Merging clusters of galaxies observed with XMM-Newton

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Abstract

We present results from the XMM-Newton observations of our ongoing program on merging clusters. To date three clusters have been observed, covering the temporal sequence from early to late stage mergers: A1750, A2065 and A3921. Using spatially-resolved spectroscopy of discrete regions, hardness ratio and temperature maps, we show that all three clusters display a complex temperature structure. In the case of A1750, a double cluster, we argue that the observed temperature structure is not only related to the ongoing merger but also to previous merger events. A2065 seems an excellent example of a ‘compact merger’, i.e. when the centres of the two clusters have just started to interact, producing a shock in the ICM. Using comparisons with numerical simulations and complementary optical data, the highly complex temperature structure evident in A3921 is interpreted as an off-axis merger between two unequal mass components. These results illustrate the complex physics of merger events. The relaxation time can be larger than the typical time between merger events, so that the present day morphology of clusters depends not only on on-going interaction but also on the more ancient formation history.

Key words: galaxies: clusters: general – galaxies: clusters: individual: Abell 1750, Abell 2065, Abell 3921 – galaxies: clusters: intergalactic medium, mergers – X-rays:general – X-ray:galaxies:clusters – cosmology: large-scale structure of Universe

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1 Introduction

As the largest assembled structures in the Universe, clusters of galaxies are commonly thought to form by gradual accretion of matter along filaments and by interaction and merging with previously formed structures. Hydrodynamical simulations (e.g. Rowley et al. 2004 and references therein) predict that merger events strongly affect the physical characteristics of the intracluster medium (ICM). In particular the temperature structure is thought to be an excellent indicator of the cluster dynamical state and formation history. Spectro-imaging observations with XMM-Newton and Chandra allow the building of precise temperature maps, enabling deeper investigation of the dynamical processes of cluster formation and the effect of the mergers on the ICM (e.g., Markevitch et al., 2000; Neumann et al., 2003; Henry et al., 2004; Krivonos et al., 2003; Vikhlinin & Markevitch, 2003).

With the aim of describing an evolutionary sequence of cluster formation, we have selected a small sample of galaxy clusters showing morphological evidence of ongoing merger activity. The sample was selected, on the basis of previous X-ray observations, from nearby clusters which entered the field of view of XMM-Newton. Here we summarise results for A1750 and A3921, presented in detail in Belsole et al. (2004, 2005), and we describe preliminary, new results for A2065.

2 Observations and data analysis

In Table 1 we list the main physical characteristics of the three clusters, together with basic observation information. The A1750 and A3921 observations were very little contaminated by soft proton flares (details of the data preparation can be found in Belsole et al. 2004, 2005). Unfortunately, emission from soft protons dominates the whole observation of A2065. This required an ad-hoc treatment for these data, which allowed us to model the background. A2065 will be re-observed with XMM-Newton, and thus here we discuss only preliminary results.

The background estimates were obtained using a blank-sky observation consisting of several high-latitude pointings with sources removed (Lumb et al. 2002), and source and background events were corrected for vignetting using the EVIWEIGHT task in the Science Analysis System (SAS), enabling us to use the on-axis response matrices and effective area.
Table 1

| Parameter     | Abell 1750 | Abell 2065 | Abell 3921 |
|---------------|------------|------------|------------|
| $z$           | 0.086      | 0.072      | 0.096      |
| RA (J2000)    | 13$^h$30$^m$52$^s$ | 15$^h$22$^m$42.6$^s$ | 22$^h$49$^m$38.6$^s$ |
| Dec(J2000)    | $-01^\circ$50'27" | $+27^\circ$43"21" | $-64^\circ$23'15" |
| Obs time (ks) | 30         | 23         | 30         |
| $N_H(10^{20}\text{ cm}^{-2})^a$ | 2.39 | 2.95 | 2.94 |
| Global T (keV)| 3.87 (2.84)$^b$ | 5.4 | 5.0 |

$a$ From Dickey & Lockman (1990)

$b$ A1750C (A1750N)

3 Results

We show in Figure 1 the images of A1750 and A3921 in the 0.3-7.0 keV band; for A2065 a lower energy band [0.1-1.4 keV] is shown to enhance cluster emission above the strong particle background. We observe that the morphology of the clusters is very different, reflecting already a difference in their dynamical state. A1750 is a prototype of a binary cluster, although the system appears to have at least three components (Beers et al., 1991). The main cluster, A1750C, is at the centre of the field of view, and a slightly less massive cluster (A1750N) lies to the north. A2065 looks rather unperturbed on the outskirts, but the central regions display a clear compression of the isophotes towards the south-east, and a sharp edge to the east. Finally, the X-ray image of A3921 is dominated by the main cluster at the centre of the field of view, and we observe an elongation of diffuse emission to the west, where the X-ray emission from two of the three brightest galaxies in the cluster can also be seen.

3.1 Morphology

One approach to evaluate any deviation from a dynamically relaxed cluster is to assume a $\beta$-model (Cavaliere & Fusco-Femiano, 1976) as a description of a relaxed isothermal system. The large soft proton contamination of the A2065 observation reduced the significance of any substructure when this method was applied and thus we do not discuss it further.

We thus generated low energy (0.3-2.0 keV, where the density distribution is least temperature dependent) surface brightness maps for A1750 and A3921, and fitted them with a bi-dimensional $\beta$-model. The two clusters belonging
Fig. 1. (a) XMM-Newton EPIC 0.3-7.0 keV energy band count image of A1750; (b) MOS1+MOS2 0.1-1.4 keV energy band count image of A2065, the band chosen to enhance cluster emission above the strong particle background; (c) XMM-Newton EPIC 0.3-10 keV energy band count image of A3921. These are raw, non-background subtracted images.

to A1750 were taken into account simultaneously. We found that A1750 does not show significant residuals above a $\beta$-model, in the region between the two clusters, but there is some excess emission in their cores.

On the other hand, A3921 shows large residuals to the west (other than those
Fig. 2. Surface brightness maps of A1750 (a) and A3921(b) in the soft energy band (0.3-2.0 keV). Contours are the residuals above a 2D $\beta$-model which was subtracted from the image. The first contour is at 1$\sigma$.

in the centre of the main cluster), indicating that a significant substructure is present and it is related to one or both the brightest galaxies in that area. The two galaxies are at 7 arcmin (RA = 22$^h$48$^m$49$^s$, Dec = $-64^\circ$23$'$10$''$ (J2000)) to the north-west (BG2) and at 8 arcmin (RA = 22$^h$49$^m$04$^s$, Dec = $-64^\circ$20$'$35$''$ (J2000)) to the WNW (BG3) from the central brightest galaxy BG1 (RA = 22$^h$49$^m$58$^s$; Dec = $-64^\circ$25$'$46$''$ (J2000); see Belsole et al. 2005 for details).

3.2 Temperature distribution

We computed temperature maps for A1750 and A3921 by applying the multi-scale spectro-imagery algorithm described in [Bourdin et al., 2004]. EMOS cameras only were used for this analysis. For A2065, we obtained an hardness ratio (HR) map once the particle contamination was modelled and subtracted from the images. This gives us qualitative, but significant results about temperature substructure in this cluster. The temperature maps are shown in Figure 3.

All three clusters show significant temperature variations, even in the cases where surface brightness substructures were not detected (A1750). As is confirmed by extraction of spectra from discrete regions [Belsole et al., 2004], the region between A1750N and A1750C has a temperature which is significantly (30%) hotter than the global temperature of either the two clusters. Additional temperature gradients are observed in A1750C, indicating that this
Fig. 3. Temperature maps. The wavelet algorithm described in Bourdin et al. (2004) was used for A1750 (a) and A3921 (c). In the case of A2065 (b) the image is an hardness ratio map (see text for details).
cluster was already perturbed in the past.

The temperature enhancement, coincident with the isophotal compression, observed in the A2065 HR map points to a bow shock. We also detect a cool core, coincident with the peak of X-ray emission.

The orientation of the striking hot temperature bar in A3921 represents our strongest proof against the interpretation that this is a merger before close core passage. The temperature here varies between 7 and 8 keV, up to 60% higher than the main cluster temperature.

4 Discussion

For each cluster we summarise the results obtained in the previous sections.

A1750

(1) From the morphological analysis we found: off-centre cores and twist of the isophotes, but lack of substructure in the region between the two clusters.

(2) the temperature increases weakly (∼30%), but significantly, in the region between the two clusters.

(3) strong temperature variations are observed within the main cluster (A1750C) and we also measured a discontinuity in the gas density profile of order 20%.

(4) we found a high entropy in the core of the two clusters (see Belsole et al. 2004)

The combination of these results lead us to interpret A1750 as an ongoing merger between two clusters of similar masses, which have just started to interact at a real distance comparable to their virial radii. These two units will be in the compact phase (core passage) within 1 Gyr. However the temperature and density variations within A1750C itself are not explicable by the merger event occurring with A1750N and are intrinsic to this cluster. The most likely interpretation is that this is the signature of (a) previous merger(s). A1750 is a good observational test case to be compared with numerical simulations, since it shows all of the signatures expected from gravitationally dominated processes. However, the fact that effects of a previous merger are observed strongly supports the necessity of taking into account time dependent quantities, such as the relaxation time, in using galaxy clusters for cosmological purposes.
A2065

The surface brightness shows an isophotal compression towards the south-east, at $\sim 80$ arcsec from the X-ray peak. The feature is accompanied by a forward shock in the same axis (NW-SE); moreover a surviving cooling core is detected.

Despite the limited quality of the data, A2065 shows clear signatures of being an ongoing merger in the compact phase, when the detection of strong shocks is the most favourable. This is similar to what is observed in numerical simulations of head-on collisions of merging clusters. The fact that the core of the main cluster is cool suggests that this is probably the remnant of a cooling core, and thus the colliding object was probably of smaller mass (e.g. Gómez et al. 2002). The new XMM-Newton observations of this object should allow us to put better constraint on these preliminary results.

A3921

Observational merger evidence includes:

1. Two peaks in both the X-ray emission and the galaxy distribution (Ferrari et al., 2005);
2. The hot bar is oriented parallel to the line joining the subclusters, it is not orthogonal, as in the case of A1750;
3. The central regions of the main cluster and the subcluster to the west are strongly perturbed;
4. There is an off-set between the galaxy distribution of the smaller subcluster and the secondary X-ray peak (Belsole et al., 2005; Ferrari et al., 2005).

This evidence cannot be interpreted as the result of a pre-merger. We are seeing maybe the best example of an X-ray observed off-axis post-merger. The subcluster has come from somewhere in the SE and is currently exiting towards the NW. The two merging units have different masses, on a ratio of 1 to 3 (or 1 to 5; see also Ferrari et al. 2005). Comparison of these high quality X-ray results with optical observations and numerical simulations yield an estimate of the age of the merger of order 0.5 Gyr after core passage. Off-axis mergers are more likely to occur than head-on ones, and they are more efficient in mixing the gas via turbulence. If anything, A3921 needs even deeper study, and the combination of these XMM-Newton data with upcoming Chandra observations will give further elements to our interpretation.
5 Conclusions

The *XMM-Newton* observations of this small sample of galaxy clusters has confirmed that the comparison of X-ray morphology and temperature is an excellent tool to understand the dynamical status of these objects. In the case of A1750 and A3921, spectroscopy of discrete regions ([Belsole et al., 2004, 2005]) has confirmed the significance of the temperature structure found with the multi-scale wavelet approach. The significance of the temperature structure in A2065 will be investigated with the upcoming *XMM-Newton* observation. For the better studied cases we have confirmed the previous interpretation of a recent merger (A1750), but have added new evidence suggesting that at least one of the subclusters is itself a merger remnant. Good quality X-ray data have allowed us to completely revolutionise the interpretation of the dynamical state of A3921.

We can organise these clusters along an evolutionary path, where A1750 represents the beginning of a merging event, which in a timescale of order 1.5 Gyr will be in the same state as A2065, when a bow shock is departing in the direction of motion after the two cores have collided, and the two (or maybe more) colliding objects are not physically separable anymore. Finally, A3921 represents the epoch when the secondary object has already passed the close core passage phase, it is exiting on the far side with respect to the direction of motion, and it will be accreted by the main cluster on a larger timescale (of order 3-5 Gyr).

From so small a sample we cannot extract global conclusions on the population of merging galaxy clusters. However, this work supports the necessity of a wider investigation of the effect of the physics of mergers on the global characteristics of galaxy clusters, especially if these objects are to be used to derive cosmological parameters.

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