A TEXTBOOK EXAMPLE OF A BOW SHOCK IN THE MERGING GALAXY CLUSTER 1E 0657−56

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Received 2001 October 21; accepted 2002 January 15; published 2002 February 12

ABSTRACT

The Chandra image of the merging, hot galaxy cluster 1E 0657−56 reveals a bow shock propagating in front of a bullet-like gas cloud just exiting the disrupted cluster core. This is the first clear example of a shock front in a cluster. From the jumps in the gas density and temperature at the shock, the Mach number of the bullet-like cloud is 2–3. This corresponds to a velocity of 3000–4000 km s$^{-1}$ relative to the main cluster, which means that the cloud traversed the core just 0.1–0.2 Gyr ago. The 6–7 keV “bullet” appears to be a remnant of a dense cooling flow region once located at the center of a merging subcluster whose outer gas has been stripped by ram pressure. The bullet’s shape indicates that it is near the final stage of being destroyed by ram pressure and gasdynamic instabilities, as the subcluster galaxies move well ahead of the cool gas. The unique simplicity of the shock front and bullet geometry in 1E 0657−56 may allow a number of interesting future measurements. The cluster’s average temperature is 14–15 keV but shows large spatial variations. The hottest gas ($T > 20$ keV) lies in the region of the radio halo enhancement and extensive merging activity involving subclusters other than the bullet.

Subject headings: galaxies: clusters: individual (1E 0657−56) — intergalactic medium — X-rays: galaxies

1. INTRODUCTION

Galaxy clusters form via mergers of smaller subunits. Such mergers dissipate a large fraction of the subclusters’ vast kinetic energy through gasdynamic shocks, heating the outer cluster gas and probably accelerating high-energy particles (e.g., Sarazin 2001 and references therein). Shocks contain information on the velocity and geometry of the merger. They also provide a unique laboratory for studying the intracluster plasma, including such processes as thermal conduction and electron-ion equilibration (e.g., Shafranov 1957; Takizawa 1999). Some exploratory uses of X-ray data on cluster shocks were described by Markevitch, Sarazin, & Vikhlinin (1999). While many merging clusters exhibit recently heated gas (see, e.g., Henry & Briel 1995, Markevitch et al. 1999, Furusho et al. 2001, and references in those works; Neumann et al. 2001), so far only two candidate merger shock fronts were observed. One is a mild X-ray brightness edge, apparently a shock with a Mach number near 1, preceding the prominent “cold front” in A3667 (Vikhlinin, Markevitch, & Murray 2001). Another is a hot region in front of the A665 core (Markevitch & Vikhlinin 2001, hereafter MV) that shows no clear density jump, perhaps because of an unfavorable viewing geometry.

The Chandra observation of 1E 0657−56 presents the first clear example of a cluster bow shock. This $z = 0.296$ cluster was discovered by Tucker, Tananbaum, & Remillard (1995) as an Einstein IPC extended source. From ASCA data, Tucker et al. (1998, hereafter T98) derived a temperature around 17 keV, making this system one of the hottest known (see also Yaqoob 1999 and Liang et al. 2000, hereafter LHBA). ROSAT data show that 1E 0657−56 is a merger (T98). It also hosts the most luminous synchrotron radio halo (LHBA).

Below we present results from the Chandra observation of 1E 0657−56 performed in 2000 October. We use $H_0 = 100\ h\ \text{km}\ \text{s}^{-1}\ \text{Mpc}^{-1}$ and $\Omega_0 = 0.3, \Lambda = 0; \Gamma = 0.172\ h^{-1}\ \text{Mpc}$ at the cluster redshift. Confidence intervals are 90% for one parameter, unless specified otherwise.

1 Also at the University of California, San Diego.

2 A combination of blank-field observations normalized by the exposure time (see http://asc.harvard.edu/cal, click “ACIS,” then “ACIS Background”).

2. DATA ANALYSIS

1E 0657−56 was observed by ACIS-I at the focal-plane temperature of $-120^\circ\text{C}$ for a useful exposure of 24.3 ks. To derive the gas temperature for a given region of the cluster image, the telescope and detector response were modeled as described in MV. The ACIS background rate did not vary during the exposure but was higher than expected by a factor of about 1.3, most likely due to anomalous “space weather.” This required special background modeling. To do this, we extracted a spectrum from the ACIS-I region outside an $r = 8.6' (1.5\ h^{-1}\ \text{Mpc})$ circle centered on the cluster, which should be free of cluster emission. Point sources were excluded. The observed excess over the nominal background$^2$ was well modeled in the 0.7–10 keV band by the sum of two power laws $E^\alpha$ with photon indices $\alpha = -0.6$ and 3.0 (dominant below and above $E \sim 5$ keV, respectively) originating inside the detector, i.e., without applying the mirror effective area and CCD efficiency to the model. Such a background anomaly in the ACIS-I chips is rare and not yet understood. We assumed that this component is distributed uniformly over the detector and added it (normalized by solid angle) to the nominal background spectra. High-energy residuals in the overall cluster fit indicated that the normalization of the corrected background required an additional 10% increase (perhaps indicating some spatial nonuniformity of the excess), which we applied to the spectra from all cluster regions.

To make a 0.5–5 keV image for the gas density analysis, we compared the observed background rate far from the cluster with the nominal model background (without the above additional component) and derived a correction factor of 1.35 for this wide band, which was applied to the model background image. This is of course consistent with the above spectral correction. A 10% background uncertainty was included in deriving the confidence intervals for all quantities. This approximate background modeling is adequate for our present
3. RESULTS

The ACIS image of the cluster is shown in Figure 1a. It shows a “bullet” apparently just exiting the cluster core and moving westward. This subcluster was previously seen in the ROSAT data (e.g., T98), but the high-resolution Chandra image makes its nature and direction of motion clear. The bullet is preceded by an X-ray brightness edge that resembles a bow shock. To determine whether it is indeed a shock (and not a cold front; e.g., Markevitch et al. 2000; Vikhlinin et al. 2001), below we derive the gas temperatures on both sides of the feature (see § 3.1). Figure 1b shows X-ray contours overlaid on an optical image. A subcluster of galaxies (e.g., Barrena et al. 2002) is seen leading the X-ray bullet, which is apparently swept back from the galaxies by the ram pressure of the ambient cluster gas.

3.1. Temperature Map

We first fitted an overall cluster spectrum within $r = 3'$ (0.5 $h^{-1}$ Mpc) as described in § 2 using the Kaastra (1992) plasma model. We obtain $T = 14.8^{+1.7}_{-1.2}$ keV and an abundance of $0.11 \pm 0.11$ solar, fixing the absorption at $N_{\text{HI}} = 4.6 \times 10^{20}$ cm$^{-2}$ as derived by LHBA from radio and ROSAT PSPC data. This temperature agrees with their ASCA + ROSAT fit of $14.5^{+2.3}_{-1.0}$ keV and is consistent with the $17.4 \pm 2.5$ keV ASCA fit by T98. If $N_{\text{HI}} = 6.5 \times 10^{20}$ cm$^{-2}$ from Dickey & Lockman (1990) is used instead, we obtain $T = 13.6$ keV. When $N_{\text{HI}}$ is fitted as a free parameter, it is consistent with both those values; the present low-energy ACIS-I calibration is not reliable for measuring $N_{\text{HI}}$ independently. Below we fix $N_{\text{HI}} = 4.6 \times 10^{20}$ cm$^{-2}$. Within the $r = 0.5$ $h^{-1}$ Mpc aperture, the cluster’s 0.5–5 keV (rest-frame) luminosity is $(8.7 \pm 0.5) \times 10^{44}$ $h^{-2}$ ergs s$^{-1}$ and $L_{\text{bol}} = (2.3 \pm 0.2) \times 10^{45} h^{-2}$ ergs s$^{-1}$.

Figure 2 shows a temperature map made by dividing the
cluster image into several regions and fitting their temperatures and abundances as above. Despite large uncertainties, the map shows that the gas outside the shock feature (region P) is cooler, or at least not hotter, than that inside (region S), confirming that it is indeed a shock front. The temperature at the tip of the bullet is low (~7 keV) and is likely to have been the temperature of the subcluster. The hottest region of the cluster is its southeastern X-ray brightness elongation. The optical image shows several large galaxies in that area, suggesting that this is the main merger site. As seen in Figure 3, this also is where the radio halo is enhanced (LHBA). The halo also extends to the western shock front. A spatial correlation between the halo brightness and the local gas temperature (in addition to the general similarity to the X-ray brightness; e.g., LHBA; Govoni et al. 2001) was noticed by MV in two other merging clusters and supports the merger shock origin for the relativistic halo electrons (e.g., Tribble 1993).

4. DISCUSSION

4.1. The Shock Front

The temperature map confirms that the western X-ray brightness edge is a shock front. We can derive its Mach number from either the temperature or density jump across the front using the Rankine-Hugoniot shock adiabat. Figure 4a shows an X-ray brightness profile in a 120° sector centered on the bullet’s center of curvature and directed along its apparent motion. There are two brightness edges whose shapes indicate spherical gas density discontinuities in projection. We fitted this profile by the projection of a gas density model consisting of two power laws $r^\beta$ centered on the bullet representing the bullet gas and the shock region, respectively. These are immersed in a $\beta$-model centered on the main cluster (region j) representing the outer, undisturbed gas. All components are spherically symmetric around their respective centers; it is an adequate assumption in the sector of interest. Free parameters are the three slopes, two jump amplitudes, and two jump radii. A reasonable range of core radii and center positions for the $\beta$-model was explored (obviously, these cannot be restricted by the fit) and found to have a small effect on our main interesting parameter, the density jump at the shock. Its confidence interval includes this modeling uncertainty. The observed temperature difference has a negligible effect on the derived density.

The best-fit density model is shown in Figure 4b; it describes the brightness profile in Figure 4a well. The best-fit radial slopes are $\alpha \approx 0.15$ for the bullet and $\alpha \approx -0.3$ for the shock region; $\beta \approx 0.7$ assuming a core radius of 125 $h^{-1}$ kpc. The density jumps by factors of at the bullet edge and at the shock front. Figure 4b also shows an approximate pressure profile (the density model times the temperatures from Fig. 2). The approximate pressure continuity at the first jump indicates that the bullet boundary is a cold front, or contact discontinuity, similar to those recently discovered in other clusters. As expected, there is a large pressure increase at the shock front.
A density jump of $3.2 \pm 0.8$ at the shock corresponds to a Mach number $M = 3.4 (\gtrsim 2.1 \text{ at } 90\%)$ for a $\gamma = 5/3$ gas and a one-dimensional shock (strictly speaking, the latter approximation applies only along the direction of the motion, but we can use it as a qualitative estimate for our wide sector). The observed temperature jump from $8.3^{+2.1}_{-1.1}$ to $18.8^{+3.3}_{-1.8}$ keV corresponds to $M = 2.1 \pm 1.1$ (again, for a qualitative estimate, we assume constant temperatures in regions P and S). These two independent derivations for the Mach number agree within their 90% uncertainties, and we conclude that $M = 2$–3. In the stationary regime, the subcluster should move with the shock velocity. Such Mach numbers and the observed gas temperatures correspond to $v \sim 3000$–$4000 \text{ km s}^{-1}$, implying that the bullet has passed the center of the main cluster ($\sim 0.3 \text{ h}^{-1} \text{ Mpc away}$) just 0.1–0.2 Gyr ago.

In principle, $M$ could also be estimated from the Mach cone: the asymptotic angle $\varphi$ of the shock with respect to the symmetry axis should satisfy $\sin \varphi = M^{-1}$. For $M = 2$–3, $\varphi$ should be $20^\circ$–$30^\circ$, whereas the image suggests $\varphi \gtrsim 45^\circ$. A deviation of the velocity vector from the sky plane could widen the Mach cone in projection; however, a sufficiently large inclination angle also would smear the observed sharp brightness edges. An optical measurement of the subcluster relative line-of-sight velocity in the comoving frame, $\sim 800 \text{ km s}^{-1}$ (Barrena et al. 2002), combined with our value of $M$, also indicates only a small ($10^\circ$–$15^\circ$) deviation from the sky plane. The Mach cone relation assumes a uniform preshock medium and constant velocities, and the cone angle discrepancy is probably due to the cluster’s radially declining density profile and the deceleration of the bullet.

4.2. The Bullet Subcluster

The $0.5$–$5$ keV luminosity of the bullet subcluster is $\sim 5 \times 10^{43} \text{ h}^{-2} \text{ ergs s}^{-1}$, $10$%–$15$% of the typical value for a cluster with the bullet’s temperature; this fraction would change little if adiabatic compression of the bullet by the surrounding hot gas is taken into account. The high gas density in the bullet (Fig. 4b) is of the order of that in the cooling flow clusters at comparable radii. This suggests that the bullet is a remnant of a density peak (cooling flow) that once was at the center of the merging subcluster, perhaps around its brightest galaxy (Fig. 1b). The subcluster’s less dense outer gas was probably shocked and ram pressure–stripped to the radius where the pressures are balanced (see Fig. 4b). Most of the stripped gas may reside in the north-south barlike structure near the center of the main cluster seen in Figure 1a (which may be a pancake in projection), since that is where the ram pressure on the moving subcluster was the highest. Disruption of a cooling flow by a merger was considered theoretically by, e.g., Fabian & Daines (1991) and Gómez et al. (2002).

The shuttlecock shape of the bullet clearly shows that it continues to be actively destroyed by gasdynamic instabilities (e.g., Jones, Ryu, & Tregillus 1996). The gas being swept back from the cool bullet appears to be quite hot (region a in Fig. 2) and clumpy (regions a and b), suggesting interesting physics at the interface of the two gases. This interface will be studied in detail using a longer Chandra observation planned for 2002.

4.3. High Overall Temperature

The existence of a few extremely hot clusters such as 1E 0657–56 have been used in the past to derive cosmological constraints under the assumption that the high temperature indicates high virial mass. However, the results presented here show that the assumption of hydrostatic equilibrium in 1E 0657–56 can easily overestimate the mass by a significant factor because of the ongoing merger and a temporary increase in temperature (see, e.g., simulations by Ricker & Sarazin 2001 and Ritchie & Thomas 2002). It is thus difficult to make any strong cosmological conclusions without a better estimate of the cluster mass.

4.4. Possible Future Measurements

The unique shock and supersonic subcluster in 1E 0657–56 enable us to make several interesting measurements. Since the gas density and temperature jumps at the shock are related, their accurate measurement may give the equation of state for the intracluster plasma. Magnetic fields, a relativistic particle population with sufficient pressure, a significant lag between the electron and ion temperatures, and large nonthermal energy losses in a shock could all change the true or the apparent value of $\gamma$.

From the velocity of the bullet and the density of the ambient gas, we can derive the ram pressure on the bullet. The gas bullet appears to be pushed away from the subcluster’s dark matter potential well just now, so the gravitational pull of the subcluster should equal the ram pressure. This may give an independent estimate of the subcluster’s total mass (Markevitch et al. 1999).

The cluster also presents an interesting opportunity to constrain the collisional nature of dark matter (e.g., Spergel & Steinhardt 2000; Furlanetto & Loeb 2002). There is a clear offset between the centroid of the bullet subcluster’s galaxies and its gas. If one measures the location of the subcluster’s dark matter density peak (e.g., from weak lensing or detailed modeling of the gas distribution), one may determine whether the dark matter is collisionless, as are the galaxies, or whether it experiences an analog of ram pressure, as does the gas.

5. Summary

The Chandra observation of 1E 0657–56 presents a prototypical example of a merger bow shock. The shock propagates in front of a cooler gas bullet, apparently a remnant of a dense central region of the merging subcluster whose outer gas was stripped by ram pressure. The subcluster Mach number is 2–3, and its velocity is 3000–4000 km s$^{-1}$. Thus, the subcluster traversed the main cluster core only 0.1–0.2 Gyr ago. The bullet is at the final stage of being destroyed by gasdynamic instabilities. Its gas lags behind the subcluster galaxies because of the ram pressure of the shocked gas. The hottest gas resides in a different region of 1E 0657–56 where additional merging activity occurs. The overall high temperature of 1E 0657–56 is unlikely to represent its virial temperature because of the ongoing merger.

We thank L. Grego, H. Tananbaum, and the referee for useful comments. Support was provided by NASA contract NAS8-39073, grant NAG5-9217, the Smithsonian, and the CfA fellowship program.
REFERENCES

Barrena, R., Biviano, A., Ramella, M., Falco, E., & Seitz, S. 2002, Tracing Cosmic Evolution with Galaxy Clusters, ed. S. Borgani, M. Mezzetti, & R. Valdarnini (San Francisco: ASP), in press

Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215

Fabian, A. C., & Daines, S. J. 1991, MNRAS, 252, 17P

Furlanetto, S. R., & Loeb, A. 2002, ApJ, 565, 854

Furusio, T., Yamasaki, N. Y., Ohashi, T., Shibata, R., & Ezawa, H. 2001, ApJ, 561, L165

Gómez, P. L., Loken, C., Roettiger, K., & Burns, J. O. 2002, ApJ, in press

Govoni, F., Ensslin, T. A., Feretti, L., & Giovannini, G. 2001, A&A, 369, 441

Henry, J. P., & Briel, U. G. 1995, ApJ, 443, L9

Jones, T. W., Ryu, D., & Tregillus, I. L. 1996, ApJ, 473, 365

Kaastra, J. S. 1992, An X-Ray Spectral Code for Optically Thin Plasmas (Internal SRON-Leiden Rep., updated version 2.0)

Liang, H., Hunstead, R. W., Birkhainsh, M., & Andreani, P. 2000, ApJ, 544, 686 (LHBA)

Markevitch, M., et al. 2000, ApJ, 541, 542

Markevitch, M., Sarazin, C. L., & Vikhlinin, A. 1999, ApJ, 521, 526

Markevitch, M., & Vikhlinin, A. 2001, ApJ, 563, 95 (MV)

Neumann, D. M., et al. 2001, A&A, 365, L74

Ricker, P. M., & Sarazin, C. L. 2001, ApJ, 561, 621

Ritchie, B. W., & Thomas, P. A. 2002, MNRAS, 329, 675

Sarazin, C. L. 2001, in XXXVI Rencontres de Moriond Conf., Galaxy Clusters and the High Redshift Universe Observed in X-Rays, ed. D. Neumann, F. Durret, & J. Tran Thanh Van, in press (astro-ph/0105458)

Shafranov, V. D. 1957, Soviet Phys.—JETP Lett., 5, 1183

Spergel, D. N., & Steinhardt, P. J. 2000, Phys. Rev. Lett., 84, 3760

Takizawa, M. 1999, ApJ, 520, 514

Tribble, P. 1993, MNRAS, 263, 31

Tucker, W., et al. 1998, ApJ, 496, L5 (T98)

Tucker, W. H., Tananbaum, H., & Remillard, R. A. 1995, ApJ, 444, 532

Vikhlinin, A., Markevitch, M., & Murray, S. S. 2001, ApJ, 551, 160

Yaqoob, T. 1999, ApJ, 511, L75