Non-Thermal and Thermal Hard X-ray Emission from Clusters of Galaxies

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Abstract

Some recent Suzaku and XMM-Newton results on the thermal and non-thermal hard X-ray emission from clusters of galaxies are presented. The Coma cluster has the brightest cluster radio halo in the sky. We do not find significant evidence for non-thermal inverse Compton hard X-ray emission in Coma. Instead, we find that the Suzaku and XMM-Newton spectra are best explained by hot thermal gas in the cluster. Our upper limit on the non-thermal hard X-ray emission in Coma is well below the previous claimed detections with RXTE and BeppoSAX. However, since the field of view of the Suzaku HXD PIN detector is smaller than that of RXTE and BeppoSAX (although still bigger than the angular size of the radio halo), our upper limit and the previous detections might be consistent if the non-thermal emission comes from a very extended region which is much larger than the radio halo. Abell 3667 is a merging cluster with two cluster radio relics. The northwest radio relic is the brightest diffuse cluster radio source in the sky (brightest halo or relic). Our Suzaku observations show evidence for a very hot thermal component ($kT > 13$ keV) in the center of this cluster. This emission may be associated with merger shocks. The Suzaku spectra do not show clear evidence for non-thermal inverse Compton hard X-ray emission from the NW radio relic. We recently obtained a deep XMM observation of the region of the NW radio relic. The XMM image shows a surface brightness discontinuity at the outer edge of the radio relic. The image and spectra of this region are consistent with the jump being a merger shock with a Mach number of about 2. Alternatively, the X-ray emission in this region might be non-thermal emission from the radio relic. Our Suzaku and XMM observations imply that the magnetic field in the relic is $B \gtrsim 3$ μG, which is a surprisingly large field at such a large distance (about 2.2 Mpc) from the center of a cluster. This indicates that there is a nontrivial contribution of non-thermal pressure in this region.

Key words: galaxies: clusters: general — galaxies: clusters: individual (Coma, Abell 3667) — intergalactic medium — radio continuum: general — shock waves — X-rays: galaxies: clusters

1. Introduction

Both observations and theory indicate that clusters of galaxies are forming at the present time through massive cluster mergers. Major cluster mergers are the most energetic events which have occurred since the Big Bang, involving total energies of $\sim 10^{64}$ ergs. Merger shocks driven into the intracluster gas are the primary heating mechanism of the gas in massive clusters.

Enigmatic extended cluster radio sources with very steep spectra and no clear optical counterparts have been known for over 30 years (for a review see Feretti 2008). Fairly symmetric sources which are projected on the cluster center are often referred to as “radio halos” while similar elongated sources usually located on the cluster periphery are called “relics.” In every case, such diffuse cluster radio sources have been found in irregular clusters which are apparently undergoing mergers. This suggests that the radio emitting electrons are accelerated or re-accelerated by shocks or turbulence associated with these cluster mergers. One possible theoretical picture is that the radio halos are accelerated by turbulence following the passage of merger shocks, while the relics are the direct result of merger shock acceleration (e.g., Feretti 2008).

The same relativistic electrons which produce the radio synchrotron radiation will produce hard X-ray (HXR) emission by inverse Compton (IC) scattering of Cosmic Microwave Background (CMB) photons. However, the detection of this emission has been difficult and remains controversial (e.g., compare Fusco-Femiano et al. 2004; Rossetti & Molendi 2004). The radio synchrotron luminosity depends on the energy in relativistic electrons times the energy density in the magnetic field. Similarly, the IC HXR luminosity depends on the energy in relativistic electrons times the energy density in the CMB, which is well-known. Thus, if both radio and IC HXR emission can be detected, one can determine both the energy in relativistic electrons and the magnetic field strength. On the other hand, if radio is detected but one has only an upper limit on the IC HXRs, then this leads to an upper limit on the energy in relativistic electrons, and, somewhat paradoxically, to a lower limit on the strength of the magnetic field.

Here, some recent results on the non-thermal and thermal hard X-ray emission from merging clusters are reviewed.

2. Coma Cluster

The Coma cluster is the brightest non-cool-core X-ray cluster, and hosts the brightest radio halo (Deiss et al. 1997). It has been the focus of many efforts to detect IC HXR emission. Thus far, claimed detections of this emission in Coma are controversial (e.g., Fusco-Femiano et al. 2004; Rossetti & Molendi 2004). We observed the central part of the Coma cluster with the Suzaku HXD for roughly 156 ks in order to detect or limit IC HXR emission; for a detailed description of the data and results, see Wik et al. (2009). The field-of-view (FOV) of the Suzaku HXD PIN detector is a bit larger than the size of the Coma radio halo, which should be ideal if the IC HXRs follow the radio halo.

Two key issues with the analysis of the Suzaku HXD PIN for Coma (and other clusters as well) are the systematic error in modeling the non-X-ray background (NXB) due to particles in the detector, and the proper modeling of the hard X-ray thermal emission from the hot gas in the cluster. The later problem is particularly acute for Coma, because it is a very bright and very hot cluster, and the radio halo is centrally located. To deal with the thermal contribution, we have used the XMM mosaic data (Fig. 1) on the Coma cluster (Schuecker et al. 2004). XMM spectra were accumulated in regions of nearly constant Suzaku PIN response, and then the spectra were weighed by the Suzaku PIN response and summed. This "PIN equivalent" XMM spectrum was fit simultaneously with the Suzaku PIN spectrum.

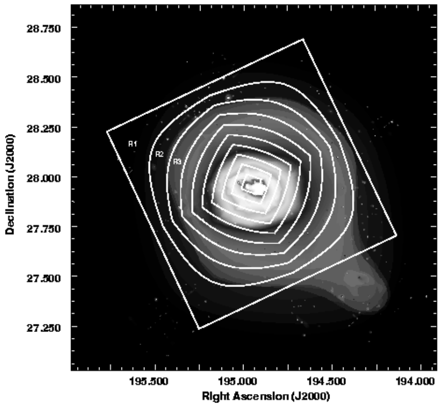

Fig. 1. XMM mosaic EPIC-pn 2–7.5 keV wavelet smoothed X-ray image of the Coma cluster. The regions in white indicate a constant Suzaku HXD PIN effective area, with the values ranging from 0% to 90% of the response for a point source at the center. These regions were used to collect XMM spectra.

We fail to find statistically significant evidence for non-thermal emission in the spectra, which are better described by only a single or multi-temperature model for the ICM. Figure 2 shows a single temperature fit to the Suzaku PIN and XMM spectra in which the non-X-ray background (NXB) was increased by its systematic error. No non-thermal emission was required. Including systematic uncertainties, we derive a 90% upper limit on the flux of non-thermal emission of 6.0×10^{-12} erg s^{-1} cm^{-2} (20-80 keV, for $\Gamma = 2.0$), which implies a lower limit on the cluster-averaged magnetic field of $B > 0.15\,\mu$G. Our flux upper limit is 2.5× lower than the detected non-thermal flux from RXTE (Rephaeli & Gruber 2002) and BeppoSAX (Fusco-Femiano et al. 2004). We suggest that complex thermal structure in Coma may have been interpreted as non-thermal emission in the past. The thermal interpretation of the hard Coma spectrum is consistent with recent analyses of INTEGRAL (Eckert et al. 2007) and Swift (Ajello et al. 2009; Okajima et al. 2009) data. However, if the non-thermal hard X-ray emission in Coma is more spatially extended then the observed radio halo, the *Suzaku* HXD-PIN may miss some fraction of the emission.

3. Suzaku Observation of the Abell 3667 Cluster

In many ways, Abell 3667 is the ideal site to study mergers and radio relics. It is a very bright X-ray cluster at a low redshift ($z = 0.0552$). The ROSAT and ASCA observations showed that it is a spectacular merger with shock heated gas (Markevitch et al. 1999). Abell 3667 contains a pair of curved cluster radio relics (Figs. 1 & 2; Röttgering et al. 1997). Their location on either side of

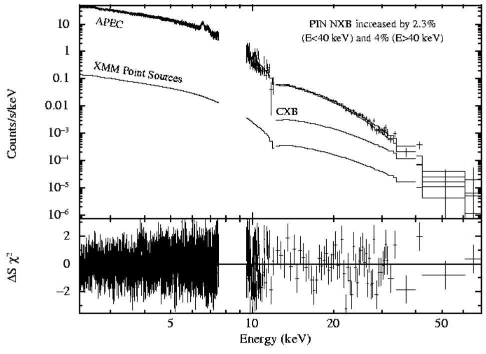

Fig. 2. The Suzaku HXD PIN (above 12 keV) and XMM-Newton (below 12 keV) spectra of the radio halo region of the Coma cluster. The curve labeled "APEC" is the best-fit single temperature model. The lower curves give the contributions of the CXB and of point sources. In this fit, the level of the NXB was increased to the upper limit based on the systematic error. The fit shows that non-thermal emission is not required to fit the observed spectra, given the systematic errors.

the cluster center and sharp, inwardly curved outer edges are exactly what is expected for merger shocks. Models which reproduce the optical and inner X-ray properties of A3667 predict shocks at or near these locations (Roettiger et al. 1999; Ricker & Sarazin 2001). The relics have very sharp outer edges, as expected if this is the location of the merger shock and shock particle acceleration. The radio spectra steepen with distance from the outer edge (Röttgering et al. 1997) as expected if the electrons are accelerated there, and the higher energy electrons lose energy due to synchrotron and IC emission as they are advected away from the shock. The synchrotron polarization suggests that the magnetic field in the region was increased by shock compression.

The northwest radio relic in Abell 3667 is the brightest (highest flux) cluster radio relic or halo source which is known, with a flux at 20 cm of 3.7 Jy (Johnston-Hollitt 2004). Since the electrons which emit the IC HXR emission are basically the same ones which emit radio synchrotron, for a given magnetic field the HXR flux should be nearly proportional to the radio flux. Thus, Abell 3667 might be expected to be the brightest non-thermal (NT) cluster hard X-ray source. Since this relic is at a large radius, if anything the magnetic field should be lower than in other objects, implying an even larger HXR flux.

We made three Suzaku observations of Abell 3667, with the longest observation centered on the NW radio relic (Fig. 3). For more details on the observations and results, see Nakazawa et al. (2009). In addition to the results on the NW radio relic, the observations showed that hot gas extended out 2.6 Mpc from the cluster center (approximately the virial radius). Also, very hard X-ray emission was seen from the region of the cluster center. If thermal, this emission corresponds to $kT > 13$ keV. This emission might be associated with merger shocks near the cluster center.

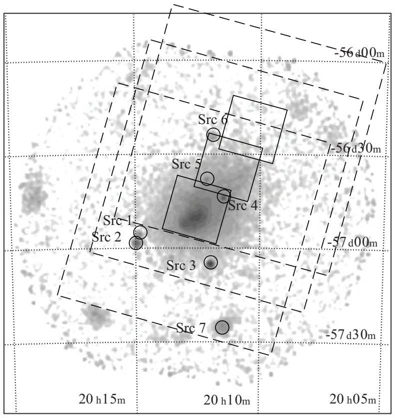

Fig. 3. The ROSAT PSPC image of Abell 3667. The FOVs of the three Suzaku HXD PIN exposures are shown as dashed rectangles, while those of the XIS are shown as solid rectangles. Several point sources are also marked.

The Suzaku HXD PIN spectrum of the NW radio relic was studied using techniques similar to those described above for Coma. When the systematic uncertainty in the NXB was included, no reliable evidence for non-thermal emission was seen. We found an upper limit of 7.1×10^{-12} erg/cm^2/s in the 12–70 keV band. This implied a lower limit on the magnetic field of $B > 0.6\ \mu$G.

4. New XMM-Newton Observation of the Abell 3667 NW Radio Relic

Recently, we made a new observation of Abell 3667 centered on the NW radio relic with XMM-Newton. The purpose of this observation was to better characterize the X-ray emission in this region, including getting a better determination of the thermal spectrum for modeling along with the Suzaku PIN data, searching for the merger shock thought to exist in this region, and detecting or constraining the non-thermal emission in the XMM passband. The total scheduled time of observation was 55 ksec.

Figure 4 shows the resulting XMM mosaic image including the new data. Comparison to previous XMM X-ray images (Briel et al. 2004; Nakazawa et al. 2009) shows the significant gain in spatial coverage achieved with the new observation. The contours show the 843 MHz radio emission in the region near the NW radio relic from the SUMMS survey.

The XMM image of Abell 3667 shows a sharp surface brightness discontinuity to the northwest, which corresponds with the position of the outer edge of the radio relic. We note that this position corresponds to the expected location of the proposed merger shock associated with the radio relic. Our previous Suzaku XIS image

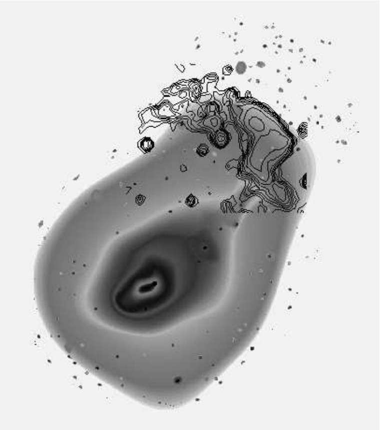

Fig. 4. XMM mosaic EPIC-pn 0.5-2.0 keV wavelet smoothed X-ray image of the Abell 3667 cluster, including the new observation of the NW radio relic. The image has been background subtracted and exposure corrected. The contours show the radio image of the region around the NW radio relic from the SUMSS 843 MHz survey. Note particularly the large number of point sources to the NW of the relic, and the sharp X-ray surface brightness drop at the outer edge of the relic.

of this region did not show this edge (Nakazawa et al. 2009). We note that there is a steep gradient in the cluster emission to the northwest. Also, Figure 4 shows a large number of point and extended sources just to the northwest of the relic. We believe that these two features, blurred by the large Suzaku XIS PSF, are the reason that we did not detect this shock feature in the Suzaku XIS data.

We extracted spectra from regions through out the NW part of the cluster, and fit these spectra with both thermal and power-law models. The thermal fits indicate that the increase in X-ray surface brightness at the outer edge of the radio relic is accompanied by an increase in temperature, and both are consistent with the properties of a Mach number $M \approx 2$ shock. This is about the Mach number expected from hydrodynamical models of the merger (Roettiger et al. 1999; Ricker & Sarazin 2001).

The jump in the surface brightness can also be attributed to the non-thermal emission associated with the relic. This outer edge of the relic might still correspond to a merger shock, with the shock (re)accelerating the relativistic electrons in the relic which produce both the radio and hard X-ray emission. If the X-ray emission at the outer edge of the relic is non-thermal IC emission, then the magnetic field in this region is $B \approx 3\ \mu$G. If the emission is thermal, then the upper limit on the non-thermal X-ray emission leads to a lower limit on the magnetic field (§ 1.). Thus, we expect that the magnetic field in this region is $B \gtrsim 3\ \mu$G. Faraday rotation studies towards background radio sources have suggested similar fields in the radio relic (Johnston-Hollitt 2004). This is a remarkably strong magnetic field at a projected radius of about 2.2 Mpc out in a cluster. This would imply that a nontrivial portion ($\gtrsim$20%) of the pressure support in this relic is non-thermal. On the other hand, this doesn't mean that the outer regions of most clusters have such large values of the magnetic field and non-thermal pressure support. After all, Abell 3667 was selected for study because it is a clear and very violent merger, and has the brightest diffuse radio source observed in any cluster.

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