, for all these objects, in excess of what is expected in the case of optically thin thermal emission. Unfortunately, the above authors do not quote errors for their measurements, thus making it difficult to assess the significance of their results. A detailed modeling of the resonant scattering effect, performed through Monte Carlo simulations (Tawara et al. 1997), yields predictions that are, according to Akimoto and coworkers, in disagreement with the measurements they made on the clusters listed above. Again, the lack of errors reported in the measurement of the data makes it difficult to understand how severe the disagreement is.

The outline of this paper is as follows. In § 2, we give some information about the BeppoSAX observation of Perseus and the data preparation; a more complete presentation will be given by Molendi et al. (1998). In § 3, we present the results of the analysis of the Fe Kβ and Fe Kα lines measured in a spectrum extracted from a circular region, with radius 6.4 (corresponding to ~200 kpc), centered on the emission peak. We compare the observed line ratio with that expected from an optically thin plasma and discuss a number of possible explanations for the difference between the two ratios. In § 4, we measure the Fe Kβ/Fe Kα line ratio for five concentric annuli centered on the emission peak. We argue that the observed decrease in the Fe Kβ/Fe Kα line ratio strongly favors the interpretation involving resonant scattering. In § 5, we discuss the implications of the attenuation of the Fe Kα line on the iron abundances in Perseus and similar clusters. In § 6, we summarize the main results of the paper. Throughout the paper we assume a Hubble constant of \( H_0 = 50 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \) and a redshift of \( z = 0.018 \) for NGC 1275. Under the above assumptions, an angular distance of 1 corresponds to 32 kpc. All spectral fits have been performed using XSPEC version 9.01. Quoted confidence intervals are 68% for one interesting parameter (i.e., \( \Delta \chi^2 = 1 \)), unless otherwise stated.

2. OBSERVATION AND DATA PREPARATION

The central region of the Perseus Cluster was observed by the BeppoSAX satellite (Boella et al. 1997a) between 1996 September 20 and 21 during the science verification phase (SVP). The observation was rather long, with a total effective exposure of 89 ks for the MECS (Boella et al. 1997b).

MECS data preparation and linearization were performed using the SAXDAS v.1.0 package under an FTOOLS environment.

3. ANALYSIS OF SPECTRAL LINES

We have accumulated a MECS spectrum from a circular region centered on the emission peak using an extraction radius of 6.4, corresponding to ~200 kpc. We modeled the spectrum in the 3–10 keV band using a bremsstrahlung for the continuum and two Gaussian lines, one for the 6.8 keV iron complex and the other for the 8 keV iron-nickel complex. Data at energies below 3 keV have been excluded because they are significantly contaminated by the cooling flow (e.g., Fabian et al. 1994). We find a temperature of \( 4.9 \pm 0.1 \, \text{keV} \) for the continuum component, an energy \( E_1 = 6.76 \pm 0.01 \, \text{keV} \) and a width \( \sigma_1 = 0.04 \pm 0.04 \, \text{keV} \) for the lower energy line, and an energy \( E_2 = 8.06 \pm 0.04 \, \text{keV} \) and a width \( \sigma_2 = 0.30 \pm 0.05 \, \text{keV} \) for the higher energy line, where both \( E_1 \) and \( E_2 \) are given in the source rest frame. The 8 keV feature is clearly broad and is most likely due to a blend of different lines from highly ionized iron (Fe xxv and Fe xxvi) and nickel (Ni xxvii).

Fits with thermal emission codes such as MEKA, MEKAL, or Raymond-Smith do not reproduce satisfactorily the 8 keV feature. All of these models significantly underestimate the intensity of the emission feature. In Figure 1 we present a fit of the MECS spectrum with a MEKAL model; the top panel shows the data and the folded model, and the bottom panel shows the residuals in the form of a ratio of the data over the model. A broad excess centered around 8 keV is clearly visible in the bottom panel. To better understand this discrepancy, we simulated thermal spectra at different temperatures using the MEKAL, MEKA, and Raymond-Smith codes and the MECS response matrix. We have then fitted the simulated data with a bremsstrahlung component for the continuum and two Gaussian lines, one for the 6.8 keV complex and the other for the 8 keV complex. Finally, we computed the ratio of the flux in the 8 keV complex to the flux in the 6.8 keV complex. This ratio varies between 0.11 and 0.13 for temperatures in the range 4–8 keV. The ratio obtained from the real data, which is computed using the same spectral model applied to the simulated data (i.e., bremsstrahlung component for the continuum and two Gaussian lines), is 0.20 ± 0.02.

Since the MECS mirrors are made of gold-coated nickel and nickel fluorescence Kα lines are found at ~8 keV, we have performed a number of checks to verify that the emission feature we see at 8 keV is not contaminated by a contribution of instrumental nature. We verified that the spectra of extremely bright galactic sources such as Cyg X-1 and Crab show no evidence of such a feature. We also verified

![Fig. 1.—MECS spectrum of the core of the Perseus Cluster. Data are extracted from a circular region with a radius of 6.4, corresponding to ~200 kpc. The top panel shows the data and the best-fitting MEKAL model. The bottom panel shows the residuals in the form of a ratio of the data to the model.](image-url)
that the spectrum of the instrumental background, which in any case has an intensity ≤ 1% of the source at 8 keV, does not show any such feature. Finally, in order to rule out possible Ni fluorescence from the backside of the mirrors, we analyzed the spectrum of the galactic source GX 5−1 observed at an off-axis angle of 40°. In such an observational configuration, the fraction of photons that after having scattered once on the gold-coated side of the mirror, scatter a second time on the back side (made of nickel), and produce Ni fluorescence photons, is maximized. Even for this extreme case we find no evidence of an emission feature at ~8 keV in the observed spectrum. For all these reasons we conclude that the 8 keV feature is not contaminated by instrumental contributions.

We performed an independent measurement of the 8 keV/6.8 keV line flux ratio using data collected on 1993 August 6 with the GIS detectors on board the *ASCA* satellite. We accumulated GIS2 and GIS3 spectra from a circular region with the same radius (i.e., used for the MECS data). By fitting the two spectra simultaneously in the energy range 3.5−10 keV, with a bremsstrahlung component for the continuum and two Gaussian lines, we find a line flux ratio of 0.19 ± 0.03. We note that the GIS measurement is in agreement with the MECS measurement. We also note that the difference between the ratio measured with the MECS and the expected one is statistically more significant than the difference between the ratio measured with the GIS and the expected one. The main reason for this is that the MECS observation (89 ks) is considerably longer than the GIS observation (17 ks).

There are a number of possible explanations for the discrepancy between the observed line flux ratio and the expected one. One possibility is that nickel is substantially overabundant with respect to iron. If we fit the MECS spectrum in the energy range 3−10 keV with a thermal emission model (MEKAL) that requires that the Ni abundance be the same as the Fe abundance, we find a best-fitting value of 0.42 ± 0.01 solar. If we fit the spectrum using a thermal model with free nickel abundances (VMEKAL), we find a significant improvement in the fit (>99% significance with an F-test) and a best-fitting value of the nickel abundances of 0.88 ± 0.22 in 0.05 solar; the iron abundances remain unvaried.

However, there are two points that make this interpretation difficult to support. First, the extreme Ni abundance is hard to reconcile with the Fe abundances of ~0.4 solar (see Arnett 1995). Second, although the inclusion of the line does improve the fit significantly, visual inspection of the residuals shows that the data are still in excess with respect to the model around 8.4 keV, where the dominant contribution to the emission complex is expected to come from Fe XXV and Fe XXVI.

Another possibility is that the gas responsible for the emission of the Fe 6.7−6.9 keV complex is not the same gas responsible for the emission of the 8 keV complex. Indeed, since the emission around 6.8 keV is produced, on average, by iron that is less ionized than that responsible for the emission at 8 keV, a particularly intense 8 keV component could be explained by the presence of a hot thermal component. Such a component would be characterized by an 8 keV/6.8 keV line flux ratio substantially larger than that expected from a component with a temperature of ~5 keV. We have tested this possibility by comparing the ratio of the flux in the 8 keV complex with the flux in the 6.8 keV complex, expected from thermal emission codes such as MEKA, MEKAL, and Raymond-Smith, with the observed ratio. The line ratios expected from the thermal emission codes have been computed by performing fits on simulated spectra as already detailed in this section. We find that even for extremely high temperatures (i.e., ~14 keV) all codes predict ratios smaller than 0.14, while the observed ratio is 0.20 ± 0.02. This result forces us to reject the two-temperature interpretation. Indeed, if line emission resulted from a mixture of gas at different temperatures, a significant fraction of the gas would have to be at extremely high temperatures and produce continuum emission, which is not observed.

Another line of interpretation involves the ionization equilibrium of the gas. Emission codes assume that the gas is in collisional ionization equilibrium, with both ions and electron populations following a Maxwell-Boltzmann distribution; this may not be completely true in the central region of Perseus. Indeed, NGC 1275 is known to harbor an AGN that is extremely active at radio wavelengths (Nesterov, Lyuty, & Valatoja 1995). Moreover, Böhringer al. (1993), by comparing radio and X-ray high-resolution images, have found convincing evidence of interaction between the relativistic particles in the radio lobes of NGC 1275 and the intracluster plasma. One piece of evidence that argues against this possible interpretation comes from the analysis of other clusters: Abell 644, Virgo, Abell 496, and Abell 3266 (Akimoto al. 1997) all show 8 keV/6.8 keV line flux ratios in excess of the expected value. Thus, an interpretation based on the unique characteristics of the central object in Perseus does not appear to be very attractive.

Another possibility is that the gas is indeed in thermal ionization equilibrium but the emission codes are wrong. Evidence of discrepancies between the observed ratio of Fe XXVI/Fe XXV with respect to the expected one has been found in solar flares (Tanaka 1986). However, as mentioned by Arnaud & Raymond (1992), one cannot exclude that the X-ray–emitting gas in solar flares is not in collisional equilibrium.

The last mechanism that we consider in order to explain the observed anomalous ratio is the photon redistribution due to resonant scattering. As pointed out by G86, the intergalactic medium in clusters, while optically thin to the continuum and many lines, may be optically thick in the center of some lines. Let us consider first the 6.8 keV complex. It is dominated by H- and especially He-like recombination lines. At these temperatures the strongest line in the complex is the 6.7 keV H-He-like resonant line, which accounts for more than 50% of the total emission. Its central optical thickness along the whole cluster is, for Perseus, about 1.5−2, assuming, for simplicity, constant temperature ($kT \sim 6$ keV) and abundances (~0.5 solar) and a $\beta = \frac{3}{2}$ model for the density, with a central density of $5 \times 10^{-3}$ cm$^{-3}$; see G86 and Sarazin (1988) for the relevant formulae. (Note that this is likely to be an underestimate because of the neglect of the cooling flow.) The two most

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9 Akimoto al. (1997), who have investigated the 8.0 keV/6.8 keV line ratio in Perseus using *ASCA* GIS data, present a further argument against the Ni overabundance. They remark that the Ni abundance required to explain the excess 8.0 keV emission is not consistent with the Ni abundance estimated from the L-shell Ni emission that they measure at ~1 keV. The MECS data imply an Ni overabundance that is considerably smaller than that estimated by Akimoto al. (1997) and is not inconsistent with the Ni abundance estimated by Akimoto et al. (1997) from the L-shell emission.
important H-like lines localized at 6.97 keV, which are both resonant, as well as the intercombination 6.67 keV He-like line, accounting all together for most of the remaining emission of the complex, have central thicknesses an order of magnitude lower. The 6.65 keV He-like forbidden line has a negligible depth, but it accounts for no more than 15% or so of the total emission. On the other hand, the 8 keV complex is dominated by the Ni He-like Kα lines, 7.8 keV, and the Fe He-like Kβ lines, 7.9 and 8.2 keV, which have optical depths about 20 and 7 times, respectively, smaller than the 6.7 keV He-like line. It is therefore clear that optical-depth effects are considerably more relevant for the 6.8 keV complex than for the 8 keV one.

After the absorption, all photons are reemitted; for these ions, Auger deexcitation cannot work. The process is then purely diffusive (resonant scattering) and has the effect of redistributing the line photons over the cluster. Assuming spherical symmetry, the effect is to decrease the observed line emissivity in the central region, where the line-of-sight column density is greater and is balanced by an excess emissivity in the outer regions. Since this redistribution effect is greater for larger optical depths, we expect a gradient in the ratio of the two line complexes. We have therefore performed a spatially resolved analysis, which is described in the next section.

4. SPATIALLY RESOLVED SPECTRAL ANALYSIS

We have accumulated spectra from five concentric annuli centered on the emission peak and with bounding radii of 0′′-2′′, 2′′-4′′, 4′′-6′′, 6′′-8′′, and 8′′-10′′, respectively. We have fitted each spectrum in the 3.5–9.5 keV range. We have modeled the spectra with a bremsstrahlung component for the continuum and two Gaussian lines, one for the 6.8 keV complex and the other for the 8 keV complex. The ratio of the flux in the lines varies with the radius (see Fig. 2); a $\chi^2$ test rejects a constant line ratio at the 98% confidence level.

The solid line in Figure 2 is the ratio expected in the case of optically thin thermal emission for temperatures of $\sim$ 5 keV. The dotted line represents the expected ratio when the 8 keV line complex flux in excess of what is expected from an optically thin thermal plasma is distributed as if it came from a point source coincident with the X-ray emission peak.

![Fig. 2.—Ratio of the 8 keV line complex flux to the 6.8 keV line complex flux vs. apparent cluster radius. The solid line represents the expected ratio for an optically thin plasma at a temperature of 5 keV. The dotted line represents the expected ratio when the entire 8 keV line complex flux extends of what is expected from an optically thin thermal plasma is distributed as if it came from a point source coincident with the X-ray emission peak.](image)

Akimoto et al. (1997) have performed a similar analysis of the line ratio in Perseus using ASCA GIS data. They find a radial gradient that appears to be different from ours. It is rather difficult to make a more detailed comparison, mainly because in their Figure 1, the radii are reported in units of the core radius, but the value of the core radius is not given, and errors are not shown, so we cannot assess how significant the difference actually is. The same authors present a radial profile of the expected line ratio based on numerical simulations that include the effects of resonant scattering. This profile appears to be in disagreement with our measurements as well as theirs. Even though the authors do not give many details on the parameters chosen for the simulation, from the line ratio predicted in the case of optically thin emission, also shown in their Figure 1, it would seem that they assume a strong temperature gradient within the core of Perseus, possibly to mimic the cooling flow. An analysis of the MECS data shows that, excluding energies below 3 keV, where the cooling flow is prominent, the radial temperature gradient in the innermost 200 kpc is rather modest, $\Delta T \sim 1.5$ keV. If this is indeed the case, then the decrement in the Fe Kα line complex intensity may be considerably larger than that estimated through simulations by Akimoto et al. (1997).

We note that explanations of the anomalous line flux ratio involving the ionization equilibrium cannot easily explain the results of the spatially resolved analysis. Indeed, if the ionization equilibrium is not thermal because of the active nucleus in NGC 1275, we would expect the ratio to be anomalous only in the innermost spatial bin (the radio lobes extend out to less than 1′ from the nucleus). The data show that this is not the case. Moreover, if the anomalous ratio is the result of an error in the thermal emission codes then, of course, the ratio should be the same throughout the cluster.

The interpretation in terms of photon redistribution by resonant scattering appears to be the only viable one among those considered. It is rather difficult to check it quantitatively, since one should consider in detail the abundance and temperature gradients as well as deviations from a simple King profile for the density due to the cooling flow. The treatment of this problem in real cluster conditions then requires a detailed radiative transfer solution and is deferred to future works. We here limit ourselves to noting that, according to the G86 calculations, the observed factor-of-2 relative depletion of the 6.8 keV complex in the cluster center is consistent with the order-of-magnitude difference in the optical depth of the two complexes.

5. ABUNDANCES

From the analysis of the spatially integrated and resolved spectra of the core of Perseus, we have found that resonant scattering provides the only acceptable explanation for the anomalous line flux ratio. In this section, we discuss the implications of this result.

If we accept that emission from the core of Perseus is optically thick at the Fe Kα line, then the common assumption that the equivalent width of the line can be used to directly measure the abundance of iron breaks down. As already noted by G86, iron-abundance measures derived by
fitting spectra with standard thermal emission codes, which assume emission to be optically thin at all wavelengths, will significantly underestimate the true abundance.

We have computed an “apparent” abundance radial profile by fitting the spectra from four concentric annuli with bounding radii of $0'-2'$, $2'-4'$, $4'-6'$, and $6'-8'$, with a MEKAL model in the energy range $3.5-7.7$ keV (energies larger than $7.7$ keV have been excluded to avoid fitting the 8 keV complex). We find that the measured Fe abundance is largest at the center, with a value of $0.48 \pm 0.01$ solar, and decreases with increasing radius, reaching a value of $0.29 \pm 0.01$ solar at $6'-8'$ ($\sim 220$ kpc) from the cluster center (see Fig. 3).

Assuming, for simplicity, that the lines contributing to the 8 keV blend are totally unaffected by resonant scattering, an estimate of the real iron-abundance profile can be obtained in two different ways: by dividing the values of the “apparent” abundances obtained through spectral fitting with the MEKAL model by the ratio between the observed line flux ratio and the line flux ratio expected for optically thin emission; or by measuring the abundances directly with the Fe K$\alpha$ line, which can be done by refitting the observed spectra with the MEKAL model, having first excluded the region of the spectrum, 6–7.5 keV, where the K$\alpha$ line contributes significantly to the total emission. Abundances estimated in either of these two fashions should be regarded as lower limits. Indeed, if some of the lines contributing to the 8 keV blend are attenuated by resonant scattering, the real abundances will be even larger than the ones we compute. The two methods yield values of the abundances that are always in agreement, although the abundances obtained by fitting the K$\beta$ line are somewhat smaller than those obtained by correcting the “apparent” abundances (see Fig. 3). The reason for this difference is likely due to the difficulty of excluding completely the contributions of the Fe K$\alpha$ line to the observed spectrum when computing the abundances with the Fe K$\beta$ line. Both methods yield an abundance profile characterized by a gradient that is considerably larger than the one observed in the “apparent” abundance profile. The Fe abundance in the innermost circular region, with a radius of $2'$, corresponding to $\sim 30$ kpc, is $\sim 0.9$ solar and consistent with 1. The obvious implication is that a very large fraction of the gas in the core of Perseus has been processed in stars. It is interesting to note that the abundance gradient extends out to $\sim 200$ kpc from NGC 1275. This scale length is comparable to the one characterizing the cooling flow observed in the core of Perseus (e.g., Fabian et al. 1981). The association of these two phenomena, i.e., the abundance gradient and the cooling flow, may not be casual. One could speculate that an iron-rich gas outflow from NGC 1275 may have increased the gas density in the core of Perseus and, consequently, have triggered the cooling flow.

We do not expect iron line emission from the AGN in NGC 1275 to alter in a significant way our estimate of the abundance in the innermost radial bin. Observations in the hard X-ray band with the PDS instrument on board BeppoSAX (Molendi et al. 1998) indicate that the AGN should contribute less than 10% to the continuum emission in the 6–9 keV band. Moreover, eventual contributions to the Fe K$\beta$ line complex at 8 keV, which we have used to estimate the iron abundance, should be negligible since iron line emission in AGNs is observed in the 6–7 keV band and practically never around 8 keV.

The values of the gas density and temperature in the core of the Perseus Cluster imply an optically thick Fe K$\alpha$ line (see G86). Similar values of the gas density and temperature are measured in the core of many rich clusters; thus, resonant scattering is likely to operate in many objects. The high Fe K$\beta$/Fe K$\alpha$ flux ratio measured in the core of Abell 644, Virgo, Abell 496, and Abell 3266 (Akimoto et al. 1997) clearly supports this possibility. If resonant scattering operates effectively in the core of many clusters, then iron may be considerably more abundant in these objects than we have so far believed.

6. SUMMARY

The analysis of the MECS spectrum of the central region of Perseus has shown that the ratio of the flux in the 8.0 keV line complex to the flux in the 6.8 keV line complex is about a factor of 2 larger than expected for an optically thin thermal plasma. Moreover, this ratio presents a radial gradient in the sense that it decreases with increasing cluster radius. We have considered various possible explanations for the behavior of the ratio of the flux of the 8 keV line complex to the 6.8 keV line complex: (1) instrumental effects, (2) a high nickel abundance, (3) a second hot thermal component, (4) nonthermal ionization equilibrium, (5) errors in the computation of the collisional ionization equilibrium, and (6) resonant scattering of the Fe K$\alpha$ line. We have argued that resonant scattering is, by far, the most likely explanation for the observed line ratio behavior.

We have discussed the implications of an optically thick Fe K$\alpha$ line. We have found the Fe abundances in the core of Perseus to be significantly larger than previously believed, with the true abundances being extremely high ($> 0.9$ solar in a circular region with a radius of $\sim 60$ kpc centered on the emission peak). We have argued that similar underestimations of the Fe abundance may have also occurred for other rich clusters.

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