On the X-Ray and Mass Distribution in the Merging Galaxy Cluster 1E 0657−56: Ram Pressure-Stripping in Substructures with an NFW Density Profile

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Abstract

We investigated the X-ray and mass distribution in the merging galaxy cluster 1E 0657−56. We also studied head-on collisions of two virialized clusters with an NFW density profile in the ΛCDM universe using an N-body plus hydrodynamical code. A clear off-set of an X-ray peak from a mass peak, which is like what is reported in Clowe, Gonzalez, and Markevitch (2004), was first reproduced in N-body plus hydrodynamical simulations. We estimated the ram pressure-stripping conditions of the substructure in mergers of two NFW dark halos using a simple analytical model. We find that the ram pressure dominates the gravity of the substructure when the smaller cluster’s mass is less than approximately one tenth of the larger cluster’s mass. The characteristic X-ray and mass structures found in 1E 0657−56 suggest that neither the ram pressure nor the gravitational bound force overwhelms the other, and that the mass ratio between the progenitors is near the critical value mentioned above.

Key words: galaxies: clusters: general — galaxies: clusters: individual (1E 0657−56) — galaxies: intergalactic medium — gravitational lensing — hydrodynamics

1. Introduction

According to the standard scenario of cosmological structure formation, clusters of galaxies form through mergers of smaller subclusters. In fact, some of them are forming now. Merging clusters are the sites of structure formation in the universe, which can be investigated in detail via different types of observations. Mergers play important roles in cluster evolution. Cluster mergers cause bulk flow motion, turbulence, shocks, and/or contact discontinuities in the intracluster medium (ICM), which give us clues to investigate various physical processes in the ICM [see Sarazin (2002) for a review]. Turbulence and shocks most likely play crucial roles in particle acceleration in the ICM (e.g. Takizawa, Naito 2000; Ohno et al. 2002; Takizawa 2002; Fujita et al. 2003; Brunetti et al. 2003). Strong bulk flow motion and violent pressure changes in the ICM during mergers may affect the star-formation activities of the member galaxies (Fujita et al. 1999; Bekki, Couch 2003). N-body plus hydrodynamical numerical simulations have been carried out to study cluster merger physics (e.g. Schindler, Müller 1993; Ishizaka, Mineshige 1996; Roettiger et al. 1997; Takizawa 1999, 2000; Ricker, Sarazin 2001; Ritchie, Thomas 2002). Comparisons of such numerical simulations with different kinds of observations give us deep insight into the cluster physics.

1E 0657−56 is one of the most well-known examples of a merging cluster. It is the hottest known cluster and has a very powerful radio halo (Liang et al. 2000). Its simple geometry makes this cluster one of the most suitable cases to investigate cluster merger physics. There are two peaks in both the X-ray surface brightness distribution (Markevitch et al. 2002) and the galaxy distribution (Barrena et al. 2002), but their positions do not agree with each other. Observations of the line-of-sight velocities of the member galaxies suggest that its collision axis is almost perpendicular to the line-of-sight (Barrena et al. 2002). From X-ray observations, a bow shock and a cold front are found in front of the smaller subcluster, which suggest that its Mach number is 2–3 (Markevitch et al. 2002).

Recently, Clowe, Gonzalez, and Markevitch (2004) investigated the mass distribution in 1E 0657−56 through weak gravitational lensing. They showed clear offsets of the mass density peaks from the X-ray peaks, and that the mass distribution is quite similar to the galaxy one. The smaller substructure in mass is ahead of the X-ray one. They claim that this structure occurs because ICM experience ram pressure, but dark matter (DM) and galaxies do not. Although the above-mentioned naive ram pressure-stripping scenario seems to be correct, such characteristic off-sets of X-ray peaks to mass peaks have never been reported in past numerical simulations. In this paper, we show the first results that successfully reproduce such characteristic structures in the N-body plus hydrodynamical simulations, and discuss their implications using a simple analytical model.

The rest of this paper is organized as follows. In section 2, we describe the adopted numerical method and initial conditions for our simulations. In section 3, we present the simulation results. In section 4, we show a simple analytical estimation for a ram pressure-stripping conditions in mergers of two clusters with an NFW density profile. In section 5, we summarize the results.

2. The Simulations

2.1. The Numerical Method

In the present study, we consider clusters of galaxies consisting of two components: collisionless particles corresponding to the galaxies and DM, and gas corresponding to the ICM. When calculating gravity, both components are
considered, although the former dominates over the latter. Radiative cooling and heat conduction are not included. We use the Roe total variation diminishing (TVD) scheme to solve the hydrodynamical equations for the ICM [see Hirsch (1990)]. The hydrodynamical part of the code used here was identical with what was used by Takizawa (2005). Gravitational forces were calculated by the Particle-Mesh (PM) method with the standard FFT technique for the isolated boundary conditions [see Hockney and Eastwood (1988)]. The size of the simulation box and the number of the grid points were 11.8 Mpc × (5.92 Mpc)² and 256 × (128)², respectively. The total number of the N-body particles used in the simulations was 256 × (128)², which is approximately 4.2 × 10⁶.

2.2. Models and Initial Conditions

We considered mergers of two virialized subclusters with an NFW density profile (Navarro et al. 1997) in the ΛCDM universe (Ω₀ = 0.25, Λ₀ = 0.75) for DM. The DM masses of the larger and smaller subclusters were 1.00 × 10¹⁵ M☉ and 6.25 × 10¹³ M☉, respectively. Thus, the mass ratio was 16 : 1. The initial density profiles of the ICM were assumed to be those of a beta-model, where the core radius is half of the scale radius of the DM distribution, and β = 0.6. The gas mass fraction was set to be 0.1 inside of the virial radius of each subcluster. The parameters, such as the virial radius, r_v, and the concentration parameter, c, for each subcluster are summarized in Table 1. We calculated these parameters following a method in Appendix of Navarro, Frenk, and White (1997). The radial profiles of the ICM pressure were determined so that the ICM would be in hydrostatic equilibrium within the cluster potential of the DM and ICM, itself. The resultant temperature profiles are similar to those of the initial cluster model in Ricker, Sarazin (2001). The velocity distribution of the DM particles was assumed to be an isotropic Maxwellian. The radial profiles of the DM velocity dispersion were calculated from the Jeans equation with spherical symmetry, so that the DM particles would be in virial equilibrium in the cluster potential. The coordinate system was taken in such a way that the center of mass was at rest at the origin, and the x-axis was along the collision axis. The centers of the larger and smaller subclusters were initially located at the sides of x > 0 and x < 0, respectively. The initial distance between the subcluster’s centers was 4.93 Mpc. The initial relative velocity was estimated as in section 2 of Takizawa (1999). The resultant value is 8.98 × 10² km s⁻¹, which is approximately two thirds of the infall velocity, assuming that they were at rest at infinite distance.

3. The Simulation Results

Figure 1a shows the X-ray surface brightness distribution (colors) and projected total surface mass density (contours) at a time of 0.67 Gyr after passage of the subcluster through the core of the larger one. A clear off-set of the mass density peak from the X-ray peak is seen for the smaller subcluster remnant. The mass peak and X-ray peak are located at x ≈ 1.5 Mpc and x ≈ 1.0 Mpc, respectively. This is clearly because the ICM in the smaller subcluster is lagged by the ram pressure. Figure 1b shows the X-ray surface brightness distribution (contours) overlaid with the emissivity-weighted temperature distribution (colors) at the same epoch. A weak jump in the X-ray surface brightness distribution at x ≈ 1.5 (near the smaller mass peak) is a bow shock, and the emissivity-weighted temperature is higher on the brighter side, and vice versa. A more prominent jump in the X-ray brightness just in front of the smaller X-ray peak is a contact discontinuity, and the emissivity-weighted temperature is lower on the brighter side, and vice versa. Therefore, this will be recognized as a cold front in actual X-ray observations. Figure 2a and b show the ICM density and pressure profiles along the collision axis (y = z = 0) in front of the smaller X-ray peak, respectively. The bow shock is located at x ≈ 1.55 Mpc, where jumps are clearly seen in both the density and pressure profiles. The contact discontinuity is at x ≈ 1.1 Mpc, where a jump is seen only in the density profile, and the pressure profile does not have any discontinuity there. As for the overall ICM and DM structures of 1E 0657−56 around the west smaller X-ray and mass peak, our results agree qualitatively with the observations.

4. Discussion on the Ram Pressure-Stripping Conditions

Let us discuss the ram pressure-stripping conditions in the merger of two clusters with an NFW DM density profile. We consider the merger of two clusters with masses M₁ and M₂ (M₁ > M₂), respectively. We concentrate on the physical status of the ICM in the core region of the smaller subcluster. If the gravity on the subcluster’s ICM is weaker than the ram pressure force in unit volume, the ICM will be stripped from the substructure potential. This means

\[ \frac{G m_1 \rho_1}{r_2^2} < A (\pi r_2^2 \rho_1 v^2) \left( \frac{4}{3} \pi r_2^3 \right)^{-1}, \]

where G is the gravitational constant, and ρ₁ and ρ₂ are the central gas density of the subcluster 1 and 2, respectively. r₂ and m₂ are the scale radius of the DM profile and the DM mass inside r₂ for the cluster 2, respectively. Therefore, the relation between m₂ and M₂ is

\[ g(M_2) = \frac{m_2}{M_2} = \frac{\ln 2 - 1/2}{\ln(1 + c) - c/(1 + c)}, \]

where, c is a concentration parameter of an NFW profile, and weakly depends on the halo mass. A is a fudge factor having an order of unity. It is most likely that A ≤ 1 because all of the ram pressure force is not effective in stripping the gas from the substructure. Some might be used on the excitation of small-scale eddies through a Kelvin-Helmholtz instability, and some on the adiabatic compression and shock heating of the ICM.

| Table 1. Parameters for each subcluster. |
|------------------------------------------|
| M_M (M☉) | r_v (Mpc) | c  |
|-----------|------------|----|
| cluster 1  | 1.00 × 10¹⁵ | 1.97 | 5.66 |
| cluster 2  | 6.25 × 10¹³ | 0.784 | 7.56 |
Fig. 1. (a) Projected total surface mass density (contours) overlaid with the X-ray surface brightness distribution (colors) at a time of 0.67 Gyr after the core passage. A clear off-set of the mass density peak from the X-ray peak can be seen. (b) X-ray surface brightness distribution (contours) overlaid with the emissivity-weighted temperature distribution (colors) at the same epoch.

Fig. 2. Electron number density (a) and pressure (b) profiles along the collision axis \((y = z = 0)\) in front of the substructure at the same epoch as in figure 1. A bow shock is located at \(x \simeq 1.55\) Mpc, where jumps are clearly seen in both the density and pressure profiles. A contact discontinuity is located at \(x \simeq 1.1\) Mpc, where a jump is seen only in the density profiles, and the pressure profile has no discontinuity there.

The collision velocity, \(v\), has an order of
\[
v^2 \simeq \frac{2G(M_1 + M_2)}{R_1 + R_2},
\]
where \(R_1\) and \(R_2\) are the virial radii for cluster 1 and 2, respectively. It is convenient to introduce a new parameter, \(\alpha \equiv M_2/M_1\). Then, the stripping condition of inequality (1) becomes
\[
F(\alpha : M_1) \equiv \alpha^{2/3-w} \frac{1 + \alpha^{1/3}}{1 + \alpha} - \frac{3A}{2g(\alpha M_1)c(\alpha M_1)} < 0.
\]
In deriving inequality (4), we use the scaling relations \(R_2/R_1 = \alpha^{1/3}\) and \(\rho_2/\rho_1 = \alpha^{-w}\). In the \(\Lambda\)CDM universe \((\Omega_0 = 0.25, \lambda_0 = 0.75)\), \(w \simeq 1/4\), assuming that \(\rho_1\) and \(\rho_2\) behave like the characteristic density in an NFW profile (Navarro et al. 1997).

Figure 3 shows the function \(F(\alpha : M_1)\) for \(M_1 = 1.0 \times 10^{15} M_\odot\) in the \(\Lambda\)CDM universe \((\Omega_0 = 0.25, \lambda_0 = 0.75)\). The solid, dashed, and dot-dashed lines represent the cases of \(A = 0.6, 0.4,\) and \(0.2\), respectively. In any case, \(\alpha\) is less than \(\sim 0.1\) when \(F(\alpha) < 0\). This means that ram pressure-stripping is more effective for smaller subclusters. Although our estimation here is rather crude, it is interesting that this criteria of \(\alpha \sim 0.1\) is close to the mass ratio of our simulations, where a clear off-set appears. Obviously, such an off-set does not appear at all if the ram pressure-stripping does not work effectively. The X-ray peak will correspond to the mass peak and so on.
probably works to maintain the smaller subcluster’s gas as a distinct structure after it is stripped off the DM potential through both the magnetic tension and the suppression of heat conduction (Asai et al. 2004). The dynamical motion of the substructure, itself, possibly produces this kind of magnetic field configuration (Vikhlinin et al. 2001). Furthermore, the temperature gradients in the boundary layer might produce the magnetic field structure through Weibel-type plasma instabilities (Okabe, Hattori 2003). Three-dimensional high-resolution magnetohydrodynamic simulations will be useful in order to investigate the detailed evolution.

Please note that the off-set of an X-ray peak to a mass peak is not a structure in dynamical equilibrium, but a transient one. The characteristic timescale of the ram pressure-stripping is estimated to be $\sim R_2/v$, which becomes 0.42 Gyr for the model presented in section 2. In the simulation, it took $\sim 0.7$ Gyr to strip the ICM from the substructure potential. Certainly this is roughly equal to the above-mentioned value.

5. Summary

We investigated the X-ray and mass structures in the merging galaxy cluster 1E 0657$-56$. We first reproduced a clear off-set of an X-ray peak to a mass peak in $N$-body plus hydrodynamical simulations of mergers of two subclusters with an NFW and beta-model density profiles for DM and ICM, respectively. As for the overall ICM and DM structures of 1E 0657$-56$ around the west smaller X-ray and mass peak, our simulation results agree qualitatively with the observations. We discuss the ram pressure-stripping conditions in the mergers of two clusters with an NFW DM density profile using a simple analytical model. We find that the ram pressure dominates the gravity of the substructure when the smaller cluster’s mass is less than approximately one tenth of the larger cluster’s mass. The characteristic X-ray and DM structures found in 1E 0657$-56$ suggest that the mass ratio between the progenitors is close to the above-mentioned critical value, and that neither the ram-pressure force nor the gravity of the substructure overwhelms the other.

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