MORPHOLOGY AND 2D-TEMPERATURE DISTRIBUTION OF THE X-RAY EMITTING GAS IN GALAXY CLUSTERS, MEASURED WITH XMM-NEWTON

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Abstract

The XMM-Newton observatory with its high throughput in combination with the EPIC CCD-cameras is an ideal instrument to study extended sources like clusters of galaxies. Very deep observations of galaxy clusters reveal substructure on different levels: structure associated with bright galaxies, faint galaxies, or structure consistent with the merger of groups with the main cluster. An other indication of substructure is the deviation of the temperature of the intra-cluster gas from isothermality. We present XMM-Newton mosaic observations of the nearby clusters Coma, A3667, A754 and A2256. These clusters are good representatives of the different evolution stages that all clusters experience as they grow from mergers of smaller groups. Hence they show merging at different phases, which is also reflected in the different appearance of their temperature maps.

1 Introduction

Clusters of galaxies are the largest virialized objects in the Universe. They can easily be studied in the X-ray wavelength band, because they contain hot intracluster gas at temperatures of several keV which pervades throughout the cluster. This intracluster gas is the main baryonic component of the cluster and it follows the gravitational potential of the dark matter, which contains about 85% of the cluster mass. It is believed that galaxy groups and clusters form from initial density fluctuations which grow under the influence of their gravity. By merging with others, they grow more and more and build up the present cosmic large scale structure with voids, filaments and knots. Massive clusters are found preferentially at places where filaments are crossing.

Growing by merging also means that the galaxy clusters have significant substructure. Numerical simulations of merging processes (for example Roettiger et al. 1997, or Ricker & Sarazin 2001) show complex appearance of clusters in both, the surface brightness distribution and the temperature maps. They depend particularly on the phase of the merging, on the masses of the components and also on the infall geometry. Einstein observations have shown the variety of the surface brightness distribution (e.g. Jones & Forman 1992), and Rosat observations (e.g. Buote & Tsai 1997, or Mohr et al. 1995) have shown that substructure by merging processes is very common in nearby clusters. Temperature maps have been obtained from Rosat observations (e.g. Briel & Henry 1994; Henry & Briel 1995) and from ASCA observations (Markevitch et al. 1998). The Rosat observations were hampered by the small energy band (0.2 to 2.4 keV) whereas the ASCA observations were hampered by the energy dependent point spread function. With the new X-ray observatories Chandra and XMM-Newton much more detailed investigations of the temperature maps and intensity maps can be performed. In this paper we will report on the
temperature and intensity maps of 4 nearby Clusters, observed with the EPIC-CCD cameras (Strüder et al. 2001; Turner et al. 2001) of the XMM-Newton satellite (Jansen et al. 2001).

2 Observations and results

2.1 The Coma cluster of galaxies

The Coma cluster of Galaxies was one of the PV targets of XMM-Newton and was observed in 15 partially overlapping pointings, with three of them re-observed because of a high soft proton background during their initial observations. Coma was chosen as a PV target because it is a well-studied cluster and has a diameter, which is several times larger than the FOV of the EPIC cameras. The aim of the performance verification was to verify XMM-Newton’s ability to map large extended X-ray sources. In the left panel of Figure 1 we show the merged pn image of 13 pointings in the energy band from 0.3 to 2.0 keV, corrected for exposure and vignetting. The surface brightness distribution is slightly smoothed using a Gaussian filter of variable size. This figure is an updated version of Figure 1 of Briel et al. (2001). Although the Coma cluster was long believed to be the archetype of a relaxed cluster of galaxies, the X-ray image taken during the ROSAT all sky survey revealed its complex large-scale structure, especially the subgroup around NGC 4839, probably in the process of merging with the main cluster (Briel et al. 1992). New in the XMM-Newton raster scan is the excess emission between the center of the cluster and the NGC 4839 subgroup. Spectroscopic investigations of that region showed that the temperature of this intra cluster gas is significantly higher than the average cluster gas temperature (Briel et al. 2001, Arnaud et al. 2001). Combining XMM-Newton’s pn and MOS data, a hardness ratio map (2.0–5 keV / 0.5–2.0 keV) was constructed, which is shown in the middle panel of Figure 12 (from Neumann et al. 2003). In this map, red corresponds to kT below 6 keV, yellow to 6 keV < kT < 8 keV and white to kT above 8 keV. The contours denote the excess in the surface brightness distribution, obtained by subtracting an elliptical best-fit beta model from the image. The hardness ratio map confirms the hotter region between the center and NGC 4839 and also the cool region towards the east, from which another group around NGC 4911 is probably on its way to merge with the cluster.

The right panel of Figure 1 is yet another demonstration of the richness of substructures in the Coma cluster. It is a wavelet-filtered image of the combined pn and MOS data. The filtering was done in such a way as to show variations in the surface brightness distribution down to a 5-sigma significance (Briel et al., in prep.). It very clearly shows the several subunits and the irregular structure at different scales, especially the swept back material around the NGC 4839 group as well as the displacement of the galaxy from the center of the group’s ICM, probably caused by the ram-pressure as the group merges with the main cluster.

2.2 A3667

The Abell Cluster A3667 was observed with ROSAT (Knopp et al. 1996) and recently with Chandra (Vikhlinin et al. 2001; Mazzotta et al. 2002). The ROSAT image revealed a surface brightness of varying ellipticity and a surface brightness discontinuity SE from the core. The counting statistics of the ROSAT observation was to low to obtain a temperature map, but it was concluded that the cluster is not in a relaxed configuration but rather in the process of merging since the fit to a constant temperature was rejected by 95% confidence. Evidence was found for excess emission towards the NW, apparently coincident with a group of galaxies. The recent Chandra observations revealed a very steep drop in surface brightness in the SE coincident with a cold-front (Vikhlinin et al. 2001). This was interpreted as a large cooler gas cloud moving through the hotter ambient gas. In a second paper, a hydrodynamic instability was identified perpendicular to the cold front (Mazzotta et al. 2002). All those findings indicate that A3667 is not in equilibrium but rather in the process of a major merger and evidence was found for a
Kelvin-Helmholtz instability in the cluster atmosphere.

With XMM-Newton A3667 was observed in a raster scan of 6 partially overlapping pointings, each lasting for approximately 15 ksec (Briel et al., in prep.). In the middle panel of Figure 2 we show the merged exposure and vignetting corrected soft (0.5 to 2.0 keV) image of the cluster after it was wavelet-filtered as described in the section on Coma. We used all the EPIC-pn and -MOS data during times when the particle background was low. We clearly detect the very irregular shape of the cluster’s surface brightness distribution and also the very steep drop around the cold front. In addition to the three peaks in the center of the cluster we find striking evidence of turbulence down-stream of the cold front especially towards the north (confirming the findings of Chandra) and also towards the NW. This turbulence is even more evident in the hardness-ratio map shown in the right panel of Figure 2 (with overlaid contours of the surface brightness distribution shown in the middle panel). For this hardness ratio map we built two wavelet-filtered images, the one shown in the middle panel of Figure 2 and a corresponding hard image in the energy range from 2.0 to 7.5 keV and divided them. This map shows hot gas flowing around the cold front developing Rayleigh-Taylor and Kelvin-Helmholtz instabilities. From the indicated regions we fitted the pn-spectra with a one-temperature model to get a calibration for the hardness ratio map. For the cold front (region 1) and the hot bubble north of the cold front (region 2) we found temperatures of 4.6 +/- 0.2 keV and 8.6 +/- 1.2 keV respectively, confirming the results of Chandra, which we show in the left panel of Figure 2. For the regions 3, 4 and 5 we find 6.6 +/- 0.4 keV, 8.2 +/- 1.0 keV and 7.0 +/- 0.3 keV. These temperature variations across the face of the cluster have to be proven statistically significant by adding the MOS data to the temperature fits.

2.3 A754

The Abell cluster A754 is another example of a cluster experiencing a major merger. This was found in the observations made with ROSAT, which resulted in the first temperature map of A754, shown in the left panel of Figure 3 (from Henry & Briel 1995). In the X-ray surface brightness distribution a very significant peak with the shape of a bar was found, orientated perpendicular to the major axis of the cluster. A cool (red) region was found near that bar, and a fan-shaped hotter (yellow) region pointing away from the bar towards the west. The ROSAT temperature map was later confirmed by ASCA (Henriksen & Markevitch 1996). The features of both the temperature map and the surface brightness map are consistent with hydrodynamic calculations of mergers and are interpreted as the result of the merging of a sub-group, which originally was located in the SE and has already passed through the main cluster towards the NW.

With XMM-Newton we observed A754 in a raster scan of 4 partially overlapping pointings, each lasting for about 13 ksec (Henry et al., in prep.). In the middle panel of Figure 3 we show the merged, exposure and vignetting corrected soft (0.5 to 2.0 keV) image of the cluster after it was wavelet-filtered as described in the section on Coma. Again, we used all the pn and MOS data during times when the particle background was low. We clearly detect the very irregular shape of the cluster’s surface brightness distribution, especially the bright elongated bar with the maximum in the brightness. Moreover, the surface brightness west of the bar also shows turbulent-like substructure. As for A3667, we created a hardness ratio map, which is shown in the right panel of Figure 3. It confirms the hotter region west of the bar and it shows temperature variations across the face of the cluster. It shows that only the northern part of the bar is at a low temperature, found also recently by Chandra (Markevitch et al. 2000). The coldest part of the bar is coincident with a drop in surface brightness, possibly another cold front, which might change the interpretation of the evolution of this cluster: one possibility is that part of the group, merging from east to west, was driven towards north-west-north, building up the cold front and the discontinuity in surface brightness.
Figure 1: The Coma cluster of galaxies. Left: Soft band raster image. Middle: Hardness ratio map (from Neumann et al., 2003). Right: Wavelet-filtered soft band image.

Figure 2: The cluster A3667. Left: Temperature map, obtained with Chandra (from Mazzotta et al., 2002). Middle: Wavelet-filtered soft band image. Right: Hardness ratio map.

Figure 3: The cluster A754. Left: Rosat temperature map (from Henry & Briel 1995). Middle: Wavelet-filtered soft band image. Right: Hardness ratio map.

Figure 4: The cluster A2256. Left: Rosat temperature map (from Briel & Henry 1994). Middle: Wavelet-filtered soft band image. Right: Hardness ratio map.
2.4 A2256

As a last example we show results of the observations of the Abell Cluster A2256. This cluster was the first to be observed with ROSAT in 1990 (Briel et al. 1991). Together with a dedicated raster scan it was used to create the first temperature map of a galaxy cluster (Briel & Henry 1994). This temperature map (together with ROSAT surface brightness contours) is shown in the left panel of Figure 4. The main result was a cool (red) region west of the center, coincident with the position of a sub-cluster on its way through the main cluster, and two 'hot spots' east and west of the cooler region and perpendicular to the moving direction of the sub-cluster (yellow regions). This was the first detection of a 2-dimensional temperature variation across the face of a cluster. The appearance of the map is consistent with the at that time first simulations of cluster-cluster mergers. The cool region has been confirmed by ASCA (Markevitch 1996) and recently by Chandra observations (Sun et al. 2002). The two hot spots however were not confirmed.

A2256 was recently observed with XMM-Newton in a raster scan of 7 partially overlapping pointings, each about 15 ksec long (Briel et al. in prep.). In the middle panel of Figure 4 we show the merged exposure and vignetting corrected soft (0.5 to 2.0 keV) image of the cluster after it was wavelet-filtered as described in the section on Coma. Again, we used all the pn and MOS data during times when the particle background was low. We clearly detect the discontinuity in surface brightness, caused by the merging of the sub-unit, and find substructure within this brightest part of the cluster. In addition, SE of the center seems to be another discontinuity, which was barely seen in the ROSAT image. Further out to the SE, material seems to flow away from that discontinuity, probably caused by a shock wave in front of that discontinuity. This scenario is consistent with the temperature map we show as a hardness ratio map in the right panel of Figure 4. Inside of that discontinuity we find a lower temperature as compared to the outside region. The hot region to the SE continues into the out-flow region and is probably heated by the shock wave moving through that area. The previously found discontinuity west of the cluster center exhibits a very pronounced cold front, consistent with what was found with ROSAT, ASCA and Chandra. The NE hot spot, described in Briel & Henry (1994), is confirmed by the hot region to the north-east seen in the XMM temperature map. The second hot spot however is outside the useful XMM temperature map. We are expecting more observations of the center region of A2256 with which it will be possible to determine if the hot region found in front of the merger discontinuity continues further out.

3 Discussion

With XMM-Newton (and also with Chandra) we can now determine the 2D-temperature map and the surface brightness distribution of the X-ray emitting gas in galaxy clusters to a so far unprecedented accuracy. We have presented a sample of clusters, selected for their signatures of merging activity. Our study is motivated by the necessity to understand different morphologies of clusters, such as cD, double, core, linear or irregular, within the framework of structure formation, which is essential in order to use clusters of galaxies for cosmological studies. It has been shown by this and many previous works, that the observed appearance of the cluster is a result of previous or ongoing growth of the cluster not only by accretion, but also by merging of subsystems of comparable mass. Our observations clearly demonstrate that major features, detected in the X-ray surface brightness maps and in the temperature maps, are due to the survival of the substructure, as indicated by the possible prevalence of the cold fronts over the merger shock explanation. Still, the importance of the shock heating should not yet be discarded, and particular the advantage of XMM-Newton to study the low surface brightness regions of the cluster with a wide field of view will enable us to investigate these processes. From our observations we can draw the conclusion that the enhanced surface brightness regions may
not always be due to shock heating. This suggestion, that mergers can boost the luminosity of
the cluster (e.g. Randall et al. 2002), still needs observational confirmation, for which we also
need to observe a complete volume limited sample of merging clusters.

Acknowledgements

The XMM-Newton project is an ESA Science Mission with instruments and contributions
directly funded by ESA Member States and the USA (NASA). The XMM-Newton project is
supported by the Bundesministerium für Bildung und Forschung/Deutsches Zentrum für Luft-
und Raumfahrt (BMBF/DLR), the Max-Planck Society and the Heidenhain-Stiftung.

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