Search for Very Hot/Non-Thermal Emission and Gas Bulk Motions in Clusters

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ABSTRACT

The most energetic events in the Universe since the Big Bang are cluster mergers. Cluster collisions release a huge amount of energy, a fraction of which is expected to (i) heat the gas and generate non-thermal particles, and (ii) induce gas bulk motions. Suzaku’s high spectral capability enables us to study both phenomena. (i) We found that broad-band X-ray spectra from merging clusters (RX J1347.5–1145, A2163 etc.) can be reproduced by thermal emission including very hot (\( \sim 20 \) keV) component. On the other hand, non-thermal emission is not significant, yielding the upper limit tighter than previous reports. (ii) Based on a systematic analysis of iron-line emission spectra from nearby clusters with various X-ray morphologies, signatures of gas bulk motions are found in three clusters (Yoshida & Ota 2014). In this paper, we will review major findings regarding (i) and briefly discuss their implications.

KEY WORDS: galaxies: clusters – galaxies: intracluster medium – X-rays: galaxies: clusters – cosmology: observations

1. Introduction

Cluster merger is the most energetic event in the universe since the Big Bang, whose typical kinetic energy is \( \sim 10^{64} \) erg. Since clusters of galaxies have grown into the present shape by mergers and mass accretion from the surrounding, the merger activity dictates the cluster evolution. The huge amount of kinetic energy is released and its certain fraction is expected to heat the gas and generate high-energy particles. It is also predicted that large-scale gas motions and turbulence are generated inside the cluster potential and the amplitude of magnetic fields may also change. Our knowledge about these physical processes is, however, still not sufficient. Therefore, observational study of non-thermal phenomena is important to understand the evolution of clusters and the precise mass structure.

Non-thermal phenomena in clusters can be studied by observing X-ray emission spectra (see e.g., Rephaeli et al. 2008 for review). The soft X-ray band is dominated by thermal emission from hot intracluster gas, while in the hard X-ray band, non-thermal X-ray emission is expected to be produced via inverse Compton (IC) scattering of high-energy electrons off the CMB photons. In fact, in the radio band, extended synchrotron emission has been discovered in many merging clusters (Feretti et al. 2012), which assures the existence of accelerated particles in the intracluster space. Therefore the IC signals should be observed at a certain level in the hard X-ray band where the thermal emission diminishes. Moreover, the gas bulk motions can be directory measured by the Doppler shift of line emission, particularly the iron-K line emission. Both IC emission and line shift can be measured by using Suzaku’s high spectral capability.

2. Previous observations of very hot/non-thermal emission from clusters

One of the most extensively studied clusters in the light of non-thermal phenomena is the Coma cluster (\( z = 0.023 \)). The Coma cluster hosts bright radio halo extending over a Mpc scale. In the hard X-ray regime, there are reports on detections of strong non-thermal emission based on the RXTE and BeppoSAX observations (Rephaeli & Gruber 2002; Fusco-Femiano et al. 2004). On the other hand, Suzaku and Swift did not confirm any excess hard X-ray components and placed the upper limits on the IC flux. The reason for this mismatch is not clear. Fusco-Femiano (2011) suggested that this situation may be understood if one consider their different FOV sizes.

Another remarkable finding is the presence of the hottest gas in one of the most luminous cluster RX J1347.5–1145 (Ota et al. 2012). From the high-resolution Sunyaev-Zel’dovich data, the gas clump with temperature \( kT > 20 \) keV was found in the southeast region (Kitayama et al. 2004). We confirmed based on the Suzaku broad-band observations that the hard X-ray
emission from the cluster is dominated by thermal emission from the gas clump. The gas temperature is measured to be approximately 25 keV by the joint Suzaku and Chandra analysis, which is the hottest gas ever found in clusters and is twice higher than the ambient gas. The very hot gas is expected to be produced by a high-speed collision or the Mach number of 2 shock if the Rankine-Hugoniot condition is applied. This suggests that this systems is a Bullet cluster viewed from different angle. To see if this is a common phenomena in merging clusters, we need to increase the number of sample.

The merging clusters tend to host diffuse synchrotron emission, whose radio power is correlated with X-ray luminosity of thermal emission (Figure 1; Brunetti et al. 2009). On the other hand, relaxed clusters do not have significant radio emission. This dichotomy indicates that generation of high-energy particles is strongly related to the dynamical evolution of clusters. Suppose that X-ray luminous, massive clusters contain more high-energy particles and a certain magnetic field, such radio-loud clusters should produce non-thermal hard X-ray emission, too. Although this is a simplified working hypothesis, we attempted to search for non-thermal IC emission from merging clusters with the Suzaku satellite.

3. The sample
Our sample comprises six hot clusters at \( z = 0.2 - 0.45 \) that are bright enough to investigate hard X-ray emission and host extended radio halos, indicative of recent mergers. They are located at the brightest end of the Radio-X-ray correlation (Brunetti et al. 2009). Their basic properties (redshift, the mean gas temperature, and the bolometric X-ray luminosity; Ota & Mitsuda 2004) and the exposure time of the Suzaku HXD data are summarised in Table 1.

<table>
<thead>
<tr>
<th>Object</th>
<th>( z )</th>
<th>( kT ) [keV]</th>
<th>( L_{\text{bol}} ) [10^{44} \text{erg s}^{-1}]</th>
<th>Exposure [ks]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2163</td>
<td>0.20</td>
<td>13.5</td>
<td>6.8</td>
<td>154</td>
</tr>
<tr>
<td>RXJ1347</td>
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<td>12.9</td>
<td>11.3</td>
<td>122</td>
</tr>
<tr>
<td>Bullet</td>
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<td>13.3</td>
<td>6.5</td>
<td>80</td>
</tr>
<tr>
<td>A2219</td>
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<td>0.23</td>
<td>9.7</td>
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<td>79</td>
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<tr>
<td>A2744</td>
<td>0.30</td>
<td>9.0</td>
<td>3.5</td>
<td>193</td>
</tr>
</tbody>
</table>

4. Analysis and results
To accurately measure non-thermal hard X-ray emission, we need both careful assessment of background model and detailed modelling of thermal emission components since hard X-ray signals are generally weak. Firstly, based on a comparison between the non-X-ray background model and the data taken during the Earth occultation, the systematic error of the HXD non-X-ray background model to be 2%. This agrees with the typical value reported by the instrument team (SUZAKU-MEMO-2008-06). Secondly, to separate the non-thermal emission from the thermal emission, the accurate modelling of thermal components is needed. Therefore, in addition to simple single-temperature model, we considered the multi-temperature models because the temperature structure of merging clusters are complex. As observed in RX J1347.5–1145, there can be very hot gas that enhance hard X-ray emission and thus needs to be properly taken into account in searching for non-thermal emission. We then performed a joint analysis using Suzaku and XMM-Newton or Chandra data. This enables us to take advantage of both Suzaku’s broad-band spectral capability and XMM-Newton and Chandra’s high spatial resolution.

4.1. A2163
A2163 is the hottest Abell cluster having a powerful radio halo (Feretti et al. 2004) and complex temperature distribution (Bourdin et al. 2011; Markevitch & Vikhlinin 2001). At hard X-rays, detection of hard X-ray emission from A2163 has been reported based on the broad-band RXTE data with a long exposure time (Rephaeli et al. 2006). The non-thermal flux was measured to be \( F_{\text{NT}} = 1.1^{+1.7}_{-0.9} \times 10^{-11} \text{erg s}^{-1}\text{cm}^{-2} \), however, it was associated with large uncertainty. A2163 has been observed twice by Suzaku (Ota et al. 2014). The HXD spectra of two data sets were co-added to get the total exposure time of 150 ks. The...
counts s$^{-1}$ keV$^{-1}$. The detection is significant at the 28σ level (at the 5.5σ level if a systematic error of the non-X-ray background is considered.) The HXD spectrum alone is consistent with the single-temperature APEC model of gas temperature $kT \sim 14$ keV. Figure 2 shows the results of fitting the XMM and Suzaku broadband spectra to the single-temperature model. The 0.3–60 keV spectra were well fitted by a $kT \sim 14$ keV thermal model, indicating that the observed hard X-ray emission is likely dominated by hot thermal emission.

![Fig. 2. XMM-Newton and Suzaku/HXD spectra of A2163 in the 0.3–60 keV band fitted by the APEC model. The MOS1/MOS2/PN data are shown by the black/red/green crosses; the blue crosses denote HXD data. In the upper panel, the solid lines indicate the best-fit models for each instrument. In the lower panel, the residuals are expressed in number of standard deviations.](image)

To place a reliable limit on the IC flux, we constructed the multi-temperature model for the thermal emission by utilising the XMM data. To take into account the temperature distribution, we divided the cluster region into 25 grids (1 grid $= 2' \times 2'$) and the surrounding region within a circle of $r = 10'$ and performed the single-temperature APEC model fitting in each spectral region. The multi-temperature model was then calculated by adding contributions from all the spectral regions. In the temperature map, we confirmed the existence of high-temperature ($kT \sim 18$ keV) gas in the north-east region, whose emission contributes to 15% of the total X-ray luminosity.

The HXD spectrum is then fit by a model consisting of the best-fit XMM multi-temperature model and the power-law model (Figure 4). The photon index was fixed at that obtained from the radio observations, $\Gamma = 2.18$. The additional power-law model did not significantly improve the fit in comparison with the multi-temperature model, yielding the IC flux $F_{\text{NT}} = 5.3 \pm 0.9 (\pm 3.8) \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ (the first and second errors are the 1σ statistical and systematic errors). Thus the detection of non-thermal hard X-ray emission is marginal (1.3σ), giving the 90% upper limit $F_{\text{NT}} < 1.2 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$. The present results represent a three-fold increase in the accuracy of the broadband spectral model of A2163.

![Fig. 4. HXD spectra of A2163 in the 12–60 keV band (the crosses). The solid line indicates the best-fit multi-temperature and power-law model. The spectral components are shown as black dotted and blue dashed lines, respectively.](image)

4.2. Other clusters

To search for very hot/non-thermal emission from merging clusters, the same technique utilized in §4.1 was applied to the Bullet cluster, A2219, and A2390. Utilising Chandra and Suzaku data, we performed multi-temperature modelling analysis to investigate the origin of hard X-ray emission from the Bullet cluster carefully. The Suzaku data shows thermal components are dominant in the hard X-ray band and a stringent upper limit was derived for the IC emission ($F_{\text{NT}} < 2.4 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$; Nagayoshi et al. in preparation). This agrees with the recent NuSTAR result presented by
For A2219 and A2390, the observed HXD spectra are well fit by the thermal model constructed by the XMM-Newton data, while the non-thermal power-law component was only marginally detected, giving the upper limit on the order of $10^{-11}$ erg s$^{-1}$cm$^{-2}$. It is worth noting that we confirmed the presence of hot regions in these two clusters, too. The temperature of the hot region is by a factor of 1.5–2 higher than that of the ambient gas and the bolometric luminosity is approximately 15–30% of that of the entire cluster. For A2744, the hard X-ray emission is marginally detected with HXD and the 12–60 keV flux is estimated to be $< 9 \times 10^{-12}$ erg s$^{-1}$cm$^{-2}$.

5. Discussion

From the Suzaku or XMM/Chandra joint analysis, we found that the hard X-ray emission from the sample clusters is dominated by thermal emission and well represented by the multi-temperature model. The very hot gas is observed in all clusters and has non-negligible contribution to the hard X-ray spectra. The present results suggest that the accurate modelling of thermal component is dispensable in constraining the origin of hard X-ray emission. On the other hand, the non-thermal IC emission is not significantly detected.

We compare the Suzaku results with other clusters observed with RXTE, BeppoSAX, INTEGRAL, and Swift. Figure 5 shows the fluxes of 15 clusters as a function of gas temperature. As seen in the figure, different measurements yield different fluxes, although their error bars overlapped for most of the objects. The present IC-synchrotron measurements infer the lower limit of cluster magnetic field, $B > 0.1 – 1 \mu$G (see e.g., Ota 2012).

Since IC hard X-ray emission cannot be confirmed from these measurements, independent experiments with higher sensitivity are required. Hard X-ray Imaging by NuSTAR (Harrison et al. 2013) and ASTRO-H (Takahashi et al. 2012) will enable more accurate measurement of high-temperature thermal component which will dominate in the hard X-ray band. These instruments should identify the location of the merger shock, thereby improving the signal-to-noise ratio of the non-thermal emission.

References

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