VELOCITY GRADIENTS IN THE INTRACLUSTER GAS OF THE PERSEUS CLUSTER

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ABSTRACT

We report the results of spatially resolved X-ray spectroscopy of eight different ASCA pointings distributed symmetrically around the center of the Perseus Cluster. The outer region of the intracluster gas is roughly isothermal, with temperature ~6–7 keV and metal abundance ~0.3 solar. Spectral analysis of the central pointing is consistent with the presence of a cooling flow and a central metal abundance gradient. A significant velocity gradient is found along an axis at a position angle of ~135°, which is ~45° discrepant with the major axis of the X-ray elongation. The radial velocity difference is found to be greater than 1000 km s\(^{-1}\) Mpc\(^{-1}\) at the 90% confidence level. Simultaneous fittings of GIS 2 and 3 indicate that the velocity gradient is significant at the 95% confidence level, and the F-test rules out constant velocities at the 99% level. Intrinsic short- and long-term variations of gain are unlikely (P < 0.03) to explain the velocity discrepancies.

Subject headings: cooling flows — galaxies: clusters: individual (Abell 426) — intergalactic medium — X-rays: galaxies

On-line material: color figure

1. INTRODUCTION

X-ray determination of the physical state of the intracluster gas provides a unique tool to probe the origin and evolution of clusters of galaxies. ASCA observations have shown significant spatial-temperature variations in many clusters, indicating that clusters are currently evolving systems. This is consistent with the predictions of hierarchical cluster formation within cold dark matter (CDM) models and had been suggested in pre-ASCA times (e.g., Fitchett 1988; Ulmer, Wirth, & Kowalski 1992, and references therein).

Although early models of galaxy clusters treated them as spherically symmetric virialized systems, recent X-ray and optical studies indicate that often clusters show substructures. Furthermore, if CDM models are correct, primordial small-scale density fluctuations are not erased, and clusters are formed by infall/merging of smaller scale objects (bottom-up hierarchical scenario). The merger (infall) of subclumps creates shocks (associated with temperature substructure), bulk gas flows (associated with velocity substructure), and asymmetric velocity distributions of galaxies (e.g., Bird 1993). In order to understand the physical properties of clusters, their origin, and their evolution one has to take into account the degree and the physical scale of substructuring. Furthermore, the degree of substructuring itself can be used to determine/constrain cosmological parameters (Crone, Evrard, & Richstone 1996).

Measurements of substructure using spatially resolved X-ray spectra have some advantages over optical analysis of galaxies in clusters. First, one does not need a large number of galaxies’ redshifts in a cluster. Second, the velocity mapping of the intracluster medium (ICM) is not biased by the inclusion of foreground/background galaxies (outliers), which may bias the statistical analysis for measuring substructures (e.g., Fitchett 1988; Bird 1993). The determination of complex temperature substructure in clusters is often interpreted to be related to shocks due to cluster mergers at different stages. The link between temperature substructure and the merger stage is often done by comparison with hydrodynamical simulations. There are currently an enormous variety (different initial conditions, hydrocodes, impact parameters, matter components, etc.) of cluster formation/merger simulations in the literature (e.g., Evrard 1990; Katz & White 1993; Roettiger, Burns, & Loken 1993, 1996; Schindler & Muller 1993; Pearce, Thomas, & Couchman 1994; Navarro, Frenk, & White 1995; Evrard, Metzler, & Navarro 1996; Roettiger, Loken, & Burns 1997; Ricker 1998; Takizawa & Mineshige 1998; Takizawa 1999, 2000, and references therein), which can be used to compare to the observations.

A more straightforward way to determine the effects of a merger is to directly measure intracluster gas bulk velocities. Several simulations of cluster mergers indicate residual gas velocities of a few thousand km s\(^{-1}\) (e.g., Roettiger et al. 1993; Ricker 1998; Takizawa 1999; Roettiger & Flores 2000). To measure gas velocities one requires accurate determinations of spectral line centroids. The precision with which a line centroid can be measured, in velocity space, is \(\sim 127 \Gamma \nu(N_{\text{e,keV}})^{-1}\) km s\(^{-1}\), where \(N\) is the number of photons in the line, \(\Gamma\) is the FWHM of the line or, if the line is narrower than the instrumental width, is the FWHM of the instrument, and \(E_{\text{keV}}\) is the line energy. The energy resolution of the spectrometers on board ASCA vary from 2% [solid-state imaging spectrometer (SIS)] to 8% [gas imaging spectrometer (GIS)] at 5.9 keV. For an FWHM of 9000 km s\(^{-1}\) at 6.7 keV, which is typical of early (first 3 yr) SIS data at the Fe K\(\alpha\) line, to obtain a line centroid to a precision of 500 km s\(^{-1}\), we need ~60 line photons. This same accuracy can be obtained with the GIS with ~350 line photons. Although several clusters observed by ASCA match this requirement when observing regions within the detector field of view, the flux in the outer regions of the detector are dominated by photons coming from central regions due to the extended ASCA point-spread function, and if there are strong radial velocity gradients, the latter effect would make redshift determinations imprecise. Therefore, ideally one would like to analyze high metal abundance clusters that have several different long-exposure observations from off-center regions surrounding the cluster’s X-ray center. Some nearby clusters match this cri-
teria and therefore are well suited for the study of gas velocity distribution. Perseus is an ideal target for this analysis since it is a nearby, very bright cluster. Furthermore, it has been observed extensively by ASCA with a large number of offset pointings, covering a more or less symmetrical region around the cluster's center up to distances of greater than 1 h_50 Mpc.

In this work we analyze the spectra of eight separate pointings encompassing a region of greater than 40' radius around the center of the Perseus Cluster. We find that although the cluster is roughly isothermal (aside from the cooling flow), there is a significant velocity gradient along a direction that has an inclination ~45° with respect to the cluster's X-ray major axis. This velocity gradient is consistent with a rotation velocity of ~1000 km s^{-1} at the 90% confidence level and is unlikely to be caused by gain variations or background sources.

2. THE PERSEUS CLUSTER

The Perseus Cluster has been the subject of many studies since its discovery as an X-ray source by Fritz et al. (1971). It is one of the closest (at an optical redshift of 0.0183), X-ray bright, rich clusters of galaxies. 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). It has a cooling flow with a mass deposition rate of about (3–5) \times 10^2 M_\odot yr^{-1} (Allen et al. 1992; Ettori, Fabian, & White 1998; Peres et al. 1998). The centroid of the cluster emission is offset by ~2' to the east of NGC 1275 (Branduardi-Raymond et al. 1981; Snyder et al. 1990). 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).

The existence of an iron-abundance gradient in Perseus was first suggested by Ulmer et al. (1987) using data from SPARTAN 1. They found an iron abundance of ~0.81 solar and a temperature of ~4.16 keV within the central 5' and an abundance of ~0.41 solar and a temperature of ~7.1 keV in the outer regions (6'–20'). Further analyses have corroborated the existence of an abundance gradient (e.g., Ponman et al. 1990; Kowalski et al. 1993; Arnaud et al. 1994; Dupke & Arnaud 2001). Furthermore, the region where the abundance is enhanced is predominantly enriched by SN Ia ejecta (Dupke & Arnaud 2001, indicating that the cluster belongs to the class of clusters that present central "chemical gradients," such as A496 (Dupke & White 2000). The presence of cooling flows, global abundance, and chemical gradients suggests that the cluster has not undergone strong head-on mergers recently.

3. DATA REDUCTION AND ANALYSIS

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 arcmin^2 field of view and a usable energy range of 0.5–10 keV. The nominal energy resolution of the spectrometers are 8% and 2% at 5.9 keV for the GISs and SISs, respectively. The SIS energy resolution is steadily degrading with time and for most pointings in this work is ~4% at 5.9 keV. Eight individual pointings were analyzed in this work. The central pointing is the only one that includes the contaminating source (the center of the Perseus Cluster). The other seven pointings are distributed more or less symmetrically around the central pointing with an average distance of ~40' from the center. Five of the pointings (the most recent ones) were observed consecutively in 1997 and are spaced in time typically by a day. The pointing characteristics are listed in Table 1 and shown in Figure 1.

We selected data taken with high and medium bit rates, with cosmic-ray rigidity values \geq 6 GeV c^{-1}, and with elevation angles from the bright Earth of \geq 20° and from the Earth's limb of \geq 5° (GIS); 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. The resulting effective exposure times are also shown in Table 1. We estimated the background from blank sky files provided by the ASCA Guest Observer Facility and removed bright-point sources for each instrument in all pointings.

The SISs have a better spectral resolution (by a factor of 2–4) than the GISs. However, the analysis of SIS data for our pointings is severely limited by photon statistics (the GIS overall count rate is typically more than 10 times that of the SISs), making the SIS redshift determination very uncertain. This difference in count rate between the GISs and SISs is due to the following reasons: (1) most of the pointings analyzed in this work were observed by the SIS in 2 CCD mode, which minimizes the energy-resolution degradation due to the residual dark-current distribution and nonuniform charge-transfer inefficiency effects; (2) there have been increasing discrepancies between SIS and GIS spectra below 1 keV since 1994 because of a decrease in X-ray efficiency in the SISs, thus making the low end (<0.9 keV) problematic.

See the HEASARC Web Site at http://heasarc.gsfc.nasa.gov/docs/asca/newsletters/sis_calibration5.html.

3 See the HEASARC Web Site at http://heasarc.gsfc.nasa.gov/docs/asca/newsletters/sis_calibration5.html.

Fig. 1.—Distribution of the spatial regions for different pointings analyzed in this work. PSPC surface brightness contours of Perseus are overlaid on the central pointing (P0). The radius of each circular region is 20'.
keV) of the spectral region unusable for the SISs; and (3) the X-ray center of Perseus is not in the detector’s field of view for all outer pointings analyzed, and therefore most of the photons come from a specific direction (toward the cluster’s center). Furthermore, the GIs have a higher effective area at high energies. Therefore, we use only GIS 2 and 3 in this analysis.

In the spectral fittings we used XSPEC Version 10.0 (Arnaud 1996) software to analyze the GIS spectra separately and jointly (simultaneous fittings of data from GIS 2 and 3). The spectra were fitted using the MEKAL thermal emission models, which are based on the emissivity calculations of Mewe & Kaastra (Mewe, Gronenschild, & van den Oord 1985; Mewe, Lemen, & van den Oord 1986; Kaastra 1992), with Fe L calculations by Liedahl, Osterheld, & Goldstein (1995). Abundances are measured relative to the solar photospheric values of Anders & Grevesse (1989), in which Fe/H fixed at the corresponding Galactic value.

We extracted spectra from a circular region with a radius of 20' for each pointing, centered at the detector’s center. The best-fit values for temperature, abundance, and redshift obtained from spectral fittings of GIS2 and GIS3 separately are consistent with those obtained through the spectral fittings of both GIS 2 and 3 jointly. Therefore, we show here only the best-fit parameters of the simultaneous fittings. The resulting joint fits were very good with reduced $\chi^2 \sim 1$ for all regions.

4. RESULTS

4.1. Spectral Fittings

The best-fit values for temperature, abundance, and redshift are shown in Table 2 and plotted in Figure 2 as a function of the azimuthal angle. Here, we define the azimuthal angle with respect to the line that joins the centers of pointings P1 (northwest) and P5 (southeast), for convenience. For P1 (northwest) the azimuthal angle is set to

| Pointing | Temperature (keV) | Temperature$^b$ (keV) | Abundance (solar) | Redshift ($10^{-2}$) | $\chi^2$ |
|----------|------------------|----------------------|-------------------|----------------------|--------|
| P1 (NW) .. | 7.28$^{+0.44}_{-0.53}$ | 5.41$^{+0.22}_{-0.15}$ | 0.32$^{+0.07}_{-0.07}$ | 1.45$^{+0.40}_{-0.31}$ | 1.054 |
| P2 (N) ... | 6.96$^{+0.52}_{-0.48}$ | 5.19$^{+0.21}_{-0.19}$ | 0.23$^{+0.08}_{-0.08}$ | 1.81$^{+1.20}_{-1.06}$ | 1.097 |
| P3 (NE) ... | 6.58$^{+0.49}_{-0.48}$ | 4.99$^{+0.22}_{-0.19}$ | 0.34$^{+0.07}_{-0.08}$ | 1.71$^{+1.23}_{-0.87}$ | 1.115 |
| P4 (E) .. | 6.89$^{+0.51}_{-0.44}$ | 5.46$^{+0.15}_{-0.13}$ | 0.38$^{+0.06}_{-0.06}$ | 2.64$^{+0.46}_{-0.76}$ | 0.988 |
| P5 (SE) .. | 7.24$^{+0.56}_{-0.48}$ | 5.78$^{+0.27}_{-0.23}$ | 0.32$^{+0.07}_{-0.07}$ | 4.19$^{+0.33}_{-0.67}$ | 1.006 |
| P6 (S-SW) .. | 6.65$^{+0.39}_{-0.35}$ | 5.47$^{+0.16}_{-0.12}$ | 0.40$^{+0.06}_{-0.05}$ | 2.19$^{+0.63}_{-0.62}$ | 1.221 |
| P7 (W) .. | 7.63$^{+0.28}_{-0.25}$ | 5.98$^{+0.22}_{-0.18}$ | 0.32$^{+0.06}_{-0.05}$ | 2.16$^{+0.76}_{-0.76}$ | 1.074 |
| P0 (Center) .. | 5.76$^{+0.11}_{-0.11}$ | 4.89$^{+0.05}_{-0.05}$ | 0.42$^{+0.03}_{-0.03}$ | 2.50$^{+0.45}_{-0.45}$ | 1.067 |

* Errors are 90% confidence level.

* $N_H$ fixed at the corresponding Galactic value.
increased if the best-fit $N_H$ values are low. To test this effect, we fixed $N_H$ at its putative Galactic value in the direction of each pointing ($N_H \sim 1.6 \times 10^{21}$ cm$^{-2}$; Dickey & Lockman 1990; HEASARC $N_H$ Software). The best-fitting temperatures obtained this way have significantly worse $\chi^2$ and are also plotted in Figure 2 (open circles). The best-fit temperatures obtained when $N_H$ is fixed are lower than those obtained with free $N_H$ by $\sim 1.5$ keV. Although the azimuthal distribution of temperatures is consistent with isothermality, some pointings show mild, but significant, azimuthal variations [e.g., P7 (west), for which the temperature is significantly (>90% confidence) higher than P6 (south-southwest) and P3 (northeast) by about 1 keV].

The abundances observed in the outer parts of Perseus are generally lower than in the central region, which is consistent with observations by other authors (Ulmer et al. 1987; Ponman et al. 1990; Kowalski et al. 1993; Arnaud et al. 1994; Dupke & Arnaud 2001). The abundance measured in the central pointing is 0.43 $\pm$ 0.02 solar and in the outer parts has an average value of $\sim 0.33$ solar. There is marginal evidence of azimuthal-abundance variations. In particular, the P6 (south-southwest) best-fit abundance is higher than that measured for P2 (north) and is also consistent with the abundance measured in the central region. The best-fit abundances for each pointing are also displayed in Figure 2, where the solid lines represent the 1 $\sigma$ confidence limits for the abundance in the central pointing. The dash-dotted lines show the 90% limits for the abundance measured within a 4' region of the center of Perseus for comparison (Dupke & Arnaud 2001).

The most important azimuthal distribution is that of redshifts. Two pointings show significant (>90% confidence level) discrepant redshifts with respect to the best-fit redshift observed in the central pointing. These two redshift-discrepant pointings, P1 (northwest) and P5 (southeast), are on opposite sides of the cluster’s center. P1 (northwest) shows a best-fit redshift of 0.014 (0.003–0.0185), and P5 (southeast) shows a significantly higher (95% confidence level) redshift value of 0.042 (0.025–0.045). This redshift discrepancy is observed in both GIS 2 and GIS 3 individually, although with lower statistical significance. These differences in redshifts imply a velocity difference of 8200 (2000–12,700) km s$^{-1}$ between these two pointings. The azimuthal distribution of redshifts is shown in Figure 2, and the best-fit values are listed in Table 2. In the fittings where the column density is fixed at the Galactic value the best-fit redshifts are typically lower than those obtained with $N_H$ free. However, the inferred differences between redshifts for different pointings are virtually unaltered. Therefore, the redshift discrepancies are not due to spectral fitting uncertainties related to the GIS sensitivity to hydrogen column densities.

The two redshift-discrepant pointings show no differences in the best-fit values of temperatures or abundances. To test further the significance of the velocity difference between P1 and P5, we simultaneously fitted all four spectra (GIS 2 and 3 for each of the two pointings) and applied the $F$-test in the analysis of $\chi^2$ variations due to the change in the number of degrees of freedom. We compare the $\chi^2$ of fits that assumed the redshifts were the same in the two projected spatial regions ($\chi^2_{2P1} = \chi^2_{2P2} = \chi^2_{3P5} = \chi^2_{3P3}$) to that of fits that allowed the redshifts in the two pointings to vary independently. Within the same pointing the redshifts were still locked together for different instruments, i.e.,
\((z_{G2P1} = z_{G3P1}) \neq (z_{G2P5} = z_{G3P5})\), where \(z_{GiPj}\) is the redshift of pointing \(j\) with instrument GIS \(i\). The difference between the \(\chi^2\) of these two fits must follow a \(\chi^2\) distribution with 1 degree of freedom (Bevington 1969, p. 200). The difference in \(\chi^2\) from the fits with locked and unlocked redshifts indicates that the redshifts are discrepant at the 99% level. We show in Figure 3 the 68%, 90%, and 99% confidence contours for two interesting parameters (redshifts) of regions P1 and P5 as well as the line correspondent to equal redshifts. The spectral fits within the energy range encompassing the Fe K line complex are shown in Figures 4a and 4b. We also show in Figures 4a and 4b the residuals from the same model fits but with zero metal abundances for illustration.

The inclusion of the power-law component in the spectral fits (representing any nonthermal emission from NGC 1275) in addition to the cooling-flow component in the central region (P0) does not change significantly the best-fit values of the redshifts obtained without the power-law component. However, it does makes the best-fit redshift values less precise. Since the F-test shows that there is a significant improvement in the spectral fits when the power-law component is included, we conservatively quote in Table 2 and Figure 2 the values of the best-fit redshift for spectral fits that included an extra power-law component.

### 4.2. GIS Gain Variations

We have shown in § 4.1 that the azimuthal distribution of velocities in the Perseus Cluster shows significantly (≥90% confidence) different redshifts for three pointings: the central pointing (P0) and two other diametrically opposed pointings (P1 and P5). However, since the determination of redshifts relies on accurate measurement of line centroids (mainly the Fe K line around 6.7 keV), large variations of gain (conversion between photon energy and pulse height) can mimic, in principle, the observed effect. In this section...
we estimate the effects of gain variations in our observations.

The original gain calibration of the GISs was mainly based on the built-in $^{55}$Fe source, attached to the edge of the field of view. The gain depends on the temperature of the phototube ($\sim 1\% \cdot ^\circ C^{-1}$), the position on the detector, and time of observation. During the first several months in orbit the gain decreased by a few percent, and this trend has slowly disappeared. This gain decrease is possibly due to cosmic-ray–induced crystalline defects, decreasing the UV transmission of the quartz windows of the gas cell (Tashiro et al. 1995).

The intrinsic GIS gain is not only dependent on temperature but also on position (on the detector) due to non-uniformity in the phototube gain. Therefore, the gain-correction process involves a look-up table called the “gain map” (Tashiro et al. 1995, and references therein), which is also dependent on time and has been recalibrated using spectral lines observed during long “Day Earth” and “Night Earth” observations. This allows for more precise measurement of the azimuthal variation of gain across the detector, which is typically smaller than the radial gain variations.

The four gain corrections (short- and long-term gain variation, gain positional dependence, and long-term variation of the positional dependence) were carried out at GSFC in the standard processing (K. Ebisawa 2000, private communication). The Perseus observations analyzed in this work do have the standard gain corrections applied with the FTOOL ASCALIN Version 0.9t, which reads the gain-correction coefficients at the time of observation from the gain history file. The gain-correction coefficients were created by the FTOOL TEMP2GAIN Version 4.2, which reads the variation of the temperature housekeeping parameters and registers the gain values for every 600 s of observation taking into account the long-term and positional gain variations.

Since there are still observed small redshift fluctuations measured with GIS 2 and especially GIS 3 for the same region, we assumed that, in spite of the standard gain correction, there are still residual gain variations, and we also assumed conservatively that the magnitude of the residual gain fluctuations are on the same order as the fluctuations of the gain observed using the instrumental copper fluorescent line at 8.048 keV. Since the gain fluctuations increase with time, we used the 1997 data as our standard of reference. The radial gain distribution shows that if one excludes the very outer region ($r \geq 22\arcmin$) and the very central region ($r \leq 2.5\arcmin$) from the spectral analysis, the gain fluctuation around the mean is $\leq 0.15\%$ for both GIS 2 and 3. For all pointings observed in this work, we extracted spectra from a circular region with a $20\arcmin$ radius. The exclusion of the central 2:5 from the pointings with discrepant redshifts does not change our results. This is not surprising, since they are offset pointings (most photons come from a specific direction and not from the detector’s center).

However, the direction from which most photons are detected for pointings P1 and P5 are different, so we also need to estimate the azimuthal gain variations. We also used the gain map determined using the Cu K line at 8.048 keV. We compared the average gain values (excluding the outermost ring) of the region encompassing a 90° slice corresponding to the direction toward the real cluster’s center (which is out of the field of view) for each instrument. This should give a good idea of the magnitude of the gain fluctuations as a function of detector position for our observations. Although the gain differences for the GIS 2 obtained this way imply a small gain variation ($\sim 0.12\%$), for the GIS 3, the derived gain fluctuation is substantially larger ($\sim 0.37\%$) than that observed for the radial variations.

4.3. Redshift Dependence on Gain

In order to test the sensitivity of our observations to possible residual gain variations across the GISs, we used Monte Carlo simulations. Supposing the redshift to be constant for the two discrepant regions, we generated fake spectra for both the GIS 2 and 3 for the two pointings and compared the best-fit redshift differences. We then calculated the probability to find the same redshift differences (or greater than) that we observed in the real pointings for GIS 2 and 3. We simulated 1000 GIS 2 and 3 spectra corresponding to each real observation using the XSPEC tool FAKEIT. In generating the fake spectra we used the same spectral model (WABS MEKAL) that we used for fitting the real data with the values of temperature, abundance, and normalization corresponding to the real best-fitting values of each pointing. We used the actual background spectra extracted within the same spatial extraction region for each pointing and effective exposures corresponding to the real pointings being simulated. We also used the responses (ARF and RMF) corresponding to the real pointings. Count statistics were incorporated in the generated spectra. For all simulations, we set the redshift to that obtained through the spectral fittings of the central pointing ($z = 0.025$).

Each simulated spectrum was then grouped (25 counts channel$^{-1}$) and fitted in the same way as the real ones, and the best-fit values of the redshift were recorded. We then selected the simulated spectra that had a redshift difference equal to or greater than that observed in the real pointings for both GIS 2 and 3 ($0.0208$ for GIS 2 and $0.0302$ for GIS 3). Gain effects do not enter directly in the procedure of generating simulated spectra. Therefore, in order to estimate the effects of GIS gain variations, we added a gain uncertainty to the best-fit redshift values derived from fake spectra. We assumed that the gain variations follow a Gaussian distribution with a standard deviation ($\sigma_{\text{gain}}$), which is different for each spectrometer, and a zero mean. This gain uncertainty was then summed to the best-fit redshifts obtained from the fake spectra before calculating the redshift differences between different pointings. To be conservative we assumed as our 1σ gain variations ($\sigma_{\text{gain}}$) for the GIS 2 and 3 the largest values of the two procedures described above, i.e., $0.15\%$ and $0.37\%$ for GIS 2 and GIS 3, respectively.

The probability of observing the redshift differences in GIS 2 and 3 that we measured for the real spectra in two pointings (P1 and P5), using the procedure described above, is found to be $\leq 0.005$. To illustrate how sensitive this value

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5 See data compiled by E. Idesawa and the GIS team, available at http://heasarc.gsfc.nasa.gov/docs/asca/gain.html.

6 See data compiled by M. Tashiro and the GIS team, available at http://heasarc.gsfc.nasa.gov/docs/asca/gisnews.html (see also http://heasarc.gsfc.nasa.gov/docs/asca/gain.html).

7 Again, see data compiled by E. Idesawa and the GIS team, available at http://heasarc.gsfc.nasa.gov/docs/asca/gain.html.
This work indicates the presence of a significant velocity gradient in the ICM of the Perseus Cluster. Two regions show discrepant redshifts not just with respect to each other but also with respect to the central region. We have shown in the preceding paragraphs that this difference is unlikely to be attributed purely to gain fluctuations, and it suggests the existence of large-scale bulk motions of the intracluster gas in this cluster. The temperature measurements show a general radial positive gradient, consistent with a cooling flow in the inner regions and an isothermal distribution in the outer regions. The abundance distributions are consistent with a global central-abundance enhancement decreasing by about 30% outward.

The two symmetrically opposed discrepant regions have velocity differences of roughly $-3000 \text{ km s}^{-1}$ (or $-600 \text{ km s}^{-1}$ at the 90% confidence level) for P1 and $+5000 \text{ km s}^{-1}$ (or $+60 \text{ km s}^{-1}$ at the 90% confidence level) for P5 with respect to P0. There are no observed temperature or abundance differences in the two pointings with discrepant redshifts (P1 and P5). The velocities measured are consistent with large-scale gas rotation with a correspondent circular velocity of $\sim 4100 \pm 2200 \text{ km s}^{-1}$ (90% confidence). This implies a large angular momentum for the ICM and that a significant fraction of the gas energy may be kinetic.

The best candidate for generating this large angular momentum is off-center mergers. In off-center mergers up to $\sim 30\%$ of the total merger energy may be kinetic (can be transferred to rotation; e.g., Pearce et al. 1994). Off-center merger simulations often produce residual intracluster gas rotation with velocities of a few $10^4 \text{ km s}^{-1}$ (e.g., Ricker 1998; Takizawa 1999, 2000; Roettiger & Flores 2000). Additional evidence for merging in Perseus comes from the observed (1) offset between the optical center and the X-ray center (Branduardi-Raymont et al. 1981; Snyder et al. 1990; Ulmer et al. 1992), (2) radial change in X-ray isophotal orientation (isophotal twist; Mohr, Fabricant, & Geller 1993), and (3) asymmetric galaxy morphological distribution, with preferential eastward direction in the distribution of E+S0 types (Bruzendorf & Meusinger 1999). However, simulations also indicate other observable consequences of mergers that, in principle, can be cross-analyzed with the velocity maps to test the robustness of the merger scenario.

In a more realistic case we observed a total seven of outer pointings and not only two. Therefore, we estimated the probability of finding the same redshift differences by chance. The results are shown in Figure 5 (for the purpose of illustration, $\sigma_{\text{gain}}$ for GIS 2 and 3 are assumed to be the same). It can be seen that this probability is rather insensitive to gain variations up to a $\sigma_{\text{gain}}$ of $\sim 0.5\%$.

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to the apparent rotation axis is another difficulty posed to the off-merger explanation. In most cases, the isodensity contours are elongated perpendicularly to rotation axis, except in some short-lived merger stages viewed from specific directions (e.g., Takizawa 2000).

Two options to try to conciliate the velocity gradients that we find with merger scenarios are (1) we are seeing a premerger stage with an infalling subgroup and (2) the merger happened long ago and the cluster was able to establish a cooling flow (and create a central metal abundance gradient) or the central region has not been disrupted. An argument against the former scenario is that we do not observe X-ray surface brightness enhancement in the direction of the redshift-discrepant regions. ROSAT Position Sensitive Proportional Counter (PSPC) images of P5 do not show any source bright enough to contaminate the overall flux and consequently the measured redshifts. However, we do observe a mild enhancement in surface brightness toward the east region of Perseus, coinciding with our P4 pointing. This enhancement was noticed previously by Schwarz et al. (1992) and Ettori et al. (1998) with better significance and has been interpreted as evidence for merging group, which could also explain the lower temperatures detected toward the east by Schwarz et al. (1992). We do not detect a temperature gradient toward the east, but since our eastern pointing (P4) is in a region of higher $N_H$, the lack of sensitivity of the GIS to the hydrogen column density could mask a small temperature decline. However, in order to match the low temperatures found by ROSAT in P4, $N_H$ would have to be significantly higher.\(^9\) Although there is no clear optical evidence of a subgroup toward the direction of P5 that corroborates this scenario, the region of surface-brightness enhancement (P4) is associated with a high fraction of early-type galaxies (Brunzendorf & Meusinger 1999). Brunzendorf & Meusinger (1999) optically detected a possible cluster at $z \sim 0.05$, $\sim 90'$ north of NGC 1275. The position of this “cluster” coincides with a surface-brightness-enhanced region detected with ROSAT (Kowalski 1994).\(^1\) However, its location is far north (beyond the region analyzed by ASCA and closer to the region where we detect low redshifts), and it is unlikely to explain the redshift discrepancy that we find in P5 and P1.

\(^9\) Even when $N_H$ was fixed to be twice as high for P4 as its correspondent Galactic value, the best-fit temperature found in that region was still $4.23 \pm 0.13$ with $\chi^2 \sim 1.46$.

\(^1\) There is also a region of enhanced surface brightness $\sim 100'$ to the northeast of NGC 1275, which is out of the region covered by ASCA (M. P. Kowalski 2000, private communication).

The second scenario would imply that large rotational velocities can be maintained for longer periods of time (comparable to a Hubble time if cooling flows are disrupted in off-center mergers).\(^11\) In some off-center merger simulations high rotational velocities can be maintained for $\geq 3$ crossing times (e.g., Ricker 1998). However, typically the gas velocities are higher toward the central cluster’s regions, which could not be detected in Perseus. If cooling flows are not disrupted in off-center mergers, then the results are consistent with a large off-center merger event that took place roughly $\geq 4$ Gyr [assuming a cluster mass of $5 \times 10^{14} M_\odot$ at a radius of 1 Mpc (Ettori et al. 1998) and that the rotating gas at $\sim 7$ keV is gravitationally bound].

Since we cannot measure the X-ray elongation along the line of sight to make better comparisons with simulations and since it is not clear whether cooling flows and central-abundance gradients can actually survive mergers (e.g., McGlynn & Fabian 1984; Fabian & Daines 1991; Allen et al. 1992; Gomez et al. 2000; Markevitch et al. 2000) and given the necessary poor spatial scale required to measure gas velocities reliably with the GISs, the results shown in this paper cannot constrain different merger scenarios accurately. However, it provides new challenges to numerical simulations of cluster mergers. Any merger explanation for the velocity differences observed in Perseus will have to take into account the presence of (1) a moderately high cooling flow, (2) a central metal abundance gradient, and (3) a chemical gradient, i.e., a central dominance of SN Ia ejecta (Dupke & Arnaud 2001). Velocity measurements of the intracluster gas with the Chandra and especially XMM-Newton satellites will be able determine ICM velocities in the central regions more precisely, thus providing information on the gas velocity curve, which will strongly constrain cluster-cluster merger models or suggest alternatives for generating the large angular momentum observed.

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\(^11\) The cooling time in the center of Perseus is $\sim 1$ Gyr, and it is $\sim 10$ Gyr at $\sim 200$ kpc, where a mass deposition rate of $\sim 500 M_\odot$ yr$^{-1}$ is inferred (Ettori et al. 1998).

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