Evidence for Intracluster Medium Heating by the Radio Galaxy 3C 28.0 in the Off-Axis Galaxy Cluster Merger Abell 115

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ABSTRACT

In an examination of the northern sub-cluster of A 115 in a 50 ksec Chandra ACIS I exposure we discovered jumps in the X-ray surface brightness of the intercluster medium (ICM) in the south-western section of the sub-cluster. The X-ray surface brightness profiles can be modeled with a central sphere and three concentric shells, each containing ICM of constant emissivity. Although the dense ICM of the northern sub-cluster appears to be pushing through the thinner ICM surrounding the sub-cluster, we do not find evidence for an shock associated with any of the discontinuities. A pressure jump of $1.82 \times 10^{-10}$ dyne cm$^{-2}$ between the first and second shell (innermost and next out) gives an upper limit on the velocity of the inner shell of $0.894^{+0.063}_{-0.049}$ Mach through the outer shell. The core of the northern sub-cluster is significantly cooler (deprojected temperature $2.78^{+0.34}_{-0.31}$ keV) than outer ICM shells (deprojected temperature $3.60^{+0.50}_{-0.38}-3.81^{+1.26}_{-0.73}$ keV). The cooling time of the core ($0.036 \times 1/H_0$) is much shorter than the Hubble time. The brightest region of the northern sub-cluster encloses the central radio galaxy 3C 28.0. We find an astonishing morphological correlation of the X-ray bright region and the outer limits of the radio galaxy which strongly suggests that the radio galaxy is heating the ICM. While ICM heating by radio galaxies has widely been discussed as a solution of the cooling flow problem (the lack of cold ICM with $T \ll 2$ keV) it seems that the hot gas accumulates in a “cocoon” surrounding the radio galaxy and does not proceed via formation of “radio bubbles” which subsequently dissipate their energy in the ICM.

Subject headings: galaxies: clusters: individual (A115) (3C 28.0) — cosmology: X-rays: galaxies: clusters

1. Introduction

A 115 is a rich galaxy cluster (richness class=3) Abell et al. (1989) with two strong peaks in the X-ray surface brightness distribution Forman et al. (1981). A 115 has also

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been observed in the radio Giovannini et al. (1987) as well as optically Beers et al. (1983). Observation with the ASCA satellite Shibata et al. (1999) indicated strong temperature variations across the cluster with the two main X-ray peaks being cooler (5 keV) than the region in between (11 keV). The double peaked X-ray surface brightness distribution and the large temperature variation between the surface brightness peaks shows that A 115 is a merging system. The cluster is also interesting because it contains the strong radio galaxy 3C 28.0.

In this paper we present in Sect. 2 the data analysis and data cleaning. We describe the results on the overall morphology of the binary cluster merger as well as the detection of several strong field sources in Sect. 3.1. We discuss the overall temperature structure in Sect. 3.2. In Sect. 3.3 we present the results of a spectroscopic deprojection analysis that we used to determine the ICM temperature, pressure, particle density, and radiative cooling times. Finally, we discuss the correlation of the X-ray surface brightness and the radio morphology of 3C 28.0 and it’s possible implications in subsection 3.4. In the following we use $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$ and $\Omega_{\text{vac}} = 0.73$, putting the cluster at a luminosity distance of 950 Mpc and a angular distance of 666 Mpc; 1” corresponds to 3.2 kpc.

2. Observations and Data Preparation

We observed A 115 using the ACIS I detector for 50.4 ks, on July 11, 2002. The observation used the chips ACIS I0-I3 as well as ACIS S6. The ACIS S7 chip was turned off to keep the telemetry rate low during background flares. The data were taken in Very Faint Mode to minimize background counts. We are using the full data set as we found no background flares. We applied a filtering process specifically designed for Very Faint Mode observations that uses a 5×5 pixel event island rather than the standard 3×3 island to distinguish between X-ray events and Cosmic Ray events. The filtering resulted in a 2% drop in signal and a 30% drop in background. We flat-fielded the image using exposure maps in the 0.5-1 keV, 1-2 keV, and 2-5 keV bands. We then added these images with a spectral weight to produce the final image. The program Csmooth was used to obtain an adaptively smoothed image.

The analysis was performed with the analysis package CIAO 3.0.1. We used several off-cluster regions to estimate the background in the spectral analysis; the exact regions will be described below. We used different background regions to estimate the systematic errors, and we quote the maximum differences between the best fit values obtained with different background regions as systematic errors. Statistical errors are given on 90% confidence level. The spectral analysis uses only events from 0.5 keV to 6 keV. Above 6 keV the signal to noise ratio is poor; below 0.5 keV the response of the instrument is plagued by systematic uncertainties. The main thrust of our analysis concentrated on the northern sub-cluster surrounding the radio galaxy 3C 28.0. The study of the morphological correlation between the ICM surface brightness distribution and the radio emission of 3C 28.0 used the 1.4 GHz
3. Results

3.1. Overall Morphology of the Binary Merger

The cluster A ll5 is a binary galaxy cluster with two pronounced sub-clusters which appear to be coalescing in an off-axis merger as shown in Fig. 1. Intriguingly, the morphology of the merger is very similar to that of the Antenna galaxy merger as seen in the inset of Fig. 1 suggesting that tidal and MHD forces may act in a similar way in both systems.

The northern sub-cluster exhibits a wedge like shape and appears to be moving in the south-west direction. The brightest region in the northern sub-cluster is centered on 3C 28.0. Tidal and MHD forces skewed the southern sub-cluster and resulted in a significant elongation in the north-east to south-west direction. The absence of strong surface brightness gradients does not allow us to determine if the southern sub-cluster moves into the north-east or south-west direction. Toward the east of the binary merger, the data show a thin X-ray producing region connecting the northern and southern sub-clusters.

In addition to the cluster itself we find four localized X-ray sources with archival counterparts in other wavelengths, not previously observed in the X-ray band: one X-ray source is associated with ZHG90, a galaxy in the cluster and with Slee ACO 115 4, a radio source. Additional X-ray sources are associated with BHG83(G 28), and BHG83(G 16), both galaxies in the cluster and IRAS F00536+2611 a weak infra-red source. In addition to these sources, we found a strong field source at $\alpha (\text{J2000}) = 0:55:09.2 \delta (\text{J2000}) = +26:27:14$ designated CXOU J005509.2+262714. A simple power-law fit gave a photon index of $\Gamma = 1.04^{+0.02}_{-0.02}$ and a 1 keV flux amplitude of $P_{\text{amp}} = 3.02^{+0.10}_{-0.10} \times 10^{-6}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ with $\chi^2(\text{dof}) = 34(22)$.

3.2. Temperature structure of the ICM

We used a hardness map to get an overview of the overall temperature structure of the cluster. On the most interesting regions we ran full spectral analysis. These regions are shown on top of the smoothed surface brightness distribution in Fig. 2. The results from one component Raymond-Smith model fits are given in Table. 1. The coldest regions have been found at the center of the northern sub-cluster (2.3 keV) and near the center of the southern sub-cluster (3.2 keV). The thin region connecting the two sub-clusters is warmer than the two sub-clusters (best fit value of 15.65 keV). The region between the two sub-clusters also appears substantially hotter (best fit value of 14.34 keV) confirming previous results by Shibata et al. (1999) based on ASCA observations. The limited photon statistics do not allow us determine if there is a shock associated with the hot region between the two
sub-clusters, and the best fit temperatures depend considerably on the chosen background region (see Table 1).

3.3. Structure of the northern sub-cluster

Surface brightness profiles of the southwestern section of the northern sub-cluster show three brightness discontinuities (Fig. 3). The discontinuities are found at a distance of 12.3″, 24.6″, 41.8″ and 54.6″ (1″ = 3.2 kpc) from the core of 3C 28.0 at the center of the northern sub-cluster. At the center of the sub-cluster (within 12.3″ of 3C 28.0) we see a very bright core region. A strong brightness jump is located at 24.6″ as well as a more subtle one at 41.8″. The first, at 24.6″ is highly significant, the second one is not. The surface brightness profiles can be described by a very simple model using a sphere surrounded by three spherical shells, and assuming constant volume emissivity in the four volumes (see Fig. 3, dashed line). The small deviations between the model and the observed surface brightness profiles indicate that the plasma emissivity is decreasing with increasing sub-cluster core distance.

We performed a spectroscopic deprojection analysis Krawczynski (2002) with 4 ICM shells, the outermost shell being dominated by background counts. Using a single temperature Raymond-Smith plasma for each shell, we derive ICM particle density, temperature, pressure, and cooling time profiles. We show these profiles in Fig. 4. The first profile shows the ICM particle density. The density falls as we travel further from the center of the galaxy cluster from 0.106 particles cm\(^{-3}\) to 0.007 particles cm\(^{-3}\). The coarse resolution does not allow us to determine if there are discontinuities between the ICM shells or whether the profile seen here is simply part of a continuous decrease of the ICM particle density. The deprojected temperature rises from 2.78 keV at the sub-cluster core to 3.81 keV further outward; the large errors prevent accurate assessment of the temperature difference of the outermost two shells. Between the first and second ICM shells the deprojected ICM pressure drops by 1.82 × 10\(^{-10}\) dyne cm\(^{-2}\) Assuming that the full pressure drop originates from the

| Region                | Temperature (keV) | \(n_H\)          | Abundance       | \(\chi^2\) (dof) |
|-----------------------|------------------|------------------|-----------------|-----------------|
| N. Sub-Cluster        | 3.55\(^{+0.09}_{-0.09}\) \(^{+0.04}_{-0.03}\) | 0.059\(^{+0.006}_{-0.006}\) \(^{+0.001}_{-0.001}\) | 0.376\(^{+0.001}_{-0.001}\) \(^{+0.001}_{-0.001}\) | 63.9(57)        |
| N. Sub-Cluster Fan    | 4.85\(^{+0.15}_{-0.13}\) \(^{+0.15}_{-0.13}\) | 0.059\(^{+0.003}_{-0.003}\) \(^{+0.003}_{-0.003}\) | 0.23\(^{+0.08}_{-0.08}\) \(^{+0.08}_{-0.08}\) | 15.2(21)        |
| N. Sub-Cluster core   | 2.30\(^{+0.06}_{-0.06}\) \(^{+0.04}_{-0.01}\) | 0.054\(^{+0.004}_{-0.004}\) \(^{+0.004}_{-0.004}\) | 0.59\(^{+0.04}_{-0.04}\) \(^{+0.04}_{-0.04}\) | 27.0(21)        |
| S. Sub-Cluster        | 4.79\(^{+0.11}_{-0.07}\) \(^{+0.11}_{-0.07}\) | 0.083\(^{+0.016}_{-0.015}\) \(^{+0.019}_{-0.019}\) | 0.19\(^{+0.08}_{-0.08}\) \(^{+0.08}_{-0.08}\) | 20.2(21)        |
| Intermediate Region   | 14.34\(^{+1.16}_{-1.16}\) \(^{+8.07}_{-8.07}\) | 0.054\(^{+0.007}_{-0.007}\) \(^{+0.007}_{-0.007}\) | 0.13\(^{+0.12}_{-0.12}\) \(^{+0.12}_{-0.12}\) | 52.5(48)        |
| S. Cool Region        | 3.22\(^{+0.07}_{-0.15}\) \(^{+0.07}_{-0.15}\) | 0.103\(^{+0.010}_{-0.010}\) \(^{+0.012}_{-0.012}\) | 0.28\(^{+0.05}_{-0.05}\) \(^{+0.05}_{-0.05}\) | 73.1(70)        |
| Connecting Region     | 15.65\(^{+0.84}_{-0.68}\) \(^{+10.84}_{-10.84}\) | 0.054\(^{+0.007}_{-0.007}\) \(^{+0.007}_{-0.007}\) | 0.74\(^{+0.18}_{-0.17}\) \(^{+0.18}_{-0.17}\) | 97.5(88)        |

Table 1: Temperatures throughout the cluster. Regions correspond to those shown in Fig. 2. The values in the first parenthesis give the statistical errors and those in the second parenthesis give the systematic errors.
motion of the first through the second shell, we derive a relative velocity of \(0.894^{+0.063}_{-0.049}\) times the sound speed in the second shell, implying that the plasma discontinuity is not a shock. The cooling time decreases closer to the center of the northern sub-cluster. The ICM cooling time in the central region is significantly shorter than the Hubble time, \(0.036 \times 1/H_0\).

### 3.4. Correlation of X-ray surface Brightness and the Radio Morphology of 3C 28.0

Focusing in to the central galaxy 3C 28.0, we notice in Fig. 5 a correlation between a triangular region of weak radio emission in the center of the radio galaxy and an X-ray bright region, both with an approximate diameter of 6.9" (22.6 kpc). While the double sided jet originates at the center of the X-ray bright region and seems to have drilled 2 channels through this region, the more extended radio lobes are found outside of this region. Even more remarkable, we find a morphological correlation of the larger 17.8" (156.9 kpc) diameter X-ray bright region and the outer limits of the radio lobes. The X-ray brightness drops off sharply right after the radio lobes. If not coincidental, this correlation strongly suggests that the radio source heats the ICM in the core region. We will discuss the implications in the next section.

### 4. Discussion

#### 4.1. Off Axis Cluster Merger

The Chandra observation shows a binary cluster merger with a very clear signature for fast orbital motion of the two sub-cluster. The orbital motion results in (a) pronounced X-ray surface brightness gradients in the northern sub-cluster in the direction into which the northern sub-cluster is moving, and (b), a highly elongated ICM surface brightness distribution of the souther sub-cluster. The surface brightness discontinuities in the northern sub-cluster are somewhat similar to those produced by “sloshing” central ICM regions found in more relaxed clusters Markevitch et al. (2001, 2002).

Assuming that the two sub-clusters are in Keplerian orbital motion, we can compute a lower limit on the orbital period of the two sub-clusters. Using the sub-cluster masses from White et al. (2001), and assuming that the rotation axis is parallel to the line of sight, we compute a lower limit on the orbital period of \(3.26 \times 10^9\) years. Using the same assumptions, we infer an upper limit on the orbital velocity of the northern and southern sub-clusters of 335.6 km s\(^{-1}\) and 922.3 km s\(^{-1}\), respectively. These estimates further bolster that the first shell of the northern sub-cluster moves subsonically through the second shell.

The Chandra data confirm the earlier ASCA detection of a hot ICM region between the two sub-clusters Shibata et al. (1999). The process by which the ICM is heated remains
4.2. X-ray Observations of the Radio Galaxy Cocoon

In the core of the northern sub-cluster we found an astonishing morphological correlation between a jump in the X-ray surface brightness and the radio morphology of 3C 28.0. While ICM heating by radio galaxies has widely been discussed as a solution of the cooling flow problem (the lack of cold ICM with $T \ll 2$ keV) (e.g. Böhringer et al. 2002), it seems that the hot gas accumulates in a “cocoon” surrounding the radio galaxy and does not proceed via formation of “radio bubbles” which subsequently dissipate their energy in the ICM (e.g. Churazov e al. 2002).

The ICM might be heated by the jets near the “working surfaces” where the jet material dissipates most of its kinetic energy. Entrenched and heated ICM might flow backward and accumulate in the “cocoon” of the radio galaxy.

The ICM within the X-ray bright region (diameter 17.8", 156.9 kpc) cools radiatively with a total luminosity of about $2 \times 10^{44}$ ergs s$^{-1}$. These radiative losses equal to good approximation the radio luminosity of the radio galaxy 3C 28.0. Assuming that (i) the mechanical power of 3C 28.0 available for ICM heating is comparable to its radio luminosity, and (ii) that the observed luminosity resembles the time averaged luminosity over $\sim 100$ million years, the ICM at the northern sub-cluster core could stay at a rather constant temperature if the duty cycle of 3C 28.0 building up such warm cocoons is on the order of unity.

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Fig. 1.— The overall surface brightness distribution (0.5 keV - 5 keV) of the galaxy cluster A 115 with an inset of the Antenna galaxy (NGC 4038/4039). The similarities in morphology lead us to believe that A 115 is an off-axis merger with significant orbital motion of the 2 sub-clusters.
Fig. 2.— Image showing the regions used for spectral analysis on top of a smoothed surface brightness map of the cluster. Two of the background regions used in the spectral analysis are also shown. The third background region is on a different chip.
Fig. 3.— ICM surface brightness profiles of the pie slices A-D shown in Fig. 5. The dotted lines indicate the 4 regions described in the text: (i) the “central sphere” from 0 to 40 kpc; (ii) the first ICM shell from 40 to 80 kpc; (iii) the second shell from 80 to 136 kpc; (iv) the third shell from 136 to 178 kpc. The curve shows a surface brightness model which assumes a sphere and 3 shells, each with plasma of constant X-ray emissivity. The second vertical line shows the strongest surface brightness drop.
Fig. 4.— ICM particle density, temperature, pressure and cooling time profiles of the south-east part of the northern sub-cluster (20°west of north to due south of 3C 28.0) from the deprojection analysis with three shells and a core region.
Fig. 5.— Image of the center of the northern sub-cluster. The color image shows the X-ray brightness and the contours show the 1.4 GHz brightness. The annular sections show cross section of the shell structure we believe to be composing the northern sub-cluster. Spectral fits were performed on these shells and the results are shown in Fig. 4. The pie slices A-D are those which give the brightness profiles in Fig. 3. The ellipse designates where there appears to be a strong brightness drop. Interestingly it is directly outside the radio contours suggesting that the brightness may correspond to a cocoon.