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THE IMPACT OF SUZAKU MEASUREMENTS ON ASTROPARTICLE PHYSICS

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Abstract. Results from the *Suzaku* X-ray broad-band observations of clusters of galaxies are summarized. Aiming at understanding the physics of gas heating/particle acceleration and the cluster dynamical evolution, we search for non-thermal hard X-ray emission from merging clusters, particularly A2163 and the Bullet Cluster, based on the *Suzaku* and *XMM-Newton*/*Chandra* joint analyses. The observed hard X-ray emission is well represented by single- or multi-temperature thermal models, including super-hot ($kT \sim 20\,\mathrm{keV}$) gas. However, no significant non-thermal hard X-ray emission has been detected. Together with the presently available literature, the hard X-ray properties have been studied for about 10 clusters with *Suzaku*. The present status on *Suzaku* measurements of non-thermal X-ray emission and the cluster magnetic field are summarized and compared with those from the *RXTE*, *BeppoSAX*, and *Swift* satellites. The future prospects are briefly mentioned.

Keywords: clusters of galaxies, X-ray spectroscopy, astroparticle physics.

1. Introduction

According to the standard scenario of the structure formation in the Universe, clusters form via collisions and mergers of smaller groups and clusters. A cluster merger has a kinetic energy of the order of 10^{65} erg. This is the most energetic event in the Universe since the Big Bang. If two such objects collide with each other, a huge amount of energy may be released and a certain fraction is expected to heat the gas and accelerate particles through shock waves, and induce bulk and turbulent gas motions.

Signatures of cluster merging can be recognized in many ways. In the X-ray band, irregular morphology and complex temperature structure of the gas show that the system is disturbed due to past mergers. At radio wavelengths, synchrotron emission extending over a Mpc scale have been discovered from more than 30 clusters [12]. The existence of radio halo emission suggests that relativistic electrons are being accelerated in the intracluster space. Interestingly, there is a correlation between the non-thermal, radio synchrotron power ($P_{1.4}$) and thermal X-ray luminosity (L_X), for merging clusters, while relaxed clusters without a radio halo lie in a region well separated from the merging clusters on the $P_{1.4} - L_\mathrm{X}$ plane [4]. It is suggested that generation of high-energy particles is connected to the dynamical evolution of clusters [5]. From the observational point of view, however, a direct link between the radio synchrotron halo and the non-thermal hard X-ray property is yet to be clarified.

In X-rays, the same population of high-energy electrons is thought to interact with 3K CMB photons and then generate non-thermal Inverse-Compton (IC) emission. The IC emission in excess of the thermal emission is then predicted to be seen in the hard X-ray band (typically, above 10 keV) where the thermal emission diminishes. In addition, from radio observation alone, we cannot separate the energy of magnetic fields and the energy of high-energy electrons. However, by comparing the radio and hard X-ray fluxes, the cluster magnetic field is also estimated under the assumption that the same population of relativistic electrons scatters off of CMB photons [15]. Models for non-thermal bremsstrahlung emission caused by suprathermal electrons with energies of $10 \div 200\,\mathrm{keV}$ are presented in [31].

The existence of non-thermal IC hard X-ray emission has been reported in nearby clusters. The archetype is the Coma cluster: the non-thermal hard X-ray flux has been measured by *RXTE* [29] and by *BeppoSAX* [10]. Recent reports based on broad-band X-ray observations with *Suzaku* [35] and *Swift* [36] did not detect any significant non-thermal component and the hard X-ray flux is reproduced by thermal models. The mismatch among several satellites is suggested to be reconciled if different sizes of fields-of-view are taken into consideration [11].

Difficulty in firm detection of non-thermal hard X-ray emission from clusters seems to indicate that the IC emission is in fact very faint and/or that its spatial distribution makes it difficult to detect using the present instruments with limited imaging capability. Another issue is spectral modeling of the thermal emission component. At energies $> 10\,\mathrm{keV}$, the X-ray emission from hot clusters is still dominated by thermal bremsstrahlung emission [26, 35]. Thus detailed characterization of the thermal emission spectrum, including the multi-temperature components, is indispensable for separating the non-thermal emission from the thermal emission. As is discovered in RX J1347.5−1145 [26], the hard X-ray emission in the *Suzaku*/Hard X-ray Detector (HXD) band is originated predominately by the super-hot ($kT \sim 25$ keV) gas in the cluster. Such violent mergers often produce shock-heated gas with high ($\gg 10$ keV) temperature. This needs to be properly taken into account in the thermal modeling in order to study high-energy populations in the intracluster space.

2. Objectives

We search for non-thermal hard X-ray emission from merging clusters using *Suzaku* broad-band X-ray spectroscopy to reveal the origin of hard X-ray emission and obtain new insight into the gas physics and the cluster dynamical evolution. We also estimate the magnetic fields in clusters by comparing the hard X-ray and radio fluxes. Finally, we compare the *Suzaku* results with those from other satellites and summarize the present status of hard X-ray studies of clusters and briefly discuss the future prospects.

We adopt a cosmological model with $\Omega_{\mathrm{M}} = 0.27$, $\Omega_\Lambda = 0.73$, and the Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1} throughout the paper. Quoted errors indicate the 90 % confidence intervals, unless otherwise specified.

3. Sample and the *Suzaku* data

The 5th Japanese satellite, *Suzaku* [23], is equipped with X-ray CCD imaging spectrometers (XIS; [20]) and HXD [33] and enables sensitive broad-band X-ray observations thanks to the low and stable background levels. In particular, the PIN detectors of the HXD instrument are useful for the present study because they have achieved a lower background level than other missions in the $10 \div 60$ keV range [9]. In order to constrain the hard X-ray properties of merging clusters, we conducted *Suzaku* observations of several targets. We focus on X-ray bright sources with radio synchrotron halos, particularly A2163 at $z = 0.203$, and the Bullet Cluster at $z = 0.296$, since they are considered to have undergone a recent, violent merger. The *Suzaku*'s exposure times are 113 ksec and 41 ksec for A2163 south and north-east regions, and 80 ksec for the Bullet Cluster.

Figure 1 shows the *XMM-Newton* image of A2163 with overlaid the *Suzaku*/HXD field of views for the two pointing observations. A2163 is the brightest Abell cluster hosting one of the brightest radio halos [7, 13]. Previous X-ray observations showed the presence of a high temperature region in the north-east, which can be attributed to the merger shock [3, 21]. In the hard X-ray energies, [30] reported the detection of non-thermal IC emission with a flux level of $F_{\mathrm{NT}} = 1.1^{+1.7}_{-0.9} \times 10^{-11}$ erg s^{-1} cm^{-2} in the $20 \div 80$, keV band from the long *RXTE* observations, while [6] derived an upper limit of $F_{\mathrm{NT}} < 5.6 \times 10^{-12}$ erg s^{-1} cm^{-2} from the *BeppoSAX*/PDS observations. Thus the *Suzaku* observation will further provide independent measurements of hard X-ray properties of the sample.

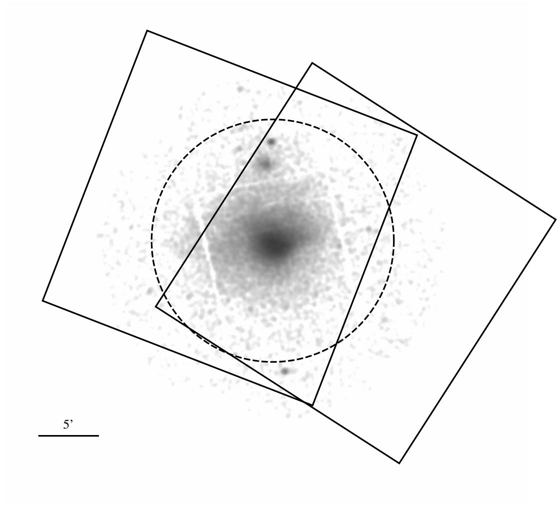

FIGURE 1. *XMM-Newton* image of A2163 (grayscale) with overlaid the *Suzaku* HXD field of views ($34' \times 34'$ in FWHM) for the two pointing observations (the solid boxes). The *XMM-Newton* integration region for the global spectrum is indicated with the dashed circle.

The Bullet Cluster exhibits extended radio halo emission [16] and a prominent strong shock feature [22]. The hottest gas with $kT > 20$ keV exists in the region of the radio halo enhancement. Possible detection of non-thermal hard X-ray emission has been reported; the non-thermal flux in the $20 \div 100$ keV band is $(0.5 \pm 0.2) \times 10^{-11}$ erg s^{-1} cm^{-2} by *RXTE* [28] and $3.4^{+1.1}_{-1.0} \times 10^{-12}$ erg s^{-1} cm^{-2} by *Swift* [2]. Thus it is worth examining the existence of IC emission with a detailed *Suzaku* analysis.

4. Analysis strategy

To accurately measure the non-thermal X-ray emission from clusters at hard X-ray energies (> 10 keV), we need:

(1.) a careful assessment of the background components,

(2.) detailed modeling of the thermal emission.

For 1., the *Suzaku* HXD background consists of the Cosmic X-ray Background and the instrumental Non-X-ray Background (NXB), and is dominated by the latter. We estimate the systematic error of NXB to be 2 % by analyzing the HXD data during the Earth-occultation and quote the 2 % systematic error (1σ) in the spectral analysis of A2163 and the Bullet Cluster. This is consistent with SUZAKU-MEMO 2008-03 by the instrument team[1].

For 2., since the merging clusters can have a complex, multi-temperature structure, including a very hot thermal gas that emits hard X-rays, we apply single-, two-, and multi-temperature thermal models

[1] `http://www.astro.isas.jaxa.jp/suzaku/doc/suzakumemo/suzakumemo-2008-03.pdf`

to the *Suzaku* spectra. As detailed later, the multi-temperature model is constructed based on the analysis of *XMM-Newton* or *Chandra* data. The *Suzaku* and *XMM-Newton*/*Chandra* joint analysis allows us to take advantage of *Suzaku*'s spectral sensitivity in the wide X-ray band and the *XMM-Newton*/*Chandra*'s high spatial resolution, as demonstrated by [26].

5. Results

5.1. A2163

With *Suzaku*/HXD, we detected X-ray emission from the cluster up to 50 keV. With the CXB and NXB components subtracted, the $12 \div 60$ keV source flux is measured to be $1.52 \pm 0.06\,(\pm 0.28) \times 10^{-11}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$. Here the first and second errors indicate the 1-σ statistical and systematic uncertainties. The 1-σ systematic error of the flux is estimated by changing the normalization of the NXB model by $\pm 2\,\%$. Thus the detection of hard X-ray emission is significant at the $> 5\sigma$ level even if the systematic error of NXB is considered.

Next we performed the joint *XMM*+*Suzaku*/HXD spectral analyses under i) the single-temperature model, ii) the two-temperature model, and iii) the multi-temperature (multi-T) model. For i) and ii), the *XMM-Newton* PN and MOS spectra were accumulated from the $r = 10'$ circular region, as shown in Fig. 1.

For i), the *XMM*+*Suzaku* broad-band spectra in the $0.3 \div 60$ keV band can be fitted by the APEC thermal emission model: the resultant gas temperature and the metal abundance are $kT = 13.5 \pm 0.5$ keV and $Z = 0.29 \pm 0.10$ solar, respectively, and χ^2/d.o.f. is 1249/1180. Thus the hard X-ray emission is likely to be dominated by the thermal emission. For ii), we have not found any significant improvement of the fits in comparison to case i). However, there is obviously a complex temperature structure as shown by the previous X-ray observations, and we attempted to construct the multi-T model for the thermal emission below.

iii) The $10'$ spectral region of the *XMM* data is divided into $2' \times 2'$ grids and the single-component APEC model is assumed for each grid. Figure 2 shows the total model of multi-T components (namely the sum of the single APEC models for the grids) fit to the *Suzaku*/HXD data. We find that this multi-T model gives an acceptable fit to the HXD spectrum. Note that the model includes a $kT \sim 18$ keV APEC component for the north-east "shock" region, which is in agreement with the previous *XMM* result [3]. The X-ray luminosity of this hot component is $5 \times 10^{44}\,\mathrm{erg\,s^{-1}}$, which contributes to the hard X-ray emission by about 15 %.

In the case of iii), the additional power-law component for non-thermal IC emission does not significantly improve the fit to the observed HXD spectrum. Assuming the multi-T+ power-law model with $\Gamma = 2.18$ (i.e., the same index in radio [7]), the

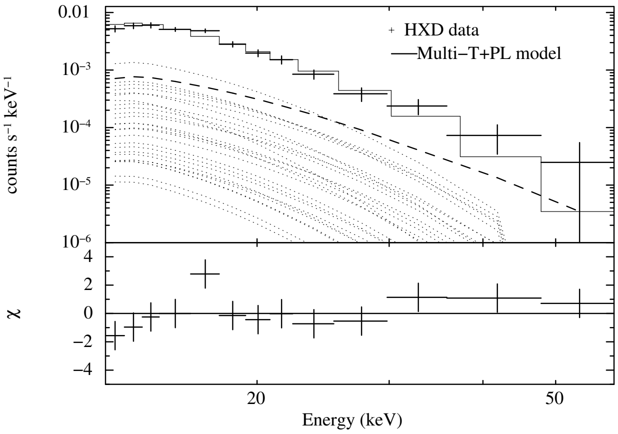

Figure 2. Upper panel: the *Suzaku*/HXD spectrum of A2163 (the crosses) fitted with the multi-T + power--law model (the solid step function). The contribution from the spectral components, i.e., multiple temperature components (the dotted lines) and the non-thermal power-law model (the dotted lines) are indicated in the figure. Bottom panel: the residual of the fitting is shown with the crosses.

90 % upper limit on the non-thermal emission is derived as $9.4 \times 10^{-12}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$. This gives 3-times stronger constraints than the upper limit obtained from *RXTE* [30], though the present result is consistent with *RXTE* and *BeppoSAX* [6] within their errors.

More details of data reduction and discussions are to be described in a forthcoming paper (N. Ota et al. in preparation).

5.2. The Bullet Cluster

Following similar methods mentioned in § 5.1, we analyzed the *Suzaku* and *Chandra* data of the Bullet Cluster. Our preliminary analysis showed that the global cluster spectrum taken with *Suzaku* is well represented by a two-component thermal model. However, the non-thermal emission is not significantly detected, yielding the 90 % upper limit on a $\Gamma = 1.5$ power-law component to be $\sim 10^{-11}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ ($20 \div 100$ keV). Note that the derived upper limit depends on the assumed photon index.

The observed broad-band *Suzaku* spectrum in the $1 \div 50$ keV band can also be fitted by the multi-T model. Here the multi-T model is constructed by analyzing the deep *Chandra* observations. We did not confirm the previous IC detections with *RXTE* and *Swift*, and the present results support the thermal origin of the hard X-ray emission. Under the multi-T model, the flux of the hot ($kT > 13$ keV) thermal component is estimated to be $F_{\mathrm{hot}} \sim 2 \times 10^{-12}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ and comparable to the non-thermal flux reported by [2], while the IC flux is suggested to be even lower than F_{hot}. More details of the analysis, including an assessment of systematic uncertainty due to the *Suzaku*–*Chandra* cross-calibration, will be presented in Nagayoshi et al. in preparation.

6. Discussion

6.1. Non-thermal hard X-ray emission

For the two hot clusters, A2163 and Bullet, the hard X-ray spectra taken with *Suzaku* are likely to be dominated by thermal emission, giving stronger limits on the non-thermal IC emission. We also note that a super-hot (~ 20 keV) gas exists in both clusters whose contribution is not negligible in the hard X-ray band. Thus this component should be properly modeled in order to accurately measure the non-thermal component. Furthermore, this hot gas is over-pressured and thus thought to be short-lived, ~ 0.5 Gyr [26]. Therefore the existence of super-hot gas supports the scenario of a recent merger.

Given the link between the radio flux and X-ray luminosity (see § 1), the generation of high-energy particles in intracluster space is likely to be connected with the merging events. Thus, *is there any relationship between L_X and IC flux (F_{NT}) or between the gas temperature (kT) and F_{NT}?*

With *Suzaku*, non-thermal hard X-ray emission has been constrained in about ten clusters. In Fig. 3, F_{NT} is plotted as a function of kT. The *Suzaku* results for nearby clusters as well as RX J1347.5−1145 were taken from the literature [8, 17–19, 25, 26, 32, 35]. The *RXTE*/*BeppoSAX*/*Swift* results [1, 2, 15, 36] are also quoted for comparison. Note that the non-thermal flux depends on the modeling of the thermal component as well as the assumption of the photon index for the non-thermal component. For *Suzaku*, non-thermal emission has not been detected and the upper limit was derived for the nearby objects including the Coma cluster, A2319 etc. Hence there is no clear relation on the F_{NT}–T plane.

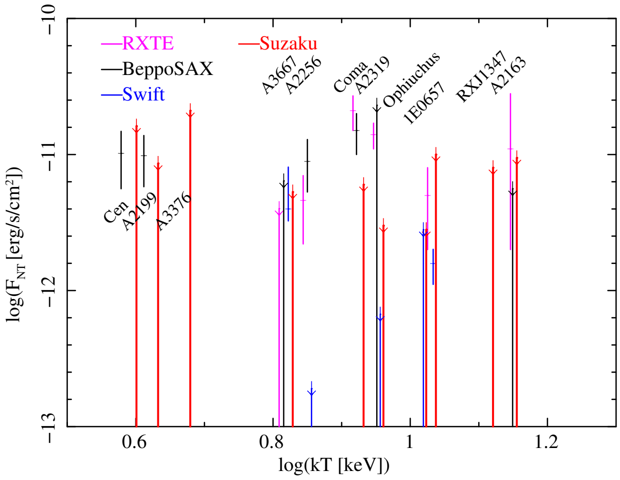

Figure 3. Non-thermal IC hard X-ray flux in ten clusters measured by *Suzaku*. The results from *RXTE*, *BeppoSAX*, and *Swift* are also shown for comparison. See § 6 for references.

6.2. Cluster magnetic field

Using the observed radio flux, S_{syn}, and the relation $S_{IC}/S_{syn} = U_{CMB}/U_B$ [15, 27], we can infer the strength of the cluster magnetic field. In the case of A2163, adopting the radio flux $S_{syn} = 155$ mJy at 1.4 GHz [7] and the IC upper limit of $S_{IC} < 0.26$ µJy at 12 keV from the this work, we obtain $B > 0.09$ µG for the multi-T + power-law ($\Gamma = 2.18$) model. For the Bullet Cluster, the magnetic field is estimated to be $B > 0.06$ µG under the two-temperature APEC + power-law ($\Gamma = 1.5$) model. Thus a lower limit of the order of $\sim 0.1 \div 1$µG has been obtained in most of the clusters observed with *Suzaku*.

7. Summary

Suzaku broad-band X-ray observations of hot clusters hosting a bright radio synchrotron halo, A2163 and the Bullet cluster, were performed in order to search for the non-thermal hard X-ray component and reveal the origin of the high-energy emission and the cluster dynamical evolution. The *Suzaku*/HXD spectra for these two clusters are well represented by single- or two-temperature thermal models. Since the merging clusters can often have shock-heated, super-hot ($kT \sim 20$ keV) gas, and its contribution is not negligible in the interpretation of the hard X-ray origin, it is essential to determine the thermal component with high accuracy. This motivated us to carry out the joint *Suzaku*+*XMM-Newton*/*Chandra* spectral analysis under the multi-T model. As a result, the observed *Suzaku* spectra are consistent with the multi-T models and we did not find any significant non-thermal IC emission from A2163 and the Bullet cluster.

The properties of hard X-rays and the cluster magnetic fields have been studied for about ten clusters so far. There is no significant detection of IC emission by *Suzaku*, giving the upper limits on the level of $\sim 10^{-11}$ erg s^{-1} cm^{-2}. Thus no clear relationship between the non-thermal X-ray and radio properties or the IC luminosity (L_{IC})–T is seen. To further constrain the physics of gas heating and particle acceleration in clusters, it is important to increase the number of cluster samples by applying the present analysis method to other clusters.

Given that the relativistic particles are localized in small, shock regions, present instruments with limited imaging capability may fail to identify their existence. If this is the case, the advent of hard X-ray imagers will benefit the cluster study. Now *NuSTAR* [14] is successfully in orbit and taking focused images of the high-energy X-ray sky. The *ASTRO-H* satellite is scheduled to be launched in 2014 [34], and will carry state-of-the-art instruments to realize sensitive X-ray observations in the $0.3 \div 600$ keV band. The Hard X-ray Imagers on *ASTRO-H* will have an effective area comparable to *NuSTAR*. These new hard X-ray imagers will enable a more accurate high-temperature thermal component and identification of the particle acceleration site to get higher signal-to-noise ratios. This will lead us to detect the IC emission to a level ~ 2 orders of magnitudes lower than the present limit. In addition, the high-spectral resolution of X-ray micro-calorimeters will enable direct measurements of bulk/turbulent gas motions [24]. *ASTRO-H* can therefore measure non-thermal energies in the form of kinetic gas motions (turbulence, bulk gas motion) and relativistic particles, leading us to draw a more comprehensive picture of the cluster structure and evolution.

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