A PUZZLING MERGER IN A3266: THE HYDRODYNAMIC PICTURE FROM XMM-NEWTON

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ABSTRACT

Using a mosaic of nine XMM-Newton observations, we study the hydrodynamic state of the merging cluster of galaxies Abell 3266. The high signal-to-noise ratio of spectroscopic data of XMM-Newton allows us to determine the thermodynamic conditions of the intracluster medium on ~50 kpc scales. High statistical quality X-ray data reveal the presence of an extended region of low-entropy gas (LEG) running northeast from the primary cluster core along the nominal merger axis. The LEG is a major feature distinguishing the merger event in A3266 from other clusters. The mass of the low-entropy gas is ~1.3 × 10^{13} M_\odot. We test the possibility that the origin of the observed low-entropy gas is related either to the disruption of a preexisting cooling core in Abell 3266 or to the stripping of gas from an infalling subcluster. We find that the low-entropy gas has a metallicity 1.5–2 times higher than the bulk of the cluster, yet lower than one-half the solar value typical for the cool cores. In addition, both the radial pressure and entropy profiles, as well as the iron abundance of Abell 3266, do not resemble those in other known cool core clusters (e.g., Abell 478). Thus, we conclude that our observations favor a scenario in which the low-entropy region corresponds to subcluster gas stripped from its dark matter halo. In this scenario the subcluster would be falling onto the core of A3266 from the foreground, having a velocity component in the observer plane toward the southwest. The arguments based on both velocity dispersion and gas mass measurements suggest a mass ratio in the merger of 1:10.

Subject headings: galaxies: clusters: individual (Abell 3266) — intergalactic medium — X-rays: galaxies: clusters

1. INTRODUCTION

Current theories of structure formation are based on hierarchical models whereby small structures form first and, by assembly, build up larger structures. In this picture, mergers play an important role, not only in driving the formation of galaxy clusters but also in affecting the properties of the intracluster medium (ICM) including their thermodynamic conditions and metal content. A merger event results in dramatic consequences for the systems that take part in it. As a large amount of energy is released in the process, the ICM is strongly stirred up, which results in the production of shocks and turbulence (Miniati et al. 2000; Schuecker et al. 2004). Furthermore, the trans/sonic infalling subsystem may be stripped of its gas by ram pressure work (Gunn & Gott 1972). This mechanism may supply the main cluster with low-entropy gas, and perhaps with high metallicity too (Motl et al. 2004). In addition, disruption of cool condensations and abundance gradients may result in the cluster center. Until now, however, evidence of the latter has been only ex post facto in that postmerger systems appear to lack central cool gas reservoirs and central abundance enhancements, so little is known of the intermediate evolutionary stages.

In this paper we study the properties of the ICM in Abell 3266 (also known as Sersic 40-6), a well-studied cluster merger of the intermediate evolutionary stages. Multiple nuclei are found in over 25% of the first rank galaxies in rich clusters (Hoessel 1980). The relative velocity of the dumbbell is 400 ± 39 km s^{-1} and, compared to the stellar velocity dispersion of the cD nucleus of 327 ± 34 km s^{-1}, indicates a significant rotational component, suggesting that the pair was formed in the recent merger. However, the asymmetric rise in the stellar velocity dispersion of the cD galaxy peaks at around 700 km s^{-1} (Carter et al. 1985), suggesting that the cD galaxy is tidally disturbed by a very massive object, more massive than the second nucleus.

Evidence of a merger in A3266 is also supported by X-ray data. This is provided by both the temperature structure of the ICM, as well as the elongated morphology of the surface brightness of the system, as seen by the Advanced Satellite for Cosmology and Astrophysics (ASCA; Henriksen et al. 2000). These findings were recently confirmed by Chandra data (Henriksen & Tittley 2002). In addition, the Chandra hardness map suggests a cool, low-entropy region running along the surface brightness elongation (the merger axis).

The temperature structure around the cluster center observed by Chandra could be produced by the propagation of a shock induced by the passage of an infalling clump during the initial phases of a merger (Henriksen & Tittley 2002). Alternatively, the plume of cooler gas could be stripped material from the cD galaxy, or a disrupted cooling flow centered on the galaxies (Henriksen & Tittley 2002).

We analyzed the XMM-Newton observations of A3266. The high signal-to-noise ratio of data and new reduction techniques (Briel et al. 2004) allow us to produce statistically accurate maps that describe the thermodynamic state of the ICM in A3266. While the qualitative picture is confirmed, the new data provide a much more detailed picture of the merging process. This may serve...
as a test bed to our understanding of the role of gas stripping on cluster scales. In particular, in data analysis we construct maps approximating as close as possible the underlying pressure and entropy uncertainties associated with effects of projection and parameter weighting associated with the use of X-ray observables.

The paper is organized as follows: in § 2 we describe the observation and in § 3 we present the results, followed by a discussion in § 4. We adopt a ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, which leads to a luminosity distance of $D_L = 265 \text{ Mpc}$ and an angular scale of 69 kpc arcmin$^{-1}$ for A3262.

### 2. DATA AND ANALYSIS

*XMM-Newton* (Jansen et al. 2001) observed A3266 as a part of the guaranteed time observation program of instrumental scientists at Max-Planck-Institut für extraterrestrische Physik. Table 1 details the mosaic images of the cluster, where column (1) is the name of the proposed field, column (2) is the assigned *XMM-Newton* archival name, columns (3) and (4) are the right ascension and declination of the pointing, respectively, column (5) is the net EPIC pn exposure after the removal of flaring episodes, and column (6) is the *XMM-Newton* revolution number. All EPIC pn observations were performed using the extended full frame mode with a frame integration time of 199 ms and with the medium filter.

The initial steps of data reduction are similar to the procedure tested on other *XMM-Newton* mosaics and are described in detail in Briel et al. (2004). Throughout our analysis we used XMMMSAS 6.5, for which most instrument intercalibration issues have been resolved (Kirsch et al. 2004; Saxton et al. 2005). Details of our light-curve screening can be found in Zhang et al. (2004). The

### Table 1

| Field Name (1) | ObsID (2) | Pointing R.A. (J2000.0) (deg) (3) | Pointing Decl. (J2000.0) (deg) (4) | Net Exposure (ks) (5) | XMM-Newton Orbit (6) |
|---------------|-----------|----------------------------------|----------------------------------|----------------------|----------------------|
| f1.............| 0105260701| 68.11125                         | -61.31277                        | 13.6                 | 149                  |
| f2.............| 0105260801| 67.81583                         | -61.25916                        | 15.2                 | 154                  |
| f3.............| 0105260901| 67.59833                         | -61.50888                        | 17.8                 | 153                  |
| f4.............| 0105261001| 67.55541                         | -61.35055                        | 4.3                  | 147                  |
| f5.............| 0105261101| 68.14791                         | -61.48361                        | 6.6                  | 146                  |
| f6.............| 0105262001| 67.90416                         | -61.56722                        | 1.9                  | 145                  |
| f7.............| 0105262101| 68.14791                         | -61.48361                        | 3.5                  | 146                  |
| f8.............| 0105262201| 67.55541                         | -61.56722                        | 2.9                  | 147                  |
| f9.............| 0105262501| 67.90416                         | -61.35055                        | 3.5                  | 598                  |

### Table 2

| Name (2) | $kT$ (keV) (3) | Fe/Fe$_{\odot}$ (4) | $S$ (keV cm$^2$) (5) | $P$ (10$^{-11}$ dyn cm$^{-2}$) (6) | $M_{gas}$ (10$^{11}$ $M_{\odot}$) (7) |
|----------|----------------|---------------------|----------------------|-----------------------------------|--------------------------------------|
| Low-Entropy Gas (LEG) |
| 16............. | Head | 6.3 ± 0.1 | 0.25 ± 0.03 | 197 ± 5 | 5.66 ± 0.14 | 4.5 |
| 19............. | Core | 7.0 ± 0.2 | 0.20 ± 0.02 | 311 ± 8 | 3.78 ± 0.09 | 13.3 |
| 3............. | Stripped core-1 | 6.6 ± 0.2 | 0.29 ± 0.05 | 294 ± 11 | 3.52 ± 0.14 | 2.7 |
| 2............. | Stripped core-2 | 5.1 ± 0.1 | 0.21 ± 0.03 | 322 ± 8 | 1.64 ± 0.04 | 11.7 |
| 25............. | Stripped core-3 | 5.0 ± 0.4 | 0.25 ± 0.11 | 376 ± 28 | 1.20 ± 0.10 | 2.0 |
| 7............. | SW core side | 7.6 ± 0.5 | 0.23 ± 0.08 | 356 ± 24 | 3.84 ± 0.27 | 1.8 |
| 11............. | S-edge of core | 7.7 ± 0.5 | 0.15 ± 0.07 | 475 ± 30 | 2.55 ± 0.16 | 3.8 |
| 20............. | Shock-1 | 8.4 ± 0.4 | 0.31 ± 0.07 | 405 ± 19 | 4.05 ± 0.20 | 3.1 |
| 15............. | Shock-2 | 9.5 ± 0.9 | 0.51 ± 0.15 | 429 ± 43 | 5.02 ± 0.52 | 1.2 |
| 14............. | Shock-3 | 10.6 ± 1.7 | 0.04 ± 0.24 | 435 ± 69 | 6.45 ± 1.05 | 0.4 |
| 5............. | Tail-1 | 5.9 ± 0.1 | 0.23 ± 0.02 | 427 ± 8 | 1.52 ± 0.03 | 37.6 |
| 30............. | Tail-2 | 6.7 ± 0.6 | 0.27 ± 0.16 | 520 ± 51 | 1.54 ± 0.16 | 1.5 |
| 33............. | Tail-3 | 5.1 ± 0.3 | 0.22 ± 0.08 | 789 ± 44 | 0.43 ± 0.03 | 17.7 |
| 10............. | S-edge of tail | 8.0 ± 0.8 | 0.01 ± 0.14 | 613 ± 64 | 1.89 ± 0.20 | 2.2 |
| 13............. | N-edge | 6.8 ± 0.3 | 0.17 ± 0.05 | 480 ± 20 | 1.81 ± 0.08 | 6.2 |
| 22............. | N-edge-2 | 6.0 ± 0.3 | 0.27 ± 0.07 | 864 ± 47 | 0.57 ± 0.03 | 16.8 |

| Other Zones |
|--------------|----------------|----------------|-----------------|-----------------|----------------|
| 1............. | Main | 7.1 ± 0.1 | 0.14 ± 0.02 | 694 ± 12 | 1.20 ± 0.02 | 121.4 |
| 21............. | Outskirts | 5.8 ± 0.2 | 0.17 ± 0.03 | 875 ± 23 | 0.50 ± 0.01 | 125.1 |
| 9............. | W group | 5.8 ± 0.5 | 0.14 ± 0.10 | 431 ± 39 | 1.43 ± 0.13 | 1.9 |
| 31............. | W group-2 | 6.7 ± 0.6 | 0.27 ± 0.16 | 520 ± 51 | 1.54 ± 0.16 | 1.5 |
| 32............. | W group-3 | 5.9 ± 0.5 | 0.29 ± 0.11 | 575 ± 45 | 0.99 ± 0.08 | 4.3 |
analysis consists of two parts: estimating the image and temperature structure of the cluster and verifying it through the spectral analysis. The first part consists in producing temperature estimates based on the calibrated wavelet-prefiltered hardness ratio maps and producing the pseudopressure and pseudoentropy maps. Wavelet filtering is used to find the structure and set the level of its significance. The background is considered differently in imaging and spectral analysis. In the first we use the in-field estimate of the background for every pointing, using events farthest from the optical axis of the telescope and bright emission zones of A3266, where instrumental background should dominate. We subtract this background using the exposure maps with no vignetting and normalized to reproduce the background level in the region selected for the background estimate.

The second, spectroscopy part of the analysis uses a mask file, created using the zones of similar hardness ratio and similar surface brightness. The first application of this technique is presented in Finoguenov et al. (2004). For background removal we use the background accumulation, obtained with the medium filter (Read & Ponman 2003), while we first refined our background subtraction by modeling the residual background observed at the outskirts of A3266. We use the 1–7.9 keV band in the spectral analysis. The \( n_H \) value is fixed at the Galactic value of \( 1.6 \times 10^{20} \) cm\(^{-2}\) (Dickey & Lockman 1990).

In our spectral analysis we use the APEC plasma code (Smith et al. 2001) to measure the temperature, element abundance (assuming the photospheric solar abundance ratio of Anders & Grevesse 1989), and emission measure. By making an estimate of the volume occupied by each emission zone, it is then possible to recover the pressure and the entropy in absolute units, as well as gas mass estimates, as detailed in Henry et al. (2004) and Mahdavi et al. (2005). To perform the volume estimates, we choose a cluster center at right ascension 04h31m15s91, declination +61°27′08″ (J2000.0), defined by the pressure peak of A3266. The locally measured gas properties are then used in making both the maps and the profiles. We also report the corresponding gas mass in Table 2.

We assume a scaling temperature of 7.1 keV, as measured for the main cluster area in Table 2, and a corresponding scaling radius \( r_{500} = 1.31 \) Mpc, calculated as \( r_{500} = 0.391 \) Mpc \((kT/\text{keV})^{0.63} h_{70}^{-1}\) using the \( M-T \) relation (F. Pacaud 2005, private communication) rederived from Finoguenov et al. (2001) using an orthogonal regression and correcting the masses to \( h_{70} \) and a \( \Lambda \text{CDM} \) cosmology.

3. RESULTS

An advantage of XMM-Newton over previous missions is the ability to provide accurate temperature measurements of the...
projected emission along the line of sight, which allow the study of the pressure and entropy state of the cluster gas. In Finoguenov et al. (2004) and Briel et al. (2004) we developed a simple technique for selecting regions for spectral analysis, using both the surface brightness and hardness ratio as inputs. The XMM-Newton exposure of A3266 allows us to produce almost 100 spatially independent temperature estimates.

Figures 1, 2, and 3 show maps of pseudoentropy, pseudo-pressure, and temperature, respectively, as obtained from the wavelet analysis (left), as well as from direct spectral analysis, where all pixels of a region in a mask are set to the best-fit values of the APEC spectral model fit to a corresponding extracted spectrum (right). The pseudoentropy map reveals the presence of a giant plume of low-entropy gas (LEG) extending over 150 to the northeast from the cluster center. The distinct value of the entropy of the LEG suggests a common origin for it. The orientation of the LEG is aligned with the projection of the major axis of the merger onto the observer’s plane, i.e., the axis of the elongated X-ray morphology. This strongly suggests that the LEG originates with the merger itself. The question is whether the LEG belongs to a cool core in A3266, now undergoing disruption, or is just gas from an infalling subcluster undergoing ram pressure stripping. This will be addressed in § 4.

The entropy in the LEG has significant structure on small but resolved scales. In particular, local enhancements are clearly visible: these are likely preexisting as contact discontinuities due to inefficient mixing but could also have been produced by relatively weak shocks. In fact, all 12 major entropy enhancements seen in Figure 1 (green) have a corresponding pressure enhancement. Finally, these maps show a great number of the entropy dips that are aligned with galaxies and galaxy subgroups. A detailed comparison of the entropy and dynamics of the cluster will be presented elsewhere.

The core region ($r < 0.2r_{500}$) exhibits fluctuations on the level of 14% ± 1% for the entropy and 12% ± 1% for the pressure, with respect to the nonparametric approximation for the sample of distant X-ray–luminous clusters in Finoguenov et al. (2005b), shown in Figure 6. The larger level of fluctuations, 24% ± 2% for the entropy and 30% ± 2% for the pressure, seen within a larger radius ($r < 0.6r_{500}$) is due to asymmetries in the azimuthal distributions, particularly northeast of the core, and is associated with the LEG, which exhibits both ~20% lower entropy and ~30% higher pressure compared to expectations. The thermodynamical properties of the A3266 ICM itself are found to lie within 10% of the scaling prediction of Finoguenov et al. (2005b). Although the amplitude of the pressure fluctuations is highest in the cluster center, reaching a factor of 2, their area filling factor is small, which results in the moderate area-weighted values quoted above.

Finally, we comment on the temperature map. Even though it is not independent of the previous two quantities, its construction is considered to be more straightforward, as it is a directly measured quantity. Figure 3 reveals a slight temperature enhancement ahead of the region covered by the LEG, which may be due to gas compression and weak shocks. The structure seen in the pseudoentropy map is also reflected in the temperature. In the core region, temperature enhancements are also clearly seen in the pseudopressure

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**Fig. 3.—**Wavelet (left) and spectroscopic (right) reconstructions of the spatial temperature distribution. The color legend is as follows: blue, green, yellow, red, and white correspond to temperatures of 4, 5, 6, 7, and 9 keV, respectively, with fractional errors on the 5%–10% level. Black contours show the surface brightness enhancements on the spatial scales 0.25–1’, excluding very small and very large spatial scales to remove smooth cluster components and emission associated with point sources. The contour levels are 1, 3, 10, 30, 100, and $300 \times 10^{-6}$ MOS1 counts s$^{-1}$ pixel$^{-1}$ (pixel size is 4” on a side). The black areas in the spectroscopic reconstruction correspond to the point sources excised from the spectral accumulation. The point sources are not removed in the hardness ratio (left panels here and in Figs. 1 and 2).

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**Fig. 4.—**Background-subtracted, exposure- and vignetting-corrected image of A3266 in the 0.5–2 keV band. Contours indicate the zones of spectral extraction with numbers in correspondence to Table 2.
map, suggesting strong interactions leading to the formation of small-scale shocks.

The results presented in the maps are summarized and better quantified in Table 2. There we use the spectral results obtained using a finer mask to define cruder regions, which absorb temperature variations of less than 1 keV. The new mask has 33 regions, shown in Figure 4, for which we repeat the spectral analysis, summarizing the measured physical properties with their errors in Table 2. In particular, columns (1) and (2) correspond to the zone labels, column (3) to the temperature in keV, and column (4) to iron abundance as a fraction of the solar photospheric value of Anders & Grevesse (1989). Derived quantities that use an estimate for the projected length, as described below, are reported in columns (5)–(7). These are entropy, pressure, and gas mass, respectively. The numbers given in the table confirm that LEG consists of lower entropy and somewhat higher Fe abundance gas. In the northeast part of the LEG (regions 22 and 33) the difference between the LEG entropy and the ICM entropy at the same distance from the center becomes marginal.

4. DISCUSSION AND CONCLUSIONS

In the low-entropy regions near the cluster core (termed LEG in Table 2) the total gas mass is $1.3 \times 10^{13} \, M_\odot$. This mass is comparable to the core gas mass ($r < 250$ kpc) of clusters with mass similar to that of Abell 3266 (Peres et al. 1998). It is also comparable to the total gas masses of cool, low-mass clusters (Mohr et al. 1999) or to high-mass groups (Mulchaey et al. 1996). Thus, the extended feature of LEG is either the core of the main cluster or gas stripped off a secondary merger component with a secondary-to-primary mass ratio of 1:10.

To tie the pseudoentropy map to the dynamics of the cluster, we have produced in Figure 5 an overlay of the Digital Sky Survey-2 (DSS-2) red (optical) image of A3266 with contours of equal pseudoentropy. Interestingly, the central concentration of galaxies, including the cD galaxy, lies well within the low-entropy region. In particular, the head of the LEG region is located at the position of the cD galaxy, although slightly shifted toward the southeast. Therefore, based on their corresponding position on the sky, one would be led to straightforwardly associate the cool LEG with the cD galaxy and its surroundings. Thus, either the cool gas belongs to A3266, in which case it may suggest the preexistence of a cool core there, or, alternatively, the cD galaxy is a part of the infalling subclump. The intracluster gas from the lower mass secondary subcluster is typically characterized by the lower temperature. We mention that the displacement of the low-entropy gas from the optical center is also seen in A754 (Henry et al. 2004).

To test these hypotheses, in Figure 6, we plot the entropy and pressure estimates from Table 2 versus their distance from the A3266 center and compare them with similarly produced profiles for several clusters: A3562 in the Shapley supercluster, A754, and A3667 (Finoguenov et al. 2005a), which are merging clusters, and Abell 478, which is a cooling core cluster. As
subclump would aim at the core of the companion cluster (so as to produce a superposition along the line of sight). In addition, such a configuration may explain the increasing apparent velocity dispersion of galaxies toward the center (Quintana et al. 1996; Henriksen et al. 2000) as being caused by a displacement between the core of the main cluster and the infalling cluster. In order for this to be consistent with the optical data the mass of the subcluster must be in a ratio of no more than 1:10 with respect to the main cluster. This ratio, based on the velocity measurements of cluster galaxies, can be compared to the gas mass estimate for the LEG. We assume that the stripped gas accounts for the matter within $r_{500}$. Based on the average temperature of A3266 of 7.1 keV, the $M$-T relation, and gas mass fraction of 13% (Sanderson et al. 2003), we estimate the gas mass of the ICM of A3266 within $r_{500}$ as $1.2 \times 10^{14} M_{\odot}$. The gas mass ratio between LEG and the main cluster is 9, which is within 10% of the dynamical constraint. Both these estimates argue in favor of the association of the LEG with the galaxy component infalling from the foreground. The temperature of the infalling cluster is predicted as 2.0 keV, and the corresponding $r_{500}$ is 0.59 Mpc. A circle of this radius fits exactly the spatial extent of the tail of the LEG.

Finally, we note that Abell 3266 may have a more complex merger history than the single 1:10 mass ratio merger that we propose. On the west side of the cluster, there is an extended collection of entropy debris. Within the debris are several peaks that appear to be associated with galaxies (see Fig. 5). The masses of the peaks are comparable to group masses. This second region of low-entropy gas may indicate an additional episode of merging, as A3266 is the most prominent cluster in the southern Horologium cluster concentration.

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Fig. 7.—Fe abundance map of A3266. Crude zones are used compared to the entropy and pressure map to achieve the required statistics. Light gray, gray, dark gray, and black colors indicate Fe abundance levels of 0.15, 0.2, 0.25, and 0.3 times solar, respectively. Black contours show the surface brightness enhancements on the spatial scales 0.25′–1′.
Note added in proof.—During the review of our paper, J. L. Sauvageot, E. Belsole, & G. W. Pratt (A&A, 444, 673 [2005]) made available results based on substantially the same data set. Their findings are in good agreement with those presented in this paper.