1. INTRODUCTION

The merging of collapsed subsystems is believed to be the primary process of formation (and growth) of galaxy clusters. Off-center merging imparts angular momentum to the intracluster gas, which can last several Gyr according to recent numerical and hydrodynamical simulations (Takizawa 2000; Gomez et al. 2002; Ricker 1998; Molot et al. 2004). The resulting kinetic pressure associated with this residual angular momentum in the intracluster medium (ICM) affects our determination of physical quantities such as total cluster mass and baryon mass fractions, which are used to constrain cosmological parameters (e.g., Bahcall et al. 1999; Allen et al. 2002). Intracluster gas bulk motions may also provide clues to explain the rich phenomenology near the clusters core such as X-ray plumes (e.g., Sanders & Fabian 2002), radio halos (Carilli & Taylor 2002), and isophotal twisting (Mohr et al. 1993). Recent Chandra measurements of cluster gas temperature and surface brightness maps suggest the presence of bulk motions of $\sim 1000$–$2000$ km s$^{-1}$ in the central regions of some galaxy clusters, e.g., Machacek et al. 2002 (Abell 2218), Markevitch et al. 2000 (Abell 2142), Vikhlinin et al. 2001 (Abell 3667), and Kempner et al. 2002 (Abell 85). In some cases the velocities inferred are as high as $4500$ km s$^{-1}$ (Markevitch et al. 2004). This suggests that bulk motions in the ICM may be common, arising from the processes of continuous cluster formation. Nevertheless, intracluster gas bulk motions have been poorly studied until very recently, mostly due to the technical difficulties involved in measuring ICM gas velocities directly.

The most direct way to detect gas bulk velocities is through the measurement of the Doppler shifts of X-ray spectral lines and, in particular, of the well-defined Fe Kα line complex at $\sim 6.7$ keV. However, direct detection of intracluster gas velocities had to wait for the development of spectrometers with high spectral resolution and good instrumental gain stability, so that velocity changes of at least a few thousand km s$^{-1}$ could be detected reliably. Recently, Dupke & Bregman (2001a, 2001b) detected directly, for the first time, ICM bulk motions in the outer regions of the Perseus (Abell 426) and Centaurus (Abell 3526) clusters using ASCA GIS data. They also measured velocity gradients, with greater significance, in the inner regions of the Centaurus cluster using the ASCA SIS, which has been recently confirmed by Chandra (Dupke & Bregman 2005). The intracluster gas velocity distributions detected in these two clusters are consistent with systematic gas bulk circulation with correspondent circular velocities $\sim 1000$ km s$^{-1}$, implying that a significant fraction of the intracluster gas energy can be kinetic. In both clusters there are other indications of relatively recent dynamical turmoil (e.g., Stein et al. 1997; Ettori et al. 1998).

The initial results on Perseus and Centaurus prompted a larger systematic search for velocity gradients in other clusters where such analysis is feasible. The direct measurement of radial velocities in the intracluster gas through Doppler shift of X-ray spectral lines is limited by the instrument’s spectral resolution, number of photons in a line and, in practice, by the spatial and temporal stability of the conversion between pulse height and photon energy (gain) across the detectors. Typically, gain fluctuations, if not taken into account, produce artificial velocities of the same order or greater than the velocities we are trying to measure. In order to compensate for intrachip gain fluctuations, one would like to have multiple consecutive exposures of the full region of interest taken at the same CCD position. This is observationally expensive, and prior knowledge about the velocity structure can significantly reduce the number of follow-up observations necessary to create a reliable velocity map. The prior knowledge about velocity distributions can be obtained through the analysis of archived observations if the instrumental gain is
relatively stable and its variations are well known. This is the case for the ASCA satellite.

The Advanced Satellite for Cosmology and Astrophysics (ASCA) (1993–2000) was unique as the first mission to combine high spectral resolution to wide frequency coverage and arcminute angular resolution. Therefore, it is the first mission in which ICM velocity gradients could, in principle, be measured. The ASCA Solid-state Imaging Spectrometers (SIS) have spectral resolutions similar to that of the Chandra and XMM-Newton nongrating spectrometers. Furthermore, the instrumental gain variations in position and time have been extensively studied and can be included in the uncertainties reliably. In this paper we present the azimuthal distributions of intracluster gas velocities (and also gas temperatures and metal abundances) in a systematic search of the ASCA archive for the clusters best suited for velocity measurements.

2. DATA REDUCTION, SAMPLE SELECTION, AND METHODOLOGY

2.1. Data Reduction and Spectral Fittings

ASCA was equipped with four X-ray telescopes. The X-ray telescopes consisted of a set of four aligned identical telescopes. Each telescope was associated with a position-sensitive X-ray detector, two Gas-Imaging Spectrometers (GIS 2 and GIS 3), and two Solid-state Imaging Spectrometers, (SIS 0 and SIS 1). The SIS consisted of four 11 mm square, 420×422 pixel CCDs (charged coupled device). It had a 22′×22′ field of view (four 11′ squared CCDs) and covered a broad energy range (0.4–10 keV). The SIS originally achieved a FWHM energy of about 150 eV at 7 keV. The SIS could work in three clocking modes: 1-CCD, 2-CCD, and 4-CCD, so that data from 1, 2, or 4 chips were read out for each detector. The gain stability of the SISs in 1-CCD mode was significantly superior to that of the GISs (see footnote 2) and also to that using 2-CCD and 4-CCD modes. Since gain stability across the detectors is very important for velocity studies, we only used data from the two SISs in 1-CCD mode for clusters with long exposure times. We selected observations where the cluster’s center was located near the CCD center so that we could carry out an complete azimuthal analysis around the cluster’s center. For all pointings analyzed in this work, we selected data taken with high and medium bit rates, with cosmic-ray rigidity values ≥6 GeV c−2, with elevation angles from the bright Earth of ≥20′, and from the Earth’s limb of ≥10′ (SIS) using bright mode (SIS). We also excluded times when the satellite was affected by the South Atlantic Anomaly. Flickering pixels were removed from the data. We estimated the background from blank sky files provided through the ASCA Guest Observer Facility. We used XSPEC (ver. 11.2) software (Arnaud 1996) to analyze the X-ray spectra.

The general geometrical configuration used to extract spectra for all clusters was chosen in such a way as to allow us to look for velocity gradients covering the region around the X-ray center. A 2′ radius circle and several “PIE” sectors with a radial extent from 2′ to 6′ (or the CCD border) were used for all clusters. The initial number of sectors was eight (corresponding to a sector angle of 45′). In some clusters of our sample many extraction regions had fitting parameters poorly constrained. After it was clear that this was happening due to poor photon statistics, we increased the “PIE” sectoral angle to 90′. The minimum number of sectors in our analysis was four. If the velocity was still unconstrained, the cluster was excluded from our sample. We also carried out the same spectral analysis with the PIE sector phased out by half the sector angle. This was done to check for “borders” where velocity gradients could be smeared out by the original region selection. This helped us to test for spurious velocity gradients by looking at the smoothness of the velocity field.

The spectra were fitted using the MEKAL thermal emission model, based on the emissivity calculations of Mewe & Kaastra (Mewe et al. 1985, 1986; Kaastra 1992), with Fe L calculations by Liedahl et al. (1995). Abundances are measured relative to the solar photospheric values (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); since there has been a decrease in X-ray efficiency of the SISs at low-energy ranges since 1994,1 we restricted the useful energy ranges of the instruments to 0.8–9.0 keV in all spectral fittings. Within this energy range the hydrogen column density (NHI) is not well constrained. There is a known degeneracy between the best-fit NHI and gas temperature parameters. Since changes in best-fit temperatures may bias the determination of line centroids, leaving NHI free to vary could produce significant variations in the best-fit velocities. To check for possible velocity variations induced by this effect, the spectra from all regions were initially fitted with the NHI parameter set free to vary. We then averaged the NHI obtained in the spectral fittings of all regions in a cluster and used this value to obtain a set of spectral fittings where NHI was fixed for all regions. The absolute value that we chose to use in the spectral fittings with fixed NHI is not important for our work since we are looking for relative bulk velocities within a cluster. Since there were no significant variations of the velocity profiles obtained with NHI free and NHI fixed, we only present here the results for which NHI was fixed at the average value.

Spectral fittings using models such as MEKAL are not very sensitive to small redshift differences within the variation ranges of the spectral parameter typical for galaxy clusters. Therefore, the minimization routines often get stuck around local χ2 minima instead of the true minimum. This, if not checked carefully, may lead to inaccurate velocity measurements. To compensate for this, we implemented the following routine. We initially performed spectral fits while varying the redshift values within reasonable ranges (with the command STEPPAR in XSPEC) to find the “true” minimum. Then we fixed the redshift at that value, re-fitted the spectra to find the best-fit values of temperature, metal abundance, column density and normalizations. We subsequently used these results as initial input values in a new spectral fitting with the redshift parameter free to vary. From that we found the new “true” χ2 minimum and estimated the errors. This process was applied recursively until the best-fit redshift no longer changed.

2.2. The Inclusion of Intrachip Gain Fluctuations

The level at which we can constrain redshifts is not just a function of photon counts, but also depends on other fitting parameters such as metal abundances (higher metal abundances leads to stronger lines and smaller errors) and how well gas temperatures are defined. The accuracy of velocity measurements also depends strongly on the variation of gain across the CCD. It is known that the SIS 0 and SIS 1 CCDs have different absolute gains, and this difference is typically higher than the intrachip gain variation across each CCD. For a more detailed description of the gain variations of the ASCA spectrometers see Dupke & Bregman (2001a, 2001b) and references therein. The

1 See http://heasarc.gsfc.nasa.gov/docs/ASCA/watchout.html, also Hwang et al. (1999).
intrachip variation across the CCDs used in this work (S0C1 and S1C3) are also different, and each has a different dependence on time. However, the variation of gain for both chips and S1C3) are also different, and each has a different dependence on time. 2,3 However, the variation of gain for both chips for different spectral lines is well known and can be reliably used to estimate the systematic errors involved in measuring gas velocity gradients (Dupke & Bregman 2001b).

The standard deviation of the line centroid with chip position in each time period can be derived from the documented gain time dependence determined using the Fe Kα line at several (up to four) positions within each CCD (see footnote 4). From that we determined the average value of the line centroid and the typical fluctuation of the measured redshifts for each period \( \sigma_{\text{gain}}(\text{CCD}, t) \). To interpolate the values of \( \sigma_{\text{gain}}(\text{CCD}, t) \) to intermediary time values we used a linear fit. The results of the fittings are shown in Figure 1. It can be seen from Figure 1 that no single CCD had continually the lowest gain variation. The values of \( \sigma_{\text{gain}}(\text{CCD}, t) \) were used to weight the average of the best-fit velocities and errors measured separately with SIS 0 and 1.

The event files analyzed in this work were corrected with the tool ASCALIN (ver. 0.9t), using the standard gain calibration file s1sph2pi_110397.fits. In the later years of the ASCA mission the Charge Transfer Inefficiency (CTI) evolved nonlinearly with time, especially for SIS 1, and this affected the overall chip gain. Its impact on intrachip gain variations is still not clear. The effect becomes noticeable for dates later than mid-1998 for SIS 1 and mid-1999 for SIS 0. Most of the clusters for which we can measure reliable velocities were observed prior to that date so that their overall gain is not expected to have been significantly affected by the nonlinear CTI variation. In order to estimate whether this effect could significantly affect the clusters in our sample, we repeated the velocity analysis for Abell 3558 using the current CTI file patch released by GSFC s1sph2pi_290301.fits. We chose Abell 3558 because it was the cluster in our sample that was observed most recently (2000 January). We show the results in Figures 6a and 6b. Even though there was a global gain shift by about 10%, there was no noticeable change in the relative azimuthal distribution using different CTI files. Since we are looking for velocity gradients within the spatial range of one CCD, we do not care for the absolute values of velocities. Therefore, global gain shifts are irrelevant to our analysis. Since this is the cluster most likely to be affected by nonlinear CTI variation, we believe that we are justified in using the standard gain calibration file for all of the clusters in our sample.

2.3. ASCA PSF

When observing regions within the detector field of view, the flux in the outer regions of the detector is contaminated by photons coming from the central regions due to the extended ASCA point-spread function (PSF; Takahashi et al. 1995). This effect is energy dependent and becomes more significant for hot clusters. If we treat the PSF effect on the outer regions as a secondary spectral “component,” PSF scattering will broaden the line, increasing fitting errors and making velocity measurements more unconstrained. However, technically, the situation is more complicated because of the weak influence that the redshift parameter has in the global spectral fittings. As mentioned in the previous paragraphs, if the continuum is changed the best-fit line centroid may be changed as well. It is clear that if the cluster does not have a bona fide velocity gradient, the PSF should not create a spurious one directly but might create one indirectly by changing the continuum, and therefore, the best-fit gas temperatures, in the outer parts. This contamination, if strong, would create a correlation of temperatures and velocities following the characteristic “cross” shaped pattern of ASCA PSF and should be relatively easily visible. To be conservative, in this work we disregarded any velocity gradients accompanied by a strong temperature gradient.

If the cluster has a true velocity gradient (either rotational or transient), the PSF scattering will tend to artificially erase it by making velocity measurements of the contaminated regions imprecise. Since the PSF is energy dependent, this effect could “mask” the presence of velocity gradients in hot clusters and may partially explain the upper limit in gas temperatures of our sample. Since intracluster gas bulk flows and higher temperatures are both expected in merging systems, a fraction of these clusters with bona fide velocity gradients may be obscured from our ASCA analysis due to PSF scattering.

2.4. Random Velocity Scatter and Its Dependence on Temperature

To test for other systematic uncertainties related to the methodology used to measure velocities we analyzed the simulated cluster spectra with different temperatures. We simulated 1000 clusters per temperature group, each group centered on a different temperature range (1.5, 5, and 9 keV). We used the tool FAKEIT in XSPEC with column densities, metal abundances, and redshifts set to \( 5 \times 10^{20} \) cm\(^{-2}\), 0.30 solar photospheric and 0.05, respectively. After simulating the clusters’ spectra we determined the best-fit redshift using the same procedure that was applied to the real clusters. We show the results in Figure 2. There, we plot the best-fit velocities for each temperature group. The scatter along the temperature axis is due to the initial input ranges, which were chosen to be slightly different for display purposes and should be neglected. In this exercise we are interested in the scatter of best-fit velocities and its variation, if any, with temperatures. We also used a high value nominal number count (27 \( \times 10^4 \) counts) since we do not want the standard statistical errors to dominate the uncertainties. In Figure 2 we show

\[ \text{Fig. 1} \] Variation of the standard deviation of the SIS gain with time from ASCA launch. Each value is calculated from a distribution of gain in several (up to four) positions across the CCD, for the Fe K line using Cas A as a reference source. We also plot the linear fit used to interpolate the values of \( \sigma_{\text{gain}} \) for different clusters. The solid lines represent the SIS 0 CCD 1 and the dotted lines SIS 1 CCD 3.
the standard deviation of the best-fit redshift values found (σ). The standard deviation shows a dependence on temperature being a factor of ~1.8 higher for a ~1.8 increase in temperature toward higher values and also increasing by ~20% for a factor of ~3.3 decrease in temperature. The latter can be attributed to the velocities being measured primarily at lower frequencies by spectral lines other than the Fe Kα. The former is likely to be associated with the relative weakness of the line flux with respect to the continuum. These errors reflect to the ability of the current software to determine line centroids accurately and were added in quadrature to the statistical and gain errors for the clusters in our sample.

3. RELEVANT CHARACTERISTICS OF THE SAMPLE

The sample analyzed here is built by elimination, based on suitability for velocity measurements. Aside from geometrical configuration and CCD mode we also performed an initial selection

on the relevant parameters for velocity measurements such as counts within the spectral lines (or overall counts) and metal abundance. After finishing the initial selection we had about 30 clusters where velocity measurements were possible. However, half of the initial sample was later discarded due to the unreliability in measuring reasonably constrained velocities using both spectrometers. The final sample is displayed in Table 1, where we also list other relevant characteristics of the clusters. One can see that there is a significant interplay between metal abundances and total number of counts that still satisfies the constraints imposed for velocity measurements. This is not surprising since the counts that matters most in finding the line centroids are those within the Fe lines.

Columns (1) and (2) in Table 1 show the cluster names and average redshift (determined optically). The average gas temperatures and metal abundances over all regions analyzed including the central region are shown in columns (3) and (4), respectively. The average $N_{\text{H}}$ in the line of sight as estimated from HEASARC W3nH6 is shown in column (5). Columns (6) and (7) show the count rate and the total number counts within the CCDs in SIS 0 and SIS 1. Previous indications of the presence of cooling flows is indicated in column (8). We list the number of years from the launch of ASCA to the year that the observation was performed in column (9). In column (10) we show the position angle of the direction of north.

Given the uncertainties involved in measuring velocities we, conservatively, used three criteria to screen out clusters that have velocity gradients from our sample: Our first criterion was that both instruments showed consistent results in the regions of interest, after taking into account global gain shifts. We show here (Figs. 4–15) weighted average plots of the results obtained with both detectors. To compensate for the dependence of the intra-chip gain fluctuations at the level that is found in the SISs.

6 See http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl.

![Graph showing the standard deviation of the best-fit velocity with average gas temperature. One thousand clusters were simulated per temperature bin using SIS 0 responses and the spectra were subjected to the same analysis as the real data. We show the standard deviation of the measured velocities as 1 σ. The statistical errors ($\sigma_{stat}$) were typically found to be 200, 250, and 350 km s$^{-1}$ for clusters with temperatures 1.5, 5.0, and 9.0 keV, respectively.](image-url)

**TABLE 1**

| Name          | Redshift (Optical) | Temperature (keV) | Abundance (Solar)$^a$ | Galactic $N_{\text{H}}$ ($10^{22}$cm$^{-2}$) | SIS 0/SIS 1 Count Rate (counts s$^{-1}$) | Total SIS 0/SIS 1 (10$^3$ counts) | Cooling Flow | Time after Launch (yr) | Position Angle (deg) |
|---------------|-------------------|------------------|-----------------------|------------------------------------------|----------------------------------------|-----------------------------------|---------------|------------------------|----------------------|
| Abell 576     | 0.039             | 3.96             | 0.64                  | 0.06                                     | 0.630±0.50                              | 28/22                             | Weak$^{b,c}$   | 3.1                    | 82.9                 |
| RX J419.6+0225| 0.0123            | 1.39             | 0.33                  | 0.12                                     | 0.640±0.49                              | 40/30                             | No$^{d}$       | 3.1                    | 159.8                |
| Abell 376     | 0.048             | 3.75             | 0.59                  | 0.07                                     | 0.360±0.29                              | 12/9                              | Weak$^{b}$     | 4.5                    | 294.0                |
| Abell 2589    | 0.041             | 3.60             | 0.59                  | 0.04                                     | 0.710±0.57                              | 12/9                              | No$^{e}$       | 6.8                    | 110.0                |
| Abell 3558    | 0.048             | 5.57             | 0.40                  | 0.04                                     | 1.43±1.13                               | 88/69                             | Weak$^{b,d}$   | 6.9                    | 253.3                |
| Abell 2052    | 0.035             | 3.11             | 0.55                  | 0.03                                     | 1.28±0.03                               | 51/41                             | Yes$^{d}$      | 3.9                    | 248.8                |
| Abell 2657    | 0.04             | 3.43             | 0.43                  | 0.06                                     | 0.660±0.53                              | 29/23                             | Weak$^{b}$     | 2.8                    | 117.4                |
| Abell 1650    | 0.085             | 5.62             | 0.51                  | 0.02                                     | 0.910±0.74                              | 48/39                             | Yes$^{d}$      | 2.9                    | 261.2                |
| Abell 2244    | 0.097             | 5.09             | 0.37                  | 0.02                                     | 0.780±0.61                              | 27/21                             | Yes$^{d}$      | 5.5                    | 60.1                 |
| Abell 3158    | 0.06             | 5.06             | 0.53                  | 0.01                                     | 1.000±0.80                              | 33/27                             | No$^{e}$       | 3.8                    | 167.6                |
| Abell 644     | 0.07             | 6.32             | 0.36                  | 0.07                                     | 1.44±1.12                               | 79/62                             | Yes$^{d}$      | 2.2                    | 80.6                 |
| MS 1111.9–3754| 0.129             | 5.17             | 0.46                  | 0.09                                     | 0.320±0.27                              | 18/15                             |               | 3.3                    | 74.3                 |

$^a$ Photospheric.
$^b$ Less than 50 $M_{\odot}$ yr$^{-1}$.
$^c$ Consistent with 0 $M_{\odot}$ yr$^{-1}$.
$^d$ Peres et al. (1998).
$^e$ From this work.
$^f$ Kempner & David (2004).
It may be argued that, instead of using the above mentioned procedure to build an “average” velocity profile, one could fit the spectra of both SIS 0 and SIS 1 simultaneously using data groups in XSPEC. However, this would require a general correction for the global CCDs gain difference, for example with the GAIN command in XSPEC. However, based on our previous experience, we noticed that the confidence level limits can be a function of how good this correction is. Therefore, we opted to fit the spectral data separately and then use the above mentioned methodology to display the joined results, as done in

Fig. 3.—SIS 0 (chip 1) smoothed image of the clusters shown in this work. X-ray surface brightness contours are overlaid. We indicate the origin (0°) of the azimuthal angle used to plot velocities, temperature, and metal abundances in Figs. 4–15. The azimuthal angle increases counterclockwise. We also show the north-south direction and the angular scale.
previous works (Dupke & Bregman 2001b). In most cases the “average” results were consistent with the individual ones, and the few exceptions are discussed below.

Our second criterion was to screen the results based on an “angular” velocity resolution criterion, i.e., only regions (or a combination of adjacent regions) larger than 90° angular slices can be used to consider the velocity gradient as nonspurious. This choice of a minimum angular slice corresponds roughly to the effectively angular resolution of ASCA at the midpoint of the sector. The final criterion that we used to determine that the velocity gradient was robust was that the velocity variations were not accompanied by significant changes of other spectral parameters, mainly gas temperatures. This is to avoid the best-fit velocities from being influenced by shifts in the continuum, as described in §§ 2.3 and 2.4.

4. RESULTS: BEST CANDIDATES FOR VELOCITY GRADIENTS

In Figure 3 we show the smoothed SIS 0 images of the clusters in our sample to illustrate how the azimuthal angle relates
to position angles. We plot our zero point, the direction to the true north and also the angular scale. All other angles mentioned henceforth will be given with respect to the zero points in Figure 3 increasing counterclockwise. When referring to a region we will cite the angle “A” at which the PIE sector is centered. The whole sector correspondent to that region would cover $A - \eta < A < A + \eta$, where $\eta$ is the minimum angular separation of the data points (either 30° or 45°).

In Figures 4–15 we show the azimuthal distribution of the best-fit gas temperatures (top), metal abundances (middle), and redshifts (bottom) for the clusters in our sample. The values plotted are an average, which is linearly weighted by the inverse of the 1 $\sigma$ gain variation $[\sigma_{\text{gain}}(\text{CCD, } t)]$ corresponding to each detector. The errors of temperature and abundance represent 90% confidence levels and for velocity (redshift plot) are 68% ($1 \sigma$). The velocity plot shows a weighted average of the results obtained with SIS 0 and SIS 1 separately, using the inverse of the 1 $\sigma$ variation of the gain at the time of the observation as weights. In the spectral fittings the hydrogen column density was shown for temperatures, abundances, and velocities are only those for which well-constrained values were obtained in both SIS 0 and SIS 1.

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In order to estimate the significance of the maximum velocity gradient we used the $F$-test. In applying the $F$-test we simultaneously fitted spectra from SIS 0 and 1 of the two regions with the highest best-fit discrepant velocities and compared $\chi^2$ variations due to the change in the number of degrees of freedom. We compared the $\chi^2$ of fits that assumed the redshifts to be the same in the two projected spatial regions to the $\chi^2$ of fits that allowed the redshifts in the two regions to vary independently,
Fig. 6a

Fig. 6.—(a) Same as Fig. 4, for Abell 3558. (b) Same as (a), but using the new CTI file patch $\texttt{siaph2pi\_290301.fits}$.

Fig. 7.—Same as Fig. 4, for Abell 376.

Fig. 8.—Same as Fig. 4, for Abell 2589.
Fig. 9.—Same as Fig. 4, for Abell 2052.

Fig. 10.—Same as Fig. 4, for Abell 2657.

Fig. 11.—Same as Fig. 4, for Abell 1650.

Fig. 12.—Same as Fig. 4, for Abell 2244.
reducing the number of degrees of freedom by one. Since there are no significant changes in the best-fit redshifts obtained by different instruments for the same region, we locked the redshifts of SIS 0 and 1 together within each of the two regions tested.

For Abell 576 we chose the regions corresponding to 30° and 210° to apply the $F$-test. The results show that these regions have different velocities at the 99.993% confidence level. In Figure 17 we show the 68% (inner), 90% (intermediary), and 99% (outer) confidence contours for two interesting parameters.
(redshifts) of these two regions as well as the line correspondent to equal redshifts. In Figures 18a and 18b we show the unfolded spectra (weighted by the photon energy) for both regions obtained with SIS 0 and SIS 1.

The high-velocity gradient found here in Abell 576 adds to the body of indirect evidence to the presence of high dynamical activity in this cluster. Rines et al. (2000) determined the mass profile of A576 using the infall pattern in velocity space for more than 1000 galaxies in a radius of $4\ h^{-1}\text{Mpc}$ from the cluster’s center. They found that the mass of the central Mpc was more than twice that found from X-ray measurements, suggesting that nonthermal pressure support may be biasing the X-ray derived mass. Their results are also in agreement with those of Mohr et al. (1996). Using galaxy photometric data, Mohr et al. (1996) found a high-velocity tail (8 galaxies) separated by $\sim3000\ \text{km s}^{-1}$ from the cluster’s mean. This high-velocity population, however, is not clearly geometrically separated from the rest of the cluster. Mohr et al. (1996) suggested that they may be due to a past merger event in A576. Rines et al. (2000) more extended analysis found also a high galaxy concentration toward A576 separated by $\sim8000\ \text{km s}^{-1}$. Kempner & David (2004) analyzed the Chandra observations of the core of this cluster and found sharp edges corresponding to jumps in gas density and pressure roughly in the N-S direction, and they suggest that the core substructures are caused by a current merger during its second core passage.

RX J0419.6+0225 is a nearby ($z = 0.0123$) cool cluster discovered in the ROSAT All Sky Survey. It is among the brightest clusters in the $0.1–2.4\ \text{keV}$ band, with the X-ray flux $4.5 \times 10^{-11}\ \text{ergs cm}^{-2}\ \text{s}^{-1}$ in the $0.1–2.4\ \text{keV}$ band. It is dominated by a single elliptical galaxy NGC 1550. This cluster was observed by ASCA for $\sim80\ \text{ks}$ in 1-CCD mode. We show the azimuthal distributions of gas temperature, metal abundance, and redshifts in Figure 5. The average temperature of this cluster is very low ($1.38\ \text{keV}$), so that the redshift measurements are not significantly influenced by the FeK line complex (Figs. 19a and 19b). The regions around 135° have lower redshifts than the other regions. The velocity difference between the averages of low-redshift regions (90°, 135°, 180°) and the high-redshift regions (0°, 45°, central) is $4.2 \pm 1.5 \times 10^{3}\ \text{km s}^{-1}$ (1 $\sigma$ confidence limits). The errors cited include the same corrections as those cited previously for A576. Since the radial distributions of temperature and abundances are flat throughout and we do not see evidence of a “cooling flow” we also included the best-fit values for the central region with those of the high-redshift regions when estimating the velocity differences. The notation is the same as that used in the previous paragraph and $\sigma_{\text{gain (CCD, t)}}$ used here is derived from the Si line. We used the Si line to estimate the gain variations for this cluster because the intracluster gas temperature in this cluster is very low and the FeK line complex is barely visible (Figs. 19a and 19b) so that the redshift is heavily biased toward the FeL complex and other low-energy lines, such as Si and S. As discussed in detail in Dupke & Bregman (2001b), the gain fluctuation is energy dependent and...
velocity measurements with and without the FeK complex often give significantly different values. Therefore, we looked for the gain fluctuation correction that corresponded to the lower energy range lines. The closest calibrated line to the FeL complex is that of silicon at $\frac{1}{C_2} 1.8 \text{ keV}$.

To perform the $F$-test we chose regions $0^\circ$ and $180^\circ$. The $F$-test shows that the velocities of these two regions are different at the 99.36% confidence level. In Figure 20 we show the confidence contour plots and the line of equal redshifts.

In Figure 16 we see that Abell 376 also has regions with consistent high internal velocity deviations from the mean. In Abell 376 there is a marginal ($\sim 3.2\sigma$) velocity gradient with higher than average velocities in the $90^\circ$–$225^\circ$ regions. Despite the apparent gradient, only two nonconsecutive regions—$135^\circ$ and $225^\circ$—show significant variations (when compared to the $315^\circ$ and central regions) (Fig. 7). We performed the $F$-test to estimate the significance of the discrepant regions $315^\circ$ and $225^\circ$. The confidence contours are plotted in Figure 21 along with the line of equal redshifts. The difference is significant at less than 97.8%. The 99% confidence contours are degenerate, and we do not have enough statistics to confirm or refute the velocity gradient in this cluster with the available observation. The temperature distribution in Abell 376 also shows indications of a mild azimuthal gradient, where the regions $30^\circ$–$90^\circ$ have lower temperatures than the regions with azimuthal angles above $180^\circ$ by $0.92 \pm 0.31 \text{ keV}$ (Fig. 7). Metal abundances are not very well constrained and are consistent with a constant value.

4.1. AGN Contamination

We are studying regions near the core of galaxy clusters where central dominant galaxies are usually found and are often active X-ray emitters. Therefore, a question that may appear is...
whether the X-ray emission scattered from the central AGN can influence the redshift measurements through changes in the continuum. The contamination from the central AGN is analogous to (and in general less important than) the contamination from the intracluster gas in the central 2" and was already discussed previously in § 2.3. However, bright background AGNs could still be a concern when analyzing cluster regions away from the center, where cluster emission drops significantly. To estimate the contamination level from background AGNs we analyzed archived Chandra images of Abell 576 and RX J0419.6+0225. Although there are no bright sources within the boundaries of the I-chips in RX J0419.6+0225, we found a few bright sources in the field of view of Abell 576. The brightest AGN is located in one of the sectorial regions where we found the best-fit redshift to be significantly above the average. However, Chandra analysis showed that the AGN’s flux accounts for less than 5% of the total within the frequency range observed with ASCA in a region similar (slightly smaller) to that used to extract spectra with ASCA. Furthermore, its spectrum is typical of other AGNs and is well fitted by an absorbed power law with index $\sim$2 and is very soft. AGNs do not influence the results presented in this paper, given their low fluxes compared to the typical brightness of the clusters at the radial distances used in this work.

4.2. Multiple Temperature Components

Given the relatively high frequency of anisotropic temperature distribution found in our sample (see next section) it may be reasonable to inquire how the velocity gradients are affected by projection effects. If there is a projected component with different temperatures from that of the main cluster in the line of sight toward one direction but not toward others there could be, in principle, a spurious redshift difference due to shifts in the temperature recovered from a one-temperature spectral model fitting, affecting the best-fit recovered redshift.

In order to assess the effect that a possible asymmetrical second component can have on the measured redshifts we performed a large number of spectral simulations similar to those used in § 2.4. We added a second temperature component to the simulated spectrum and used the same procedure that we used in the real clusters to recover the redshifts with a single temperature MEKAL model. The relative normalizations of the second component followed the ratio of counts toward different azimuthal regions of the real clusters, since this hypothetical secondary component would also add additional flux to that of the main cluster. In the simulations we used the characteristics of A576 and RX J0419.6+0225 for the primary component. These two clusters provide good temperature range coverage for the other clusters in our sample. To be conservative we chose the largest possible flux difference among all azimuthal sectors analyzed in each cluster as a basis to determine the normalization of the second component in the simulations.

We performed 50 simulations per temperature bin and measured the standard deviation of the best-fit values over 50 simulations (per bin). (b) Same as (a), for RX J0419.6+0225.

![Fig. 22a](image1.png)

Fig. 22a — (a) Redshift biases from fitting a one-temperature model to a two-temperature simulated spectra with the characteristics of Abell 576. The X-axis shows the simulated temperature of the second component. The main component has a temperature of 4 keV. The single-temperature best-fit values for redshifts and temperatures are shown in the top and middle plots. The reduced $\chi^2$ of these fits are shown in the bottom plot. The errors indicated the standard deviation of the best-fit values over 50 simulations (per bin). (b) Same as (a), for RX J0419.6+0225.

![Fig. 22b](image2.png)

Fig. 22b
model. The redshift errors shown are the standard deviation of
the best-fit values over the 50 spectral fittings. We also show the
best-fit recovered redshifts and the reduced $\chi^2$, using a one-
temperature model. When analyzing Figure 22 one should keep
in mind that this exercise only makes sense when looking for
redshift changes within the limits observed in the real clus-
ters. Furthermore, the reduced $\chi^2$ should be acceptable, i.e., the
effects of the secondary temperature components should not be
obviously ruled out. For A576, it can be seen that the best-fit
redshift for the single temperature model is very stable with no
evidence of variation in a wide range of temperatures for the
secondary component (Fig. 22a). Only when the secondary com-
ponent reaches very low values ($\sim$2 keV) is the effect in the
redshift noticeable. However, this happens for recovered tem-
peratures outside those observed in the real cluster ($>3$ keV). In
addition, $\chi^2_v$ in the regions where the redshift “jumps” is sig-
nificantly worse and a one-temperature model does not fit the
data well. Despite the overall wider variation of the recovered
redshift with temperature for RX J0419.6+0225 the results are
similar to those of A576. The recovered redshift is stable within
the regions that the recovered temperatures correspond to the
limits observed in the real cluster (1.32–1.5 keV). The average
(over both clusters) best-fit velocity scatter is 600 km s$^{-1}$, which
has been included in quadrature in the errors of the velocity
differences. We conclude that the effects of secondary spectral
components on the velocities measured does not create spurious
velocity gradients as large as those observed in the clusters with
significant velocity gradients.

5. AZIMUTHAL DISTRIBUTIONS OF THE OTHER
CLUSTERS IN OUR SAMPLE

Abell 3558.—In Figure 6a we show the azimuthal distribu-
tions for Abell 3558. The temperature profile is anisotropic, and
there is a temperature gradient, which is strongest along the di-
rection connecting the regions $\sim$90°–30° (with gas tem-
perature 5.03 $\pm$ 0.24 keV) and regions $\sim$300°–30° (with gas
temperatures 6.36 $\pm$ 0.36 keV). Metal abundances are consis-
tent with being constant throughout. The velocity distribution
suggests the presence of a gradient with the redshifts of the re-
regions 150°–240° being higher than that of the central region.
However, the significance of the velocity gradient is marginal
(average regions 150°–240° have velocities is 2.2 $\sigma$ above the
average). The value of $\sigma_{v\text{gas}}$(SIS 0, t) for the time of this ob-
ervation was already too high, which weakens the reliability of
the velocity measurements (see Fig. 6b). We also show in
Figure 6b the results using a different CTI file patch released by
GSFC sishp2pi_290301.fits. Aside from the overall red-
shift change downward by $\sim$0.005, we do not see significant
differences for any regions except 300°. The redshift values for the
300° region with new CTI file are mostly due to SIS 1. Since
the surrounding points do not show consistent behavior leading
to a region of low redshifts, we believe that data point is spurious.

Abell 2589.—From the distribution of velocities in Abell 2589
(Fig. 8) we see that the regions near (45°) seem to have a higher
redshift than that of regions 135°–180° and central. Although,
tantalizing, the significance of this “spike” in the joint SIS 0 and
SIS1 velocity profile is low ($<2 \sigma$). The temperature and metal
abundances profiles are consistent with being flat.

Abell 2052.—The temperature distribution of Abell 2052
shows a significant (at the 90% confidence level) symmetric
gradient between the regions 0°–150° and 180°–330°. (Fig. 9).
Consequently, the “cooling flow” is steeper also at higher az-
imuthal angles ($>180°$). There is an abundance gradient toward
the low-angle regions (0°–90°), where the abundance decreases
from the central value of 0.64 $\pm$ 0.07 solar to 0.45 $\pm$ 0.1 solar.
The velocity distribution is consistent with no bulk flows.

Abell 2657.—Abell 2657 (Fig. 10) also shows a mild, but
significant at >90% confidence, “cooling flow” toward the 0°–
135° direction. Its abundance profile is consistent with a flat dis-
tribution. We do not find evidence of velocity gradients and the
distribution of velocities is consistent with a flat profile within
the range of detection of the instruments.

Abell 1650.—We show the azimuthal distributions for Abell
1650 in Figure 11. We do not notice a central temperature de-
cline within the region studied. There are indications of a mild,
but significant, anisotropy in the temperature profile. The av-
temperature of the 30°–60° regions is 4.88 $\pm$ 0.32 keV.
This is significantly (>90% confidence limits) lower than the
average value of the other regions, 5.78 $\pm$ 0.44 keV. The max-
imum temperature gradient is as high as 1.4 $\pm$ 0.4 keV (see be-
low). The velocity profile (center excluded) does not show any
consistent indication of velocity structures.

Abell 2244.—SIS 1 observations of Abell 2244 do not pro-
vide many data points where velocities can be reasonably con-
strained. However, SIS 0 spectra shows much better constrained
velocities consistent with a flat distribution. The joint plot shows
temperatures consistent with a constant value. The metal abun-
dance profile is also flat (Fig. 12).

Abell 3158.—There are no significant structures seen in
the distribution of temperatures or metal abundances (Fig. 13).
The velocity profile is also marginally consistent with a flat
distribution.

Abell 644.—We do not detect significant temperature gra-
dients with respect to the central region of Abell 644 (Fig. 14),
but there are marginal azimuthal variations of temperature. Metal
abundance are consistent with a flat profile. The velocity distri-
bution shows indications of low-velocity regions near the 120°–
240°. However, these regions are seen only with the SIS 1 and
intermittent, so that there are no two adjacent regions that
show a significant difference from the average and the velocity
fluctuations are likely due to local SIS 1 temporal gain fluctua-
tions. Due to these inconsistencies we conservatively do not con-
sider A644 as a strong candidate.

MS 1111.9–3754.—The plots for MS 1111.9–3754 show a
zone (90°–135°) that has the lowest temperatures, highest abun-
dances, and lowest redshifts. Since they seem to be correlated
(Fig. 15), based on our selection criteria, we conservatively con-
sider the velocity gradient as spurious.

5.1. Anisotropic Temperature Distribution

Temperature and density inhomogeneities in the core of
“cooling flow” clusters has been found by Chandra in many
clusters previously thought to be well behaved, e.g., Centaurus
(Sanders & Fabian 2002), Perseus (Fabian et al. 2000), Abell
1795 (Fabian et al. 2001), Abell 496 (Dupke & White 2003),
Abell 2052 (Blanton et al. 2003), and others. These anisotropies
are partly believed to be due to the frequent presence of “cold
fronts” (Markevitch et al. 2000). The interaction between the
central engine of the cD and the surrounding ISM/ICM may produce
other features such as cavities (McNamara et al. 2000) and X-ray
arms that change the gas temperatures anisotropically.

The azimuthal distribution of gas temperatures within the
central 6’ of the clusters in our sample is anisotropic in half of
the clusters in our sample. The characteristic maximum tem-
perature differences and their respective 90% confidence errors
are $\sim$0.92 $\pm$ 0.31 keV (Abell 376), $\sim$1.43 $\pm$ 0.40 keV (Abell
1650), $\sim$0.46 $\pm$ 0.13 keV (Abell 2052), $\sim$1.34 $\pm$ 0.26 keV
(Abell 3558), and $\sim$0.48 $\pm$ 0.26 keV (Abell 576); all show
evidence for the presence of cold cores. This suggests the presence of high dynamical activity in cluster cores in “cooling flow” clusters, probably associated with either nuclear cold fronts generated by accretion of subclumps (Markevitch et al. 2000), cD “sloshing” in the bottom of the gravitational potential (Dupke & White 2003) or by the interaction between the AGN in the inner regions of the cD galaxy and the surrounding ISM/ICM (McNamara et al. 2000).

6. SUMMARY

The combination of X-ray derived gas density and temperature mapping has provided indirect evidence of the presence of gas bulk motions in clusters of galaxies. Previously, direct detection of bulk velocities had only been found only for the Centaurus cluster at small and large scales (Dupke & Bregman 2001a) and the Perseus cluster at large scales (Dupke & Bregman 2001a) with the ASCA satellite and possibly at very small scales with Chandra (Sanders et al. 2004) and XMM-Newton (Andersson & Madejski 2004). Here we have measured the azimuthal velocity profile for all the clusters in the ASCA archive for which velocity mapping could be performed with useful precision. The characteristics of the instruments on-board ASCA together with the particularities of the observations in the ASCA archive limits our sensitivity to detect velocity differences of \( \geq 2000 \) km s\(^{-1}\), so that only clusters with very high internal velocities as well as projected cluster alignments/infall can be measured.

We plot the maximal internal velocity splittings of the sample in Figure 23 with the correspondent 90% errors. The best candidates for velocity gradients in our sample are Abell 576 and RX J0419.6+0225. They show significant velocity gradients independently with SIS 0 and SIS 1, with no biases due to correlations with temperature or abundance gradients. After the gain uncertainties are taken into account the residual velocity differences are \( \geq 3.5 \times 10^3 \) km s\(^{-1}\) (A576) and \( \geq 1.5 \times 10^3 \) km s\(^{-1}\) (RX J0419.6+0225) at 90% confidence level. The \( F \)-test shows that the velocity gradients for Abell 576 and RX J0419.6+0225 are significant at the 99.99% and 99.36% confidence levels.

Despite the natural bias of our sample toward the brightest clusters this works suggests that strong bulk motions are present in a nonnegligible fraction of nearby clusters. The presence of bulk motions in the intracluster gas has fundamental impact in the determination of physical quantities such as gas mass and baryonic fraction and may help explain the X-ray–gravitational lens mass discrepancy in the central regions of specific clusters (e.g., Allen 1998; Machacek et al. 2002). It can, indirectly, induce the “\( \beta \)” discrepancy in clusters by providing additional kinetic support to the thermal component (e.g., Evrard 1990; Allen et al. 1992, cf. Bahcall & Lubin 1994). It is expected that the frequency of clusters with velocity gradients \( \Delta V \) falls off as \( \Delta V^{-4} \) (Pawl, Evrard & Dupke 2005), so that future similar analysis with Chandra and XMM-Newton should increase the sample by more than an order of magnitude, since they will allow us to reduce the errors associated with gain fluctuations and measure velocity gradients with magnitudes as low as \( \geq 750 \) km s\(^{-1}\).

We thank K. Mukai for providing information about ASCA SIS gain calibrations that was crucial to this work. We thank the referee for the helpful suggestions. We are thankful to Jimmy Irwin, Nestor Mirabal, and Ed Lloyd-Davies for helpful discussions. We acknowledge support from NASA grant NAG 5-3247. This research made use of the HEASARC ASCA database and NED.

FIG. 23.—90% confidence limits for the maximum velocity difference for each cluster analyzed in this work.

\[ \Delta V \sim 750 \] km s\(^{-1}\).

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