A LINE-OF-SIGHT GALAXY CLUSTER COLLISION: SIMULATED X-RAY OBSERVATIONS

J. A. ZuHone 1, P. M. Ricker 2, D. Q. Lamb 1, and H.-Y. Karen Yang 2

1 Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA; zuhone@flash.uchicago.edu, lamb@oddjob.uchicago.edu
2 Department of Astronomy, University of Illinois at Urbana-Champaign, Urbana, IL, 61801, USA; pmricker@uiuc.edu, hyang20@illinois.edu

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ABSTRACT

Several lines of evidence have suggested that the galaxy cluster Cl 0024+17, an apparently relaxed system, is actually a collision of two clusters, the interaction occurring along our line of sight. In this paper, we present a high-resolution N-body/hydrodynamics simulation of such a collision. We have created mock X-ray observations of our simulated system using MARX, a program that simulates the on-orbit performance of the Chandra X-ray Observatory. We analyze these simulated data to generate radial profiles of the surface brightness and temperature. At later times, t = 2.0–3.0 Gyr after the collision, the simulated surface brightness profiles are better fit by a superposition of two β-model profiles than a single profile, in agreement with the observations of Cl 0024+17. In general, due to projection effects, much of the post-collision density and temperature structure of the clusters is not seen in the observations. In particular, the observed temperatures from spectral fitting are much lower than the temperature of the hottest gas. We determine from our fitted profiles that if the system is modeled as a single cluster, the hydrostatic mass estimate is a factor ~2–3 less than the actual mass, but if the system is modeled as two galaxy clusters in superposition, a hydrostatic mass estimation can be made which is accurate to within ~10%. We examine some implications of these results for galaxy cluster X-ray surveys.

Key words: galaxies: clusters: general – galaxies: clusters: individual (Cl 0024+17) – methods: N-body simulations – X-rays: galaxies: clusters

1. INTRODUCTION

Clusters of galaxies have proven to be interesting laboratories for studying the dynamics of the different kinds of matter in the universe. Early measurements of galaxy velocity dispersions in clusters demonstrated that most of the mass of galaxy clusters was in the form of a nonluminous component (Zwicky 1937). Modern cosmological constraints (e.g., Turner 2000) suggest that this nonluminous material must be mostly nonbaryonic. In addition, X-ray observations of clusters of galaxies reveal that most of their baryonic mass is in the form of a hot, diffuse, X-ray emitting gas (the intracluster medium or ICM). The presence of these different types of matter (stellar, gaseous, and dark) in these systems provides not only insights into the nature of the clusters themselves but also the nature of the different components of matter and their dynamics.

In the cold dark matter (CDM) picture of structure formation, galaxy clusters are the product of many mergers between galaxies, galaxy groups, and smaller clusters of galaxies (Davis et al. 1985). Observations of galaxy clusters indicate that this process is still ongoing in many systems. A famous example is the so-called “Bullet Cluster” (1E 0657-56), a merging system in which X-ray and weak gravitational lensing observations demonstrate a clear separation between a collisionless dark matter (DM) component and the ICM (Markevitch et al. 2002; Clowe et al. 2006).

Another system that has recently attracted attention is Cl 0024+17, a cluster at a redshift z = 0.395 exhibiting both weak and strong lensing. Early attempts at reconstructing the mass profile of this system using lensing ( Tyson et al. 1998; Broadhurst et al. 2000; Comerford et al. 2006) suggested a conflict with the predictions of the standard CDM model due to the flattening of the density profile in the inner regions of the cluster. Cosmological simulations assuming CDM indicate that galaxy cluster mass profiles should exhibit a nonzero logarithmic slope in the inner regions (e.g., Navarro et al. 1997). This apparent discrepancy (and others) led to suggestions that the CDM paradigm would need to be modified (Spergel & Steinhardt 2000; Hogan & Dalcanton 2000; Moore et al. 2000), for example to include self-interaction of the DM.

Czoske et al. (2001) (2002) demonstrated that the redshift distribution of the cluster galaxies in Cl 0024+17 is bimodal, with a large, primary component and a more diffuse, secondary component, separated from the primary component in velocity space by v ∼ 3000 km s⁻¹. They suggested that the system is composed of two clusters undergoing a high-velocity collision along the line of sight. They also performed a simulation demonstrating that such a scenario reproduces not only the bimodal redshift distribution but also the flattening of the central density profile. X-ray observations of the cluster using Chandra (Ota et al. 2004) and XMM-Newton (Zhang et al. 2005) revealed that the surface brightness profile is better fit by a superposition of two ICM models rather than one. They suggested on the Basis of the isothermal temperature profile that the individual clusters of the system had returned to equilibrium after the collision and that consequently the encounter must have occurred several Gyr ago.

Recently, a weak lensing analysis presented by Jee et al. (2007) revealed a ring-like structure in the projected matter distribution. They proposed that DM from the cores of the clusters had been disrupted and ejected from the systems by the collision, and they demonstrated that such features could be reproduced in a simulation of a collision of two pure DM halos. From this they suggested the current state of the system is ~1–2 Gyr past the pericentric passage of the cluster cores. We are addressing this issue in a separate paper (ZuHone et al. 2009). Jee et al. (2007) also demonstrated that if the system is modeled as two ICM profiles in superposition, the mass determination based on hydrostatic equilibrium agrees with the result from their lensing analysis.

If the merger scenario for Cl 0024+17 is correct, it raises several important questions: how long after the collision would
the clusters appear relaxed, and correspondingly when would a mass estimate based on hydrostatic equilibrium yield an accurate measurement? What effect does viewing such a collision along the line of sight, with both cluster components in superposition, have on the observed density and temperature structure? In this paper, we seek to provide answers to these questions by simulating a similar high-speed collision between two clusters of galaxies. Most importantly, we include the dynamics of the cluster gas, which were not included in the previous simulations.

Throughout this paper we assume a flat CDM cosmology with $h = 0.5$, $\Omega_m = 1.0$, as in Ota et al. (2004).

2. SIMULATIONS

2.1. Method

We performed our simulations using FLASH, a parallel hydrodynamics/N-body astrophysical simulation code developed at the Center for Astrophysical Thermonuclear Flashes at the University of Chicago (Fryxell et al. 2000). FLASH uses adaptive mesh refinement (AMR), a technique that places higher-resolution elements of the grid only where they are needed. In our case, we are interested in capturing sharp ICM features like shocks and “cold fronts” accurately, as well as resolving the inner cores of the cluster DM halos. As such it is particularly important to be able to resolve the grid adequately in these regions. AMR allows us to do so without needing to have the whole grid at the same resolution. FLASH solves the Euler equations of hydrodynamics using the Piecewise-Parabolic Method (PPM) of Colella & Woodward (1984), which is ideally suited for capturing shocks. FLASH also includes an N-body module which uses the particle-mesh method to solve for the forces on gravitating particles. The gravitational potential is computed using a multigrid solver included with FLASH (Ricker 2008).

2.2. Initial Conditions

The cluster DM halos are initialized using the Navarro-Frenk-White profile (NFW; Navarro et al. 1997) density profile, where we follow the method of Kazantzidis et al. (2006). The NFW functional form is used for $r \leq r_{200}$:

$$\rho_{\text{DM}}(r) = \frac{\rho_s}{r/r_s(1 + r/r_s)^2}, \quad r \leq r_{200}. \quad (1)$$

Outside of $r_{200}$, to keep the mass of the halo finite and to avoid an unphysical distribution function, we implement an exponential cutoff that turns off the profile on a scale $r_{\text{decay}}$, a free parameter which we set to 0.1$r_{200}$:

$$\rho_{\text{DM}}(r) = \frac{\rho_s}{c_{200}(1 + c_{200})^2} \left( \frac{r}{r_{200}} \right)^\kappa \exp \left( \frac{-r - r_{200}}{r_{\text{decay}}} \right), \quad r > r_{200}. \quad (2)$$

Here $r_{200}$ is the radius within which the mean mass density is 200 times the cosmic mean, $r_s$ is the NFW scale radius, and $c_{200} \equiv r_{200}/r_s$ is the NFW concentration parameter. We require that at $r_{200}$ the profile and its logarithmic slope be continuous. This is achieved via the parameter $\kappa$:

$$\kappa = -\frac{1 + 3c_{200}}{1 + c_{200}} + \frac{r_{200}}{r_{\text{decay}}}. \quad (3)$$

Truncating the cluster NFW profiles at $r_{200}$ is unphysical. In real DM halos, the density profile is expected to remain NFW-like out to where the density of the halo reaches the average matter density of the universe (Prada et al. 2006; Tavio et al. 2008). The single cluster tests we have performed (as well as those performed in other studies, e.g., Ricker & Sarazin 2001) demonstrate that the truncated density profile is stable for the length of the run, with minor steepening of the profile near the cutoff radius.

The truncation also reduces the halo mass by approximately 25%. Assuming the clusters fell in from infinity, the larger halo masses would accelerate the halos to an impact velocity approximately 12% larger than the value we use. After the collision, the corresponding deceleration due to gravity would also be higher. The effect of the larger halo masses on the deceleration due to dynamical friction ($f_{\text{dyn}} \propto \rho M/2v^2$) is more complicated to determine, since although the density in the outskirts of the halos is higher (thus increasing the dynamical friction), the velocity of clusters would also be higher due to the increased acceleration (thus decreasing it). The higher infall velocity of the clusters and the increased mass outside $r_{200}$ might also lead to some increase in the dissipation of the shock energy, and therefore in the heating of the gas in the outskirts. However, in general any such effects are not accessible to current X-ray observations, due to the low densities in the cluster outskirts. We conclude that the effects due to truncation of the cluster density profile are not likely to be significant for the purposes of this study.

To initialize the gas density we choose a Burkert profile:

$$\rho_{\text{gas}}(r) = \frac{\rho_c}{(1 + (r/r_s)^2)(1 + r/r_c)^2}, \quad (4)$$

which originally (Burkert 1995) was given as a fitting function for DM profiles of dwarf galaxies but is also a good fit to the gas density profiles of non-cooling-core clusters (A. Kravtsov 2007, private communication). The more traditional $\beta$-model (Cavaliere & Fusco-Femiano 1976) is a poorer fit to the gas density profile at large $r$ in both simulations and observations (Vikhlinin et al. 2006; Hallman et al. 2007; Nagai et al. 2007). (However, we follow Ota et al. 2004 and Zhang et al. 2005 and fit $\beta$-model profiles to the X-ray surface brightness profiles in our simulated observations.)

The gas density is also fitted to an exponential taper at $r_{200}$, extending to the radius at which it equals the mean baryonic density of the universe. For the gas profiles, we choose the core radius $r_c$ to be roughly half the scale radius of the DM profile (Ricker & Sarazin 2001). We fix the gas mass fraction at $r_{200}$ to 0.12 in line with observations of real clusters (e.g., Vikhlinin et al. 2006, Sanderson et al. 2003), and the measurement of Ota et al. (2004).

From these parameters the central gas densities $\rho_c$ can be determined. The equation of state for the gas is an ideal-gas equation of state with $\gamma = 5/3$ and mean atomic mass $\mu = 0.592$. We determine the pressure, temperature, and internal energy profiles by assuming our functional forms for DM and gas density and numerically integrating the equation of hydrostatic equilibrium. The values used for the cluster parameters are given in Table 1.

Following Czoske et al. (2002) and Jee et al. (2007) we assume a mass ratio of 2:1 for the clusters. In our simulation the clusters are initialized so that their centers are separated by the sum of their respective $r_{200}$ values (approximately 3 Mpc), and they are given an initial relative velocity $v_{\text{rel}} = 3000$ km s$^{-1}$. This value is chosen because it is the inferred relative velocity of the two redshift components of Cl 0024+17 seen in the redshift histograms of Czoske et al. (2002). The results of Czoske et al. (2002) and Jee et al. (2007) suggest the clusters have already completed their first pericentric passage, and Czoske
et al. (2002) show that in their collision simulation an initial velocity of \(~3000 \text{ km s}^{-1}\) is needed to reproduce the observed distribution of redshifts after the collision. This value for the velocity is approximately \(2v_{ff}\) for the clusters, where \(v_{ff}\) is the free-fall velocity from infinity. Such an initially high relative velocity might be difficult to achieve in a \(\Lambda\)CDM universe (see, e.g., Hayashi & White 2006). However, our choice is motivated by our desire to match the relative inferred velocity of the cluster components of Cl 0024+17.

We refine the adaptive mesh using the second derivative of density, temperature, and pressure to capture the sharp features in the gas dynamics, and using the matter density to resolve the cores of the clusters. For our box size of 14.29 Mpc we achieve a finest resolution of \(\Delta x = 13.96\) kpc.

### 3. RESULTS

#### 3.1. Qualitative Description

Figures 1 and 2 show slices of density and temperature, respectively, through the \(z = 0\) coordinate plane at different times in the simulation (the \(x\)-axis is the collision axis). From \(t = 0.0–0.9\) Gyr the clusters approach each other and a shock front forms. At \(t = 1.0\) Gyr the core of the smaller cluster collides with the core of the larger cluster, driving a shock wave forward into the larger core and displacing the larger cores gas from the collision axis into streams of cold gas. There is also a stream of dense, cold gas that is pulled directly between the two DM halos. Later on, the heads of these streams of gas, along with hotter gas from between the clusters, begin to fall into the potential of the larger halo and by \(t = 2.0\) Gyr have fallen in completely. As for the gas core of the smaller cluster, it is penetrated shortly after the collision by a reverse shock, but this shock weakens as it traverses the core and so the latter remains cool, in agreement with similar investigations of high-velocity cluster mergers by Takizawa (2005) and Milosavljević et al. (2007). In this process some of the gas of the smaller cluster is also ram-pressure stripped, and a contact discontinuity forms that is similar to that observed in the 1E0657-56, and in the simulations of the latter (Springel & Farrar 2007; Mastroietti & Burkert 2008).

After penetrating the larger gas core the smaller core is forced to lag behind its DM core by ram pressure until it encounters regions of lower density (\(t > 1.2\) Gyr). At this point the gas falls back toward the DM core but overshoots the potential and begins to slosh back and forth inside it. At late times the gas of the clusters is still settling into their respective DM potential wells, and the temperature structure of the gas is still complicated. Due to the high initial velocity of the collision, the clusters are in an unbound orbit and by the end of the simulation the separation between their respective DM halo centers is still increasing. This is in contrast to many previous works involving mergers (e.g., Ricker & Sarazin 2001; Poole et al. 2006), which assumed an initial velocity \(v \approx v_{ff}\).

#### 3.2. Mock X-ray Observations

For the X-ray observations we view the system along the line of centers. Since we do not know the current state of the actual collision, we set each individual observation as if it were being observed at a redshift \(z = 0.395\). At this redshift for the assumed cosmology \(\Omega = 0.30\), \(\Lambda = 0.70\) Figure 3 shows an example of a smoothed mock X-ray image. For each observed time we extract a radial surface brightness profile and a radial temperature profile.

Cluster surface brightness profiles are extracted for the energy range 0.5–5.0 keV, within a circle centered on the surface brightness peak with a radius of 400" (\(\approx 2500\) kpc). Figure 4 shows the surface brightness profiles for times \(t = 2.0, 2.5,\) and 3.0 Gyr. The profiles are fitted with the \(\beta\)-model (Cavaliere & Fusco-Femiano 1976):

\[
S_X(r) = S_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta + 1/2}.
\]

We fit with a single \(\beta\)-model and a sum of two \(\beta\)-models. The \(\chi^2\)-statistic is used to fit the profiles. We follow Ota et al. (2004) and Jee et al. (2007) in fixing one of the \(\beta\) parameters to unity, as there exists a strong degeneracy between this parameter and its corresponding core radius \(r_c\). We include the background constant as a free parameter in the single \(\beta\)-model fit, but freeze this value for the double \(\beta\)-model fit. The fitted profiles for the \(t = 3.0\) Gyr case are shown in Figure 5. The values of the fitted parameters for epochs \(t = 2.0, 2.5,\) and 3.0 Gyr are given in Tables 2 and 3. Errors are quoted at the 90% confidence level.

### Table 1

| Cluster | \(M_{200} (M_\odot)\) | \(r_{200} (\text{kpc})\) | \(c_{200}\) | \(\eta_{\text{c}} (\text{cm}^{-3})\) | \(r_{\text{c}} (\text{kpc})\) |
|---------|----------------|----------------|--------|----------------|----------------|
| 1 | \(6.0 \times 10^{14}\) | 1739.79 | 5.0 | 0.020 | 198.83 |
| 2 | \(3.0 \times 10^{14}\) | 1380.87 | 7.0 | 0.062 | 98.65 |
Figure 1. Slices of gas density through the $z = 0$ coordinate plane for times $t = 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, \text{ and } 3.0$ Gyr. The color scale is logarithmic. Each panel is 10 Mpc on a side.

Figure 2. Slices of gas temperature through the $z = 0$ coordinate plane for times $t = 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, \text{ and } 3.0$ Gyr. The color scale is logarithmic. Each panel is 10 Mpc on a side.

Figure 3. Mock 40 ks raw counts image of the simulation viewed along the line of centers of the clusters in the 0.5–5.0 keV band. The image has been smoothed using a Gaussian with a fixed kernel radius of 3 pixels. Color scale units are counts pixel$^{-1}$. The time is $t = 3.0$ Gyr, $\sim2$ Gyr after the collision.
Figure 4. Plots of surface brightness vs. projected radius for times $t = 2.0, 2.5,$ and $3.0$ Gyr.

The projected temperature profiles for $t = 2.0, 2.5,$ and $3.0$ Gyr are shown in Figure 6. The profiles were generated by extracting spectra from four annular regions in the $0.5–7.0$ keV band centered on the peak of the surface brightness profile. Each is fitted with a MEKAL model, using the $\chi^2$-statistic with grouping to ensure at least 15 photons per bin. The radial extent of the temperature profiles is $125\arcmin$ ($\approx 800$ kpc), which is slightly greater than the radial range for which the temperature profile was extracted in Ota et al. (2004). Single-temperature fits to the spectrum of the whole cluster in the $0.5–7.0$ keV band for $t = 2.0, 2.5,$ and $3.0$ Gyr are given in Table 4.

Figure 5. Plots of single and double $\beta$-model fits for $t = 3.0$ Gyr, $\sim 2$ Gyr after the collision.

4. DISCUSSION

4.1. The Surface Brightness and Temperature Profiles

The feature in the radial profile of Cl 0024+17 pointed out by Ota et al. (2004) and Jee et al. (2007) was that a double $\beta$-model fit is a better fit to the data, as a single $\beta$-model fit underestimates the central surface brightness. The surface brightness profile of Cl 0024+17 and the single and double $\beta$-model fits to the profile are shown in Figure 7. The difference between the fits is significant; there is a difference in the $\chi^2$-statistic of $\sim 60$ for a difference of 2 degrees of freedom.

In our mock cluster observations, we find that at later times, it is also possible to make a distinction between the two surface brightness components of the two clusters from the difference in the fitted $\chi^2$-statistic (see Tables 2 and 3). At the $t = 2.0$ Gyr epoch, $\Delta \chi^2 \approx 45$ for a difference of only 2 degrees of freedom, and at later times is even larger ($\Delta \chi^2 \approx 200–260$ for a difference of 2 degrees of freedom). We also note that we can use the $\Delta \chi^2$-test to distinguish between the two clusters in our initial conditions, which we also show in Tables 2 and 3.

In Cl 0024+17, the fitted spectral temperature of $T = 4.47$ keV seems low for a system undergoing a collision or merger. In our mock observations we note a similar phenomenon; the fitted temperatures in the mock observations are significantly lower than what might be expected given the temperatures observed in the simulation. In our simulated system, the hottest cluster gas is in the larger cluster and is at a temperature of $\sim 5–6$ keV at later times. However, the measured temperatures in the mock X-ray observations barely reach $\sim 3$ keV. A close look at the temperature distribution in the simulation itself (Figure 8) reveals that the highest temperature gas is confined to the central region of the larger cluster, and the denser gas of the smaller cluster is colder, around 3 keV. In projection along the line of sight, the lower-temperature, denser gas “washes out” the higher-temperature, less dense gas, and the complicated, two-component temperature structure of the clusters is lost because of the strong density dependence of the X-ray emission ($\propto \rho^2$).

Figure 9 shows the profile of the mass-weighted temperature over the same range as Figure 6 for $t = 3.0$ Gyr. The lack of
temperatures higher than \( \sim 3 \) keV demonstrates that the denser, colder gas provides the dominant contribution to the X-ray emission.

The single-temperature fits are in general agreement with our projected temperature profiles. Attempting to fit the cluster temperature using a two-temperature model resulted in no significant decrease in the \( \chi^2 \)-statistic from the single-temperature fits, so on the basis of this analysis we cannot distinguish the two different average temperatures of the two clusters.

At late times there is still some moderate variation in the projected temperature profile with time, indicative of the continuing evolution of the system, though the average temperature of the cluster is roughly constant with time. In Ota et al. (2004), the observed isothermal temperature profile of Cl 0024+17 (reproduced in Figure 10) was taken as evidence that the merger was not recent (i.e., it was more than a few Gyr ago). Our results show that if viewed along the line of sight \( \sim 2 \) Gyr after the merger, the temperature structure of the system can appear more regular in projection than it actually is (e.g., the structure seen in Figure 2). If the results of Jee et al. (2007) regarding a ring-like DM structure indicate the clusters are being viewed along the line of sight shortly after the merger, our results show that the system can still appear relatively relaxed. This agrees with previous results of mock X-ray observations of simulations of galaxy cluster mergers (e.g., Ricker & Sarazin 2001, Poole et al. 2006).

Finally, our observed spectral temperature from our simulations of \( T \sim 2.6 \text{–} 2.8 \) keV is somewhat lower than the \( T \sim 4.47 \) keV for Cl 0024+17 measured by Ota et al. (2004) or the \( T \sim 4.25 \) keV measured by Jee et al. (2007). If the collision scenario for Cl 0024+17 is correct, this indicates that the initial conditions for our simulation are not identical to the pre-merger conditions for the real cluster. A higher impact velocity or a change in the masses of the clusters could account for the temperature difference.

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**Table 2**

| \( t \) (Gyr) | \( r_1 \) (kpc) | \( S_{01} \) (counts s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\)) | \( \beta_1 \) | \( \chi^2/dof \) |
|-----------|---------------|------------------|--------|----------------|
| 0.0       | 97.65 \( ^{+10.18} \) \( ^{-0.96} \) | \( 3.81^{+0.02} \) \( ^{-0.02} \) \( \times 10^{-6} \) | 0.798 \( ^{+0.001} \) \( ^{-0.003} \) | 407.61/195 |
| 2.0       | 172.04 \( ^{+7.58} \) \( ^{-1.73} \) | \( 1.42^{+0.03} \) \( ^{-0.03} \) \( \times 10^{-7} \) | 0.714 \( ^{+0.009} \) \( ^{-0.004} \) | 305.14/195 |
| 2.5       | 235.21 \( ^{+2.24} \) \( ^{-1.39} \) | \( 1.25^{+0.03} \) \( ^{-0.03} \) \( \times 10^{-7} \) | 0.964 \( ^{+0.005} \) \( ^{-0.031} \) | 491.04/195 |
| 3.0       | 150.24 \( ^{+1.86} \) \( ^{-12.50} \) | \( 1.42^{+0.03} \) \( ^{-0.03} \) \( \times 10^{-7} \) | 0.733 \( ^{+0.027} \) \( ^{-0.027} \) | 423.58/195 |

**Table 3**

| \( t \) (Gyr) | \( r_2 \) (kpc) | \( S_{02} \) (counts s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\)) | \( \beta_2 \) | \( \chi^2/dof \) |
|-----------|---------------|------------------|--------|----------------|
| 0.0       | 89.24 \( ^{+3.16} \) \( ^{-0.33} \) | \( 3.73^{+0.04} \) \( ^{-0.04} \) \( \times 10^{-6} \) | 1.0 (F) | 204.65 \( ^{+1.32} \) \( ^{-0.49} \) |
| 2.0       | 39.91 \( ^{+3.41} \) \( ^{-0.29} \) | \( 8.18^{+0.31} \) \( ^{-0.29} \) \( \times 10^{-8} \) | 1.0 (F) | 270.00 \( ^{+1.11} \) \( ^{-0.32} \) |
| 2.5       | 79.28 \( ^{+3.34} \) \( ^{-0.31} \) | \( 2.26^{+0.15} \) \( ^{-0.15} \) \( \times 10^{-7} \) | 1.0 (F) | 282.00 \( ^{+1.31} \) \( ^{-0.41} \) |
| 3.0       | 82.12 \( ^{+8.12} \) \( ^{-3.94} \) | \( 2.51^{+0.16} \) \( ^{-0.16} \) \( \times 10^{-7} \) | 1.0 (F) | 316.24 \( ^{+2.16} \) \( ^{-4.89} \) |

**Figure 6.** Plot of temperature profile vs. projected radius for times \( t = 2.0, 2.5, \) and 3.0 Gyr.

**Figure 7.** Cl 0024+17 X-ray surface brightness profile and single and double \( \beta \)-model fits. Reproduced with permission from Ota et al. (2004).

**Table 4**

| \( r \) (Gyr) | \( T_{\text{spec}} \) (keV) | \( \chi^2/dof \) |
|-----------|------------------|----------------|
| 2.0       | 2.67 \( ^{+0.70} \) \( ^{-0.66} \) | 140.62/177 |
| 2.5       | 2.83 \( ^{+0.80} \) \( ^{-0.76} \) | 147.98/174 |
| 3.0       | 2.71 \( ^{+0.19} \) | 128.07/167 |
4.2. The Reliability of Hydrostatic Mass Estimates

Though the temperature and surface brightness profiles are undergoing considerable evolution even at late times, it is still relevant to ask how accurate a mass estimate would be under the assumption of hydrostatic equilibrium. As previously noted, Ota et al. (2004) and Jee et al. (2007) made estimates of the mass of Cl 0024+17 using single and double $\beta$-model fits to the surface brightness profile together with an isothermal temperature profile. Although our temperature profile is not strictly isothermal, existing methods for temperature deprojection assume spherical symmetry, so we do not attempt such a deprojection here. If we assume a cluster temperature $T_{\text{spec}}$ given by the spectral temperature fit to the entire cluster, we can arrive at a rough estimate for the mass of the system under the assumption of hydrostatic equilibrium.

For a $\beta$-model fit to the cluster gas, the projected cluster mass within a cylindrical volume for a given temperature, $\beta$, and core radius $r_c$ can be estimated by (Ota et al. 1998; Jee et al. 2005)

$$M_{X,\beta}(R) = 1.78 \times 10^{14} \beta \left(\frac{T}{\text{keV}}\right) \left(\frac{R}{\text{Mpc}}\right) \frac{R/r_c}{\sqrt{1+(R/r_c)^2}} M_\odot,$$

where $R$ is the projected radius, $T$ is the gas temperature, and $\beta$ is the $\beta$-model index. We compute the estimated mass within the arc radius of the lensed galaxy in Cl 0024+17, $r_{\text{arc}} = 35'/223.65$ kpc. For the double $\beta$-model fits we assume the same temperature for both cluster components, and we add the mass contributions from the two fits together. Table 5 shows the estimated masses from the single and double $\beta$-model fits for times $t = 2.0, 2.5,$ and $3.0$ Gyr. Errors are quoted at the 90% confidence level. It is clear from the table that assuming a single-cluster model for the system will underestimate the projected mass by a factor $\sim 2–3$, whereas assuming a double-cluster model will estimate the projected mass to within $\sim 10%$. This is in agreement with the results of Jee et al. (2007).

4.3. The Effect of A Slightly Off-Axis Collision

In our simulated head-on collision, the gas in the clusters is significantly disrupted and by the end of the simulation is still settling into the potential wells created by the DM. If instead of colliding head-on the encounter were allowed to be slightly off-axis, this would result in less disruption of the cluster gas cores. Presumably the gas would relax more quickly and an even more accurate mass determination could be made under the assumption of hydrostatic equilibrium. In addition, in a
slightly off-axis collision viewed along the line of sight the two cluster components would be more clearly distinguished in the X-ray emission. Two-component fits to both the X-ray surface brightness and the temperature of the different components would enable a more accurate mass determination. This is a large parameter space of simulations that will be explored in future investigations, but is beyond the scope of this paper.

4.4. Implications for X-ray Surveys

These results have important implications for X-ray surveys. Neighboring galaxy clusters viewed in superposition, whether undergoing mergers or not, may bias temperature measurements based on spectral fitting. This can have an effect particularly on X-ray-based scaling relations. For example, previous simulated observations of merging clusters have demonstrated that for mergers occurring along the line of sight, the clusters appear to have higher temperatures for their mass (Ricker & Sarazin 2001; Poole et al. 2007). Our investigation shows that clusters viewed in superposition can make a cluster appear colder than it actually is if the colder cluster's gas is significantly denser. In addition, discrepancies between hydrostatic and lensing mass estimates may in some cases be attributed to the existence of multiple components viewed along the line of sight, as is apparent in the case of Cl 0024+17. Detailed analysis of X-ray observations would be required to discern such superpositions.

One possible way to correct for and identify such superposition effects is by using the optical redshifts of the cluster galaxies to identify separate cluster components, as Czoske et al. (2001, 2002) did in the case of Cl 0024+17. To reliably identify such separate cluster components requires accurate redshifts. Because spectroscopic redshifts are only feasible for the nearest or brightest cluster galaxies, cluster surveys must rely on photometric redshift estimators. Large optical surveys such as zCOSMOS (Lilly et al. 2007), Combo-17 (Wolf et al. 2003), and the upcoming Dark Energy Survey (The Dark Energy Survey Collaboration 2005) have photometric redshift errors $\sigma_z \sim (0.02 - 0.05)(1 + z)$.

If the only redshift determination for Cl 0024+17 were via photometry, would the separation between the two components still be discernible? To answer this question we constructed a mock “galaxy” catalog from our simulation. We chose DM particles from the two clusters as proxies for the cluster galaxies (120 from the smaller cluster, 240 from the larger) and assumed a value for $\sigma_z$. We constructed redshift histograms for the resulting galaxy distributions and fitted them to both a Gaussian distribution and a sum of two Gaussian distributions:

$$f_{\text{single}} = A_0 e^{-(z - \mu)^2/2\sigma_z^2}$$

$$f_{\text{double}} = A_1 e^{-(z - \mu_1)^2/2\sigma_1^2} + A_2 e^{-(z - \mu_2)^2/2\sigma_2^2}.$$  

The fitted parameters for these distributions for varying $\sigma_z$, given a choice of mock galaxies from our simulation, are shown in Table 6. For low values of $\sigma_z$, the mean values of the two redshift distributions are statistically distinguishable, but for higher values they are not. The histograms shown in Figures 11...
and 12 demonstrate that for \( \sigma_z \approx 0.005–0.01 \) the skewness of the distribution of galaxies is evident, but when the redshift error increases to \( \sigma_z \gtrsim 0.02 \), the resulting redshift distribution is indistinguishable from that of a single cluster.

At a redshift of \( z \approx 0.4 \) (Cl 0024+17), the expected photometric redshift errors from optical surveys would be too large at this time to distinguish between the two cluster components (\( \sigma_z \approx 0.03–0.07 \)), and at a redshift of \( z \approx 1 \) it would be worse (\( \sigma_z \approx 0.04–0.1 \)). Identification of line-of-sight mergers and collisions from redshift distributions likely will be restricted to clusters for which we have spectroscopic redshifts available.

Our X-ray fitting results might be taken to suggest that X-ray surface brightness profiles could be used in place of galaxy redshift distributions to detect clusters seen in superposition. To test this hypothesis, we placed our simulated clusters at the epoch \( t = 3.0 \) Gyr (\( \sim 2 \) Gyr after the collision, where we can clearly distinguish both cluster components) at two redshifts, the current redshift of \( z = 0.395 \) and a redshift of \( z = 1.0 \). The same analysis of the surface brightness profiles as above was performed for exposure times of 10 ks, 40 ks, and 240 ks; the former being a more typical exposure time for a given cluster in an X-ray survey. We focus here on the difference in the \( \chi^2 \) between the single and double \( \beta \)-model fits. The resulting \( \Delta \chi^2 \) for the fitted surface brightness models corresponding to the different exposure times for the different redshifts is shown in Table 7.

![Figure 12. Number of redshifts per bin vs. redshift, \( \sigma_z = 0.02 \) and \( \sigma_z = 0.08 \).](image)

Table 7

\( \Delta \chi^2 \) for Different Exposure Times and Redshifts

| \( t_{\text{exp}} \) (ks) | \( z = 0.395 \) | \( t = 3.0 \) Gyr | \( z = 1.0 \) | \( t = 2.0 \) Gyr |
|-------------------------|----------------|----------------|----------------|----------------|
| 10  | 177.69/96 – 113.21/94 | 99.20/96 – 86.05/94 | 96.41/96 – 94.40/94 | 115.42/96 – 111.74/94 |
| 40  | 425.31/195 – 203.44/193 | 242.51/195 – 173.29/193 | 305.14/195 – 245.83/193 | 217.34/195 – 209.53/193 |
| 240 | 1497.05/195 – 439.33/193 | 770.37/195 – 287.46/193 | 428.73/195 – 245.83/193 | 280.26/195 – 228.22/193 |

5. CONCLUSIONS

The galaxy cluster Cl 0024+17 is thought to be a colliding system of galaxy clusters that is viewed along the collision axis. We have performed a simulation of a high-velocity head-on collision of galaxy clusters and created mock X-ray observations, viewing the clusters from the same direction. Previous investigations of this system had focused on the collisionless dynamics of the galaxies and the DM; we also include gas in our simulation. The mock X-ray observations of our simulation indicate that the X-ray emitting gas is still undergoing moderate evolution at times \( \sim 1–2 \) Gyr after the collision. However, much of the complicated structure in density and temperature is obscured due to projection effects. The X-ray surface brightness profile is better fit by a superposition of \( \beta \)-models than a single \( \beta \)-model at times \( t = 1–2 \) Gyr after the collision, corresponding to the observed situation in Cl 0024+17. The cluster gas in the center appears colder than it really is due to the projection of denser, colder gas along the line of sight of the hotter gas. The temperature profile exhibits only moderate evolution with
time, though the temperature distribution of the clusters in the
simulation has significant structure. Though a mass estimate of
the cluster assuming one cluster component in hydrostatic equi-
lbrium underestimates the mass by a factor of \( \sim 2-3 \), a mass
estimate based on the assumption of two galaxy clusters in su-
perposition comes close (\( \sim 10\% \)) to the actual projected mass of
the system within the arc radius \( r_{\text{arc}} \), in agreement with the mass
measurements made of the cluster Cl 0024+17 under the same
assumptions. These results may be valuable when looking at
clusters discovered in X-ray surveys. With current photometric
redshift errors it will not likely be possible to distinguish such
line-of-sight collisions from single clusters discovered in X-ray
surveys at high redshift by identifying separate galaxy concen-
trations. However, our results show that it may be possible to
distinguish merging clusters and clusters in projection from sin-
gle clusters by testing multiple model fits against single-model
fits, though this will become more difficult at higher redshifts.

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APPENDIX

MOCK OBSERVATION GENERATION AND
VERIFICATION STUDY

Our mock X-ray observation generation procedure consists of
two steps: we first use the FLASH input of density and
temperature to create a flux map in sky coordinates for a range of
energies. In doing this we closely follow the procedure outlined
in Gardini et al. (2004). Second, we use this flux map as a “user
source” in MARX to generate photons in the cluster as a
set of weights, and when performing the fit we convolve the
model with a one-dimensional point-spread function (PSF). For
the spectral analysis, we construct weighted RMFs and ARFs (Redistribu-
tion Matrix Files and Auxiliary Response Files), and
use them to fit a background-subtracted spectrum. Our spectra
are grouped so that each bin has at least 15 counts.

In order to ensure the accuracy of our MARX simulations,
we have performed a few simple verification tests. We have
constructed two models: one, a gas sphere with a constant tem-
perature models. For these tests we consider the model verified
when we recover the input models. Table 10 shows the number
of photons \( s^{-1} \) at a given energy \( h\nu \) is given by

\[
L'_\nu = \int V' \nu \, \epsilon' \, dV' = \epsilon' \, L \, EM, \quad \text{(A2)}
\]

where the quantity \( EM = \int V' \nu \, n_e n_H \, dV' \) is the emission measure.
The measured flux of photons at a specific energy at a redshift
\( z \) is given by

\[
F'_{\nu} = \frac{(1 + z)^2 L'_{\nu}(1+z)}{4\pi D_L^2}, \quad \text{(A3)}
\]

where \( D_L \) is the luminosity distance for the given redshift and
cosmology.

This flux map is then used to generate photons in MARX
when using the “user source” implementation. The map is taken as
an input and used as a distribution function for the photons
to determine their position in sky coordinates, energy, and
time of detection. In the cases considered here, the FLASH
zone size is larger (typically by a factor of \( \sim 4 \)) than the size
-compact corresponding to a Chandra pixel, Within this FLASH zone
size the photon positions are uniformly distributed. After the
events file is generated, we re-bin the image by this factor to
perform our spatial analysis.

For the spatial analysis, we construct an exposure map for the
ACIS-S chips with the input spectrum of the cluster as a
set of weights, and when performing the fit we convolve the
model with a one-dimensional point-spread function (PSF). For
the spectral analysis, we construct weighted RMFs and ARFs
(Redistribution Matrix Files and Auxiliary Response Files), and
use them to fit a background-subtracted spectrum. Our spectra
are grouped so that each bin has at least 15 counts.

In order to ensure the accuracy of our MARX simulations,
we have performed a few simple verification tests. We have
constructed two models: one, a gas sphere with a constant tem-
perature and a \( \beta \)-model density profile, and the other, two gas
spheres, each with different temperatures and \( \beta \)-model param-
eters. We then subjected them to the same analysis as our simu-
lated clusters in FLASH. In the single-cluster case, we verify
that the surface brightness fits we recover the core radius \( r_c \),
\( \beta \)-parameter, and central surface brightness \( S_0 \). Also, we verify
in the spectral fit that we recover the model temperature for the
fit to the whole cluster, the normalization of the spectrum, and
the isothermal temperature profile. For the two-cluster case, we
verify that the two cluster components can be distinguished and
that the corresponding \( \beta \)-model parameters are recovered (as
in the simulated clusters, we find that we cannot distinguish a
single spectral temperature model from a sum of spectral tem-
perature models). For these tests we consider the model verified
if we can recover the model parameters within the 1\( \sigma \) errors.

For the spatial fitting, we find that as we increase the expo-
sure time of the observation, systematic effects become more
important. At an exposure time of \( t_{\text{exp}} = 240 \) ks we recover
the fitted parameters for both the single and double \( \beta \)-model cases.
This corresponds to the highest exposure time for our
simulated clusters. These results are shown in Tables 8 and 9.
However, as we go to higher exposure times, we find that we
cannot recover the input models. Table 10 shows the number

| Type | \( r_c \) (kpc) | \( \beta \) | \( S_0 \) (counts s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\)) | \( \chi^2 / \text{dof} \) | \( T_{\text{spec}} \) (keV) | \( \chi^2 / \text{dof} \) |
|------|---------------|-----|-----------------|---------------|-----------------|---------------|
| Model | 100 \( \pm 0.005 \) | 1 | \( 6.24 \times 10^{-9} \) | ... | 2.0 | ... |
| Fitted | 100.50 \( \pm 0.02 \) | 1.010 \( \pm 0.021 \) | \( (8.18 \pm 0.11) \times 10^{-9} \) | 197.92/195 | 197.92/195 | 197.92/195 |
of parameters which are not recovered and the corresponding reduced $\chi^2$-statistic for increasing exposure time. For an exposure time of 1 Ms, we can verify the single $\beta$-model but cannot verify the double $\beta$-model, and for an exposure time of 4 Ms we cannot verify either.

Possible systematic effects may include the modeling of the PSF (which is energy and spatially dependent), ACIS read-out errors and the precise dependence of the exposure map on the input spectrum. We note that for the fits that we cannot recover the parameters the resulting $\chi^2$-statistic is large, indicating that the systematic errors are dominating the statistical errors. We also note that even for these cases we find the differences in the fitted parameters and the true parameters are at most on the order of a few percent.

For the spectral fitting we find that up to a high exposure time of 4 Ms that we recover the input temperature and the normalization of the spectrum, as well as the isothermal temperature profile. The results of the fit are shown in Table 11 and the temperature profile is shown in Figure 13.

### Table 9

| $\chi^2/d.o.f.$ | $S_{2,1}$ (cts s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$) | $S_{2,2}$ (cts s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$) | $\chi^2/d.o.f.$ |
|----------------|-----------------|-----------------|-----------------|
| Model          | 200             | 0.7             | 1.38 $\times$ 10$^{-8}$ |
| Fitted         | 198.00$^{+2.41}_{-0.76}$ | 0.701$^{+0.029}_{-0.003}$ | (1.40$^{+0.02}_{-0.01}$) $\times$ 10$^{-8}$ |

### Table 10

| $t_{exp}$ (ks) | $N_{single}$ | $N_{double}$ | $\chi^2/d.o.f_{single}$ | $\chi^2/d.o.f_{double}$ |
|----------------|-------------|--------------|--------------------------|--------------------------|
| 240            | 0/3         | 5/0          | 1.01                     | 1.11                     |
| 1000           | 0/3         | 1/5          | 1.07                     | 1.20                     |
| 4000           | 2/3         | 5/5          | 1.88                     | 2.20                     |

### Figure 13

Isothermal cluster temperature profile. Dashed line is input temperature.

### Table 11

| $T_{spec}$ (keV) | $N_1$ (10$^{14}$ cm$^{-2}$ m$_{e}h_2^{-1}$ V$^{-1}$) | $\chi^2$/dof |
|------------------|---------------------------------|-------------|
| Model            | 4.0                             | ...         |
| Fitted           | 4.01$^{+0.09}_{-0.09}$ (2.554$^{+0.021}_{-0.021}$) $\times$ 10$^{-4}$ | 91.40/424 |

### REFERENCES

Broadhurst, T., Huang, X., Frye, B., & Ellis, R. 2000, ApJ, 534, L15
Burkert, A. 1995, ApJ, 447, L25
Cavaliere, A., & Fusco-Femiano, R. 1976, A&A, 49, 137
Clowe, D., Bradac, M., Gonzalez, A. H., Markevitch, M., Randall, S. W., Jones, C., & Zaritsky, D. 2006, ApJ, 648, L109
Colella, P., & Woodward, P. R. 1984, J. Comput. Phys., 54, 174
Coneford, I. M., Meneghetti, M., Bartelmann, M., & Schirmer, M. 2006, ApJ, 642, 39
Czoske, O., Moore, B., N. Kneib, J.-P., & Soucail, G. 2002, A&A, 386, 31
Czoske, O., Kneib, J.-P., Soucail, G., Bridges, T. J., Mellier, Y., & Cuillandre, J.-C. 2001, A&A, 372, 391
Dark Energy Survey Collaboration 2005, arXiv:astro-ph/0510346
Davis, M., Efstathiou, G., Frenk, C. S., & White, S. D. M. 1985, ApJ, 292, 371
Fryxell, B., et al. 2000, ApJS, 131, 273
Gardini, A., Rasia, E., Mazzotta, P., Torn, G., De Grandi, S., & Moscardini, L. 2004, MNRA, 351, 505
Hallman, E. J., Burns, J. O., Motl, P. M., & Norman, M. L. 2007, ApJ, 665, 911
Hayashi, E., & White, S. D. M. 2006, MNRA, 370, L38
Hogan, C. J., & Dalcanton, J. J. 2000, Phys. Rev. D, 62, 063511
Jee, M. J., White, R. L., Ford, H. C., Blakeslee, J. P., Illingworth, G. D., Coe, D. A., & Tran, K.-V. H. 2005, ApJ, 634, 813
Jee, M. J., et al. 2007, ApJ, 661, 728
Kazantzidis, S., Zentner, A. R., & Kravtsov, A. V. 2006, ApJ, 641, 647
Lilly, S. J., et al. 2007, ApJS, 172, 70
Markevitch, M., Gonzalez, A. H., David, L., Vikhlinin, A., Murray, S., Forman, W., Jones, C., & Tucker, W. 2002, ApJ, 567, L27
Mastropietro, C., & Burkert, A. 2008, MNRA, 389, 967
Mewe, R., Kaasstra, J. S., & Liedahl, D. A. 1995, Legacy, 6, 16
Milosavljević, M., Koda, J., Nagai, D., Nakar, E., & Shapiro, P. R. 2007, ApJ, 661, L131
Moore, B., Gelato, S., Jenkins, A., Pearce, F. R., & Quilis, V. 2000, ApJ, 535, L21
Nagai, D., Kravtsov, A. V., & Vikhlinin, A. 2007, ApJ, 668, 1
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Ota, N., Mitsuda, K., & Fukazawa, Y. 1998, ApJ, 495, 170
Ota, N., Pointecouteau, E., Hattori, M., & Mitsuda, K. 2004, ApJ, 601, 120
Poole, G. B., Babul, A., McCarthy, I. G., Fardal, M. A., Bildfell, J. C., Quinn, T., & Mahdavi, A. 2007, MNRA, 380, 437
Poole, G. B., Fardal, M. A., Babul, A., McCarthy, I. G., Quinn, T., & Wadsley, J. 2006, MNRA, 373, 881
Prada, F., Klypin, A. A., Simonneau, E., Betancort-Rijo, J., Patiri, S., Gottlöber, S., & Sanchez-Conde, M. A. 2006, ApJ, 645, 1001
Ricker, P. M. 2008, ApJS, 176, 293
Ricker, P. M., & Sarazin, C. L. 2001, ApJ, 561, 621
Sanderson, A. J. R., Ponman, T. J., Finoguenov, A., Lloyd-Davies, E. J., & Markevitch, M. 2003, MNRA, 340, 989
Spergel, D. N., & Steinhardt, P. J. 2000, Phys. Rev. Lett., 84, 3760
Springel, V., & Farrar, G. R. 2007, MNRA, 380, 911
Takizawa, M. 2005, ApJ, 629, 791
Tavio, H., Cuesta, A. J., Prada, F., Klypin, A. A., & Sanchez-Conde, M. A. 2008, arXiv:0807.3027
Turner, M. S. 2000, Phys. Rep., 333, 619
Tyson, J. A., Kochanski, G. P., & dell’Antonio, I. P. 1998, ApJ, 498, L107
Vikhlinin, A., Kravtsov, A., Forman, W., Jones, C., Markevitch, M., Murray, S. S., & Van Speybroeck, L. 2006, ApJ, 640, 691
Wolf, C., Mesenheimer, K., Rix, H.-W., Borch, A., Dye, S., & Kleinheinrich, M. 2003, A&A, 401, 73
Zhang, Y.-Y., Böhringer, H., Mellier, Y., Soucail, G., & Forman, W. 2005, A&A, 429, 85
ZuHone, J. A., Lamb, D. Q., & Ricker, P. M. 2009, ApJ, 696, 694
Zwicky, F. 1937, ApJ, 86, 217