CHANDRA OBSERVATION OF THE MOST INTERESTING CLUSTER IN THE UNIVERSE

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ABSTRACT

Chandra has recently observed 1E 0657–56, a hot merging system at $z = 0.3$ (the "bullet" cluster), for 500 ks. I present some of the findings from this dataset. The cluster exhibits a prominent bow shock with $M = 3.0 \pm 0.4$ (one of only two known $M \gg 1$ shock fronts), which we use for a first test of the electron-ion equilibrium in an intergalactic plasma. The temperatures across the shock are consistent with instant shock-heating of the electrons; at 95% confidence, the equilibration timescale is much shorter than the collisional Spitzer value. Global properties of 1E 0657–56 are also remarkable. Despite being extremely unrelaxed, the cluster fits well on the $L_X - T$ relation, yet its total mass estimated from the $M - T$ relation is more than twice the value measured from lensing. This is consistent with simulations predicting that in the middle of a merger, global temperature and X-ray luminosity may be temporarily boosted by a large factor.

Key words: galaxies: clusters: individual (1E0657–56) — plasmas — X-rays: galaxies: clusters.

1. INTRODUCTION

1E 0657–56 is the most interesting cluster in the Universe, as officially confirmed by *Chandra* Peer Review (Anonymous 2003). This system, located at $z = 0.3$, has the highest X-ray luminosity and temperature and the most luminous radio halo of all known clusters. It is also a spectacular merger occurring almost exactly in the plane of the sky (Markevitch et al. 2002), and contains one of only two known cluster shock fronts with a Mach number substantially greater than 1 (the other one is A520 with $M = 2$). *Chandra* has recently observed it with a 500 ks total exposure. The image from that dataset is shown in Fig. 1. It shows a prominent bow shock preceding a small, cool "bullet" subcluster flying west after passing through a core of a bigger cluster and disrupting it. In this paper, two interesting (preliminary) findings from this new dataset are presented, one regarding the global properties of the cluster, and another based on the high-resolution electron temperature profile across the shock front. All errors are 68%; the assumed cosmology is $h = 0.7$, $\Omega_0 = 0.3$ and $\Omega_\Lambda = 0.7$.

2. AN OVERHEATED CLUSTER

A single-temperature fit to the overall ACIS spectrum for the cluster (excluding a small region around the bullet for consistency with the "cooling flow corrected" temperatures for nearby clusters) is $T = 14.1 \pm 0.2$ keV. As shown in Fig. 2, it fits perfectly on the $L_X - T$ relation for local clusters (Markevitch 1998) after a correction for its redshift evolution (Vikhlinin et al. 2002). However, its total mass estimated from an X-ray $M_{500} - T$ relation (Vikhlinin et al. 2005b; Kotov & Vikhlinin 2005), $M_{500} = 1.9 \times 10^{15} M_\odot$, is a factor of 2.4 higher than the value within the same radius estimated from weak lensing (Clowe et al. 2004). Given the ongoing violent merger, this is not unexpected — simulations have predicted (Randall et al. 2002; Rowley et al. 2004) that during a major merger, the cluster may experience a transient

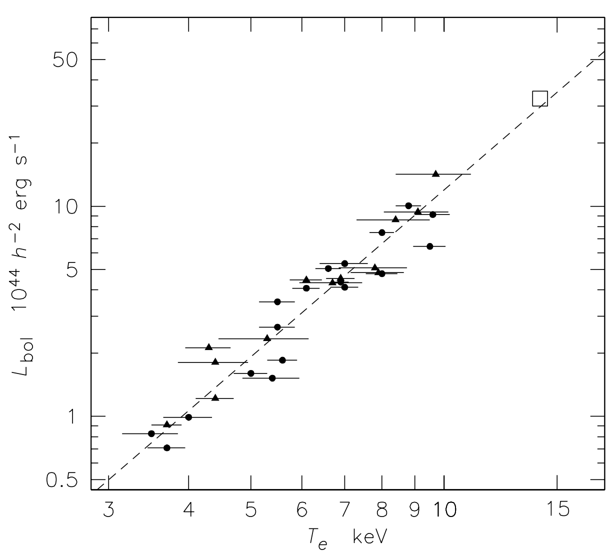

Figure 2. 1E 0657–56, shown as open square, overlaid on the local $L_X - T$ relation, after a correction of L_X of this cluster for redshift evolution of the relation.

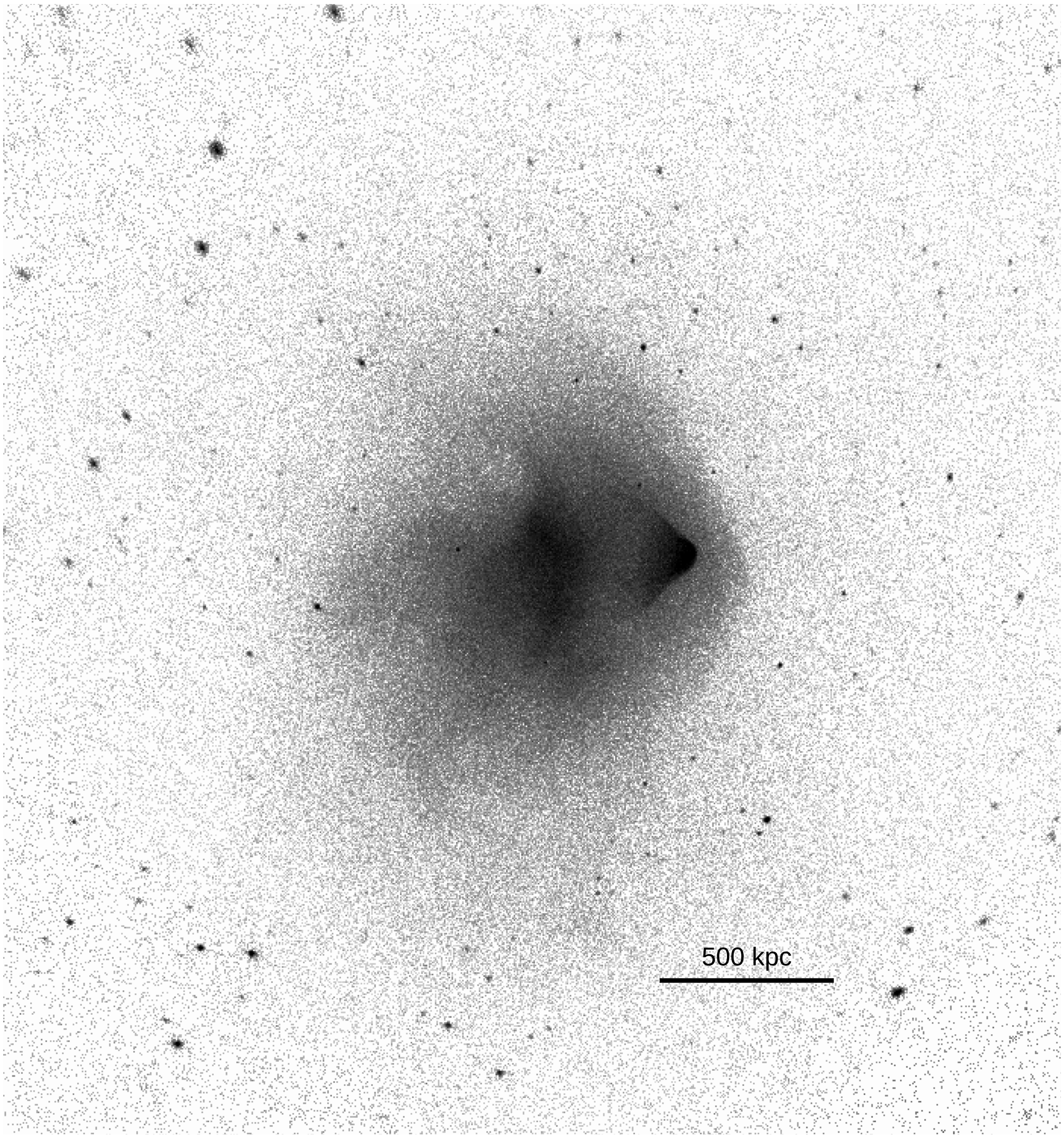

Figure 1. 500 ks Chandra ACIS-I image of 1E 0657–56 in the 0.8–4 keV band.

boost of temperature by a factor of several, lasting of order 0.1 Gyr around the moment of the subcluster core passage. In the course of this rapid change, the cluster moves approximately along the $L - T$ relation. We know from the shock velocity (Markevitch et al. 2002) that the core passage in 1E 0657–56 has indeed occurred about 0.15 Gyr ago, so this cluster appears to illustrate precisely this short-lived phenomenon.

It is interesting to try and recover a "pre-merger" temperature of the main subcluster. The gas before (west of) the shock front should not yet know anything about the merger, and stay undisturbed in the gravitational potential of the main cluster. We have therefore divided the cluster into the post-shock and pre-shock regions (approximately along the bow shock) and extracted radial temperature profiles in these regions, both centered at the mass centroid of the main subcluster (Clowe et al. 2004). The resulting profiles are shown in Fig. 3. If before the merger, the main cluster had a declining radial profile similar to that in most clusters (Vikhlinin et al. 2005a), extrapolating the "pre-shock" profile inwards would give an average temperature around 10 keV or less, compared to the present 14 keV. For such a temperature, M_{500} from the $M - T$ relation is within a factor of 1.5 of the lensing mass, which is within the uncertainty of the Clowe et al. (2004) lensing measurement. (The lensing mass would imply $T \simeq 8$ keV.)

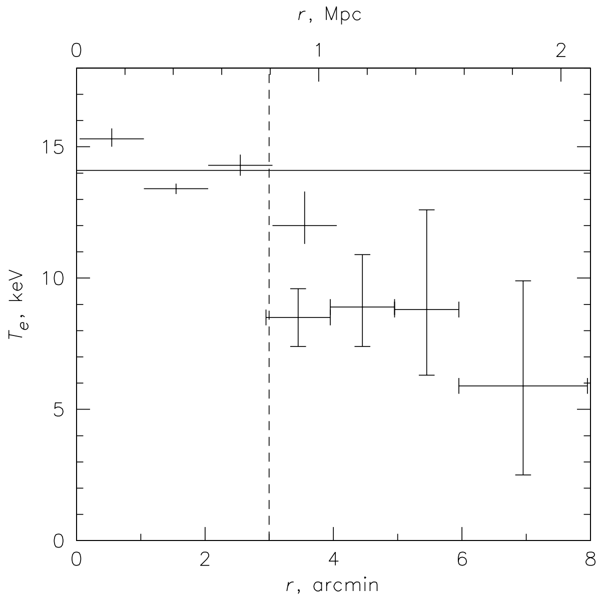

Figure 3. Radial temperature profiles for the disturbed region behind the shock (crosses without bars) and for the undisturbed region in front of the shock (barred crosses). Both profiles are centered on the main subcluster. The vertical dashed line approximately shows the shock front; the horizontal line is the average temperature.

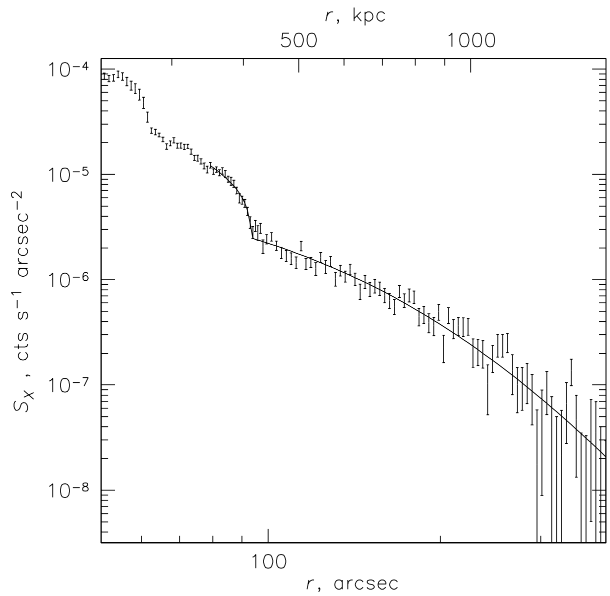

Figure 4. X-ray brightness profile across the shock front. The line shows the best-fit model (a projected sharp spherical density discontinuity at the shock).

The "overheated" cluster 1E 0657–56 may thus serve as a cautionary example for projects involving X-ray surveys of distant clusters, where total masses are proposed to be derived from low-statistics X-ray data using temperature profiles, average temperatures or even fluxes. If 1E 0657–56 was placed at $z = 1$ and observed with *Chandra* with a modest 100 ks exposure, its extremely unrelaxed state would be very difficult to detect from the X-ray image, especially if the merger was not oriented so fortunately in the plane of the sky. Its total mass would then be significantly overestimated.

3. ELECTRON-ION EQUILIBRIUM

The bow shock in 1E 0657–56 offers a unique experimental setup to determine whether electrons in the intracluster plasma are directly heated by shocks, or compressed adiabatically and then heated to an equilibrium temperature via collisions with protons (that are heated dissipatively by the shock). The collisional equilibration occurs on a Spitzer timescale (e.g., Zeldovich & Raizer 1966)

$$\tau_{\rm ep} = 2 \times 10^8 \ {\rm yr} \left(\frac{n_e}{10^{-3}\ {\rm cm}^{-3}} \right)^{-1} \left(\frac{T_e}{10^8\,{\rm K}} \right)^{3/2} \qquad (1)$$

(note that, conservatively for our measurement, this is 3 times shorter than the formula given in Sarazin 1988). We cannot measure T_i in X-rays, only T_e. However, because the shock in 1E 0657–56 propagates in the plane of the sky, we can accurately measure the gas density jump across the front and use it to predict the post-shock adiabatic and shock-heated (dissipative) electron temperatures from the pre-shock temperature (using the adiabat and the Rankine-Hugoniot jump conditions, respectively), and compare it with the observation. Furthermore, we also know the downstream velocity of the shocked gas flowing away from the shock. This flow effectively unrolls the time dependence of the electron temperature along the spatial coordinate for us. The Mach number of the shock is conveniently high, so that the adiabatic and dissipative electron temperatures are sufficiently different for us to distinguish (e.g., for $M \lesssim 2$, they would be almost the same). It is also not a strong shock, for which the density jump would just be a factor of 4 (for ideal monoatomic gas) and would not let us directly determine M. Furthermore, the distance traveled by the post-shock gas during the time given by eq. (1), $\Delta x \simeq 230$ kpc $= 50''$, is well-resolved by *Chandra*. The statistical quality of the 500 ks dataset is just sufficient — in fact, this test was the main science driver for this long observation.

Fig. 4 shows a 0.8–4 keV surface brightness profile in a narrow sector across the shock, centered on the center of curvature of the front. The inner bump is the bullet (its boundary is a "cold front"). The edge at 90″ is the shock front. There is also a subtle secondary edge between these main features, which may also be seen in the deep image. It is unrelated to the shock, so we should take care to exclude it from any fits aimed at deprojecting the shock temperatures and densities. The line in Fig. 4 shows a best-fit model consisting of the projected abrupt spherical density jump at the shock (by a factor of 3.0), a power-law profile inside the shock and a beta-model outside. The fit is perfect (the inclusion of the secondary edge does not affect it). From this density jump, we de-

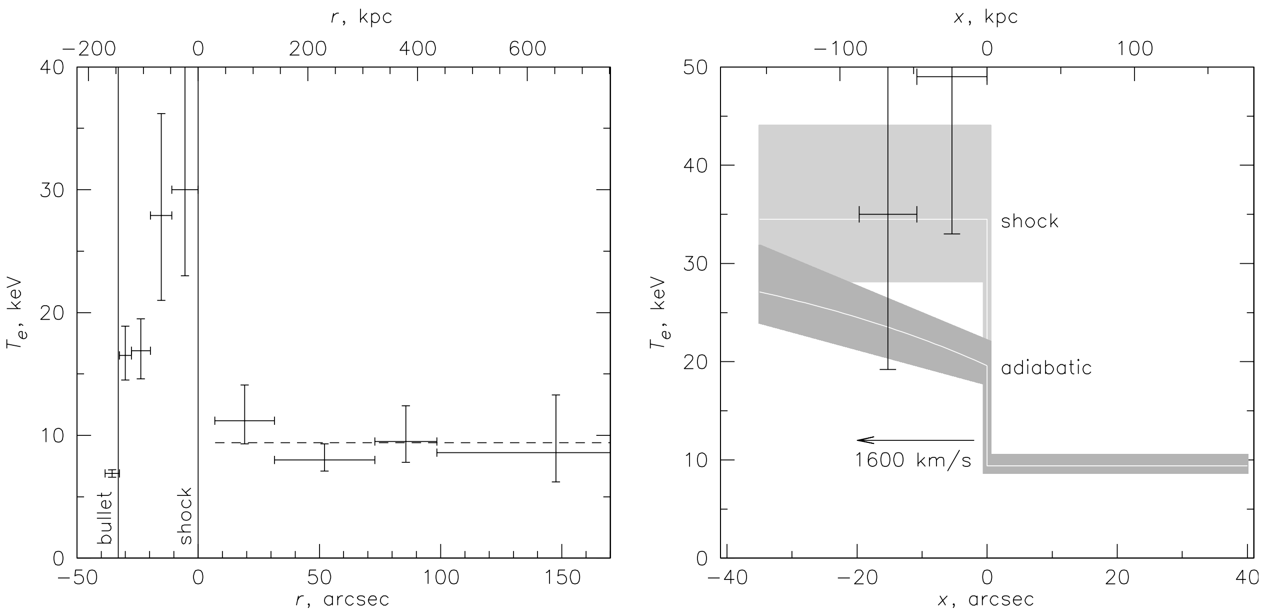

Figure 5. Left: projected temperature profile in a narrow sector across the shock. Two crosses in the shock region with lower temperatures correspond to an apparent additional edge-like structure and are not used. Vertical lines show the boundaries of the cool bullet and the shock; dashed line shows the average pre-shock temperature. Right: deprojected temperatures for the two post-shock bins overlaid on the model predictions (with error bands) for shock-heated and adiabatic electron temperatures. The velocity shown is for the post-shock gas relative to the shock.

termine $M = 3.0 \pm 0.4$, which corresponds to a shock (and bullet) velocity of 4700 km s^{-1}.

In Fig. 5 (left), we show a projected temperature profile in the same sector across the shock. There is a clear jump of the electron temperature. At the secondary edge mentioned above, the temperature goes down, which probably indicates residual cooler gas from the subcluster located ahead of the bullet. Therefore, we can only use the two bins closest to the front. Because we know the gas density profile across the shock, we can accurately subtract the contributions of the cooler pre-shock gas projected into the post-shock bins, assuming spherical symmetry. The large brightness contrast at the shock helps make this subtraction robust.

The deprojected values are shown in Fig. 5 (right). They are overlaid on the two models (gray bands), one assuming instant equilibration (i.e., electrons are heated at the shock), and another assuming adiabatic compression and subsequent equilibration with protons on a timescale given by eq. 1. (The plot assumes a constant post-shock gas velocity, which of course is not correct, but we are only interested in the immediate shock vicinity.) The deprojected gas temperatures are so high for *Chandra* that only their lower limits are meaningful. The temperatures are consistent with instant heating; the "adiabatic" model with the Spitzer timescale is excluded at a 95% confidence.

A few sanity checks have been performed. The high temperatures are not an artifact of the deprojection, because the projected temperatures in those two bins are already higher than the models. We also considered the possibility of a non-thermal contamination. The cluster is known to possess a radio halo (Liang et al. 2000) which has an edge right at the shock front (Markevitch et al. 2002). Therefore, there may be an inverse Compton contribution from relativistic electrons accelerated at the shock. However, the power-law spectrum of such emission for any M would be *softer* than thermal, so should not bias our measurements high. We also extracted a temperature profile in another sector of the shock (away from the nose), where $M \simeq 2$, and made a similar comparison. The recovered post-shock temperatures are lower than those in Fig. 5 and again in agreement with the model predictions (either one; for such M, the difference between them is very small). Thus, albeit at a relatively low significance (95%), we conclude that the electron-ion equilibration should be much faster than collisional.

It is of course unfortunate that a cluster with such a perfect geometric setup and a Mach number is so hot that *Chandra* can barely measure the post-shock temperatures; however, there is no choice of other shock fronts and so improvement upon the above measurement is unlikely in the near future.

There hasn't been a measurement of the electron-ion equilibration timescale in the intergalactic medium before. In the solar wind plasma, the equilibration is believed to be fast compared to the collisional timescale. For supernova remnants, which have strong shocks, conclusions vary between different objects (e.g., Rakowski 2005). Plasma interactions have been suggested as a fast equilibration mechanism for the solar wind, and it probably applies for the intracluster plasma as well.

4. SUMMARY

From the extra-long 500 ks *Chandra* observation of 1E 0657–56, we found that this cluster is observed at a very special, short-lived stage, when its temperature and luminosity are temporarily boosted by the merger by significant factors. The total cluster mass estimate from the X-ray $M-T$ relation turns out to be more than two times higher than the (presumably) true mass determined by lensing, indicating a very strong deviation from hydrostatic equilibrium. If this cluster were at high z and not so well exposed, it would be difficult to detect its disturbed state, thus it is a cautionary example for future high-z surveys.

The temperature profile across the shock offers a first test of the electron-ion equilibrium in the intracluster plasma. The temperatures indicate that electrons are indeed quickly heated at the shock. The slow Spitzer (collisional) equilibration rate is excluded at the 95% confidence.

This unique cluster, well-exposed by *Chandra*, is the subject of several other ongoing studies, the results of which will be reported soon.

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