The Extreme Universe in the Suzaku Era

Hard X-ray Observation of Abell 3376 with Suzaku

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Abstract

Clusters of galaxies are expected to host non-thermal hard X-ray source from accelerated relativistic electrons. We performed two pointing observations of one of the most promising clusters, Abell 3376 with Suzaku. From west radio relic region, we find a symptom of excess hard X-ray emission and determine an upper limit of $<1.4 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ (15–50 keV), with the HXD spectrum. The upper limit is a bit tighter than that obtained from BeppoSAX PDS (Nevalainen et al. 2004), within much restricted sky region of $34^\circ \times 34^\circ$. The XIS spectrum also allow us to derive an upper limit of $<1.3 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ (4–8 keV) within the sky region of $R = 7''$ circle. By means of upper limits measured with the HXD and the XIS, we discuss the distribution of possible excess X-ray emission and magnetic field of intracluster medium.

1. Introduction

Clusters of galaxies are expected to be high energy particle source in the universe for a long time. Such particles would be generated via merging, galaxy motion, and so on. In fact, Mpc-scale diffuse synchrotron radio emission, due to the interaction between relativistic electrons and the magnetic field of intracluster medium (ICM), have been observed in many clusters of galaxies (e.g. Giovannini et al., 1993). This supports that the particles are surely accelerated up to relativistic speed in galaxy clusters. The same electrons is considered to scatter off the cosmic microwave background (CMB) photons via inverse Compton process, generating the non-thermal emission in a few tens keV. The theoretical calculation also predict the existence of non-thermal X-ray emission (e.g. Inoue et al. 2005).

X-ray observation of non-thermal emission from galaxy clusters already have performed with BeppoSAX PDS detector. For example, seven clusters are reported as the most possible targets for non-thermal emission survey. Suzaku observed Abell 3376 twice on October and November, 2005. The first observation focuses on the cluster center containing the East Relic (ER) while the second one covers peripheral area centered on the West Relic (WR). The total exposure of the HXD is $\sim$90 ks and $\sim$103 ks, for Center/ER and WR region, respectively. Data for about one day is lost in the second observation by malfunction of telemetry receiver. Thanks to their long exposure, nevertheless, we can suppress the statistical fluctuation to sufficiently small level. We used the version 0.7 processing data. All the analysis was performed with HEASOFT 6.0.2 and XSPEC 11.2.0. The response matrix published

2. Suzaku Observation of Abell 3376

Abell 3376 is nearby ($z = 0.046$) on-going merging galaxy cluster. The ICM is known to have elongated X-ray morphology by merger event and moderate temperature of $\sim$4 keV from ASCA and XMM-Newton observations (Fukazawa et al. 2004; Bagchi et al. 2006). The moderate temperature of Abell 3376 is important to detect non-thermal emission with the HXD PIN detector because the thermal emission become negligible in a few tens keV range where the PIN sensitivity is the highest. BeppoSAX have detected a sign of non-thermal hard X-ray ($2.7 \sigma$) from Abell 3376 (Nevalainen et al. 2004). Moreover, two large radio relics expand over Mpc scale on the east and west end of thermal emission (Bagchi et al. 2006).

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on 20060419 and 20060213 are utilized for the HXD and the XIS spectral analysis, respectively.

3. HXD spectral analysis

For detecting faint non-thermal emission, the most important procedure is to reduce the systematic fluctuation in the NXB estimation. We here utilized the NXB model estimated by our own (for detail, see Kawano et al. in preparing), which is slightly different from the archived background model. Our model is based on the NXB maps sorted by longitude and latitude because NXB rate strongly depends on the variation of cut-off rigidity (COR) on the earth. The NXB map varies according to the energy band, and if Suzaku moves upward or downward (i.e. Suzaku passes South Atlantic Anomaly or not). Then, we divided NXB map into 16 maps (8 energy band for upward and downward, respectively). Figure 1 left is examples of NXB map in 15–20 keV. The night earth data of »2 Msec (from September 2005 to March 2006) are used for NXB map database. In the final NXB model for each observation, long-term variation is also considered by fitting a year-long light curve. As shown in figure 1 right, the estimated NXB is consistent with the real night earth data within 3.5 % (1 σ), for 100 samples which have the exposure longer than 3000 sec. Then, we define the systematic fluctuation of our background model as 3.5 %.

Figure 2 shows the background subtracted spectra of the HXD PIN. The contribution of thermal ICM, cosmic X-ray background (CXB), and point sources are plotted together. The ICM component modeled by fitting XIS spectra (§4.1). For CXB, we used powerlaw spectrum obtained from HEAO-1 observation (Boldt 1987). The flux of CXB is scaled to 7.9×10^{-12} erg s^{-1} cm^{-2} in 15–50 keV, by means of the HXD field of view. ROSAT 2RXP catalogue is utilized to model the contribution from contaminating point sources. This catalogue allows us to search point sources over the whole HXD’s field of view although it covers only lower energy (0.2–2.35 keV). We here assume a powerlaw spectrum with the photon index of 1.5. The contribution of point sources for each pointing of Abell 3376 thus estimated is quit small, »7×10^{-13} erg s^{-1} cm^{-2} in 15–50 keV. We found a weak signature of the hard X-ray excess in the Abell 3376 WR data. In order to examine whether the excess is realistic, we estimated the systematic fluctuation of each spectral component. The resulting hard X-ray flux become (6.3 ± 1.8 ± 6.2)×10^{-12} erg s^{-1} cm^{-2} (15–50 keV) when powerlaw spectrum with the photon index of 1.8 is assumed. The former and latter errors show the statistical and systematic fluctuation. Of the systematic fluctuation, NXB is predictably most dominant (»85 %) while CXB and point sources are almost negligible (»1 %). The non-thermal emission is not detected because of the large fluctuation. However, we could constrain its upper limit of < 1.4×10^{-11} erg s^{-1} cm^{-2}, which is tighter by 20 % than that observed with BeppoSAX (Nevalainen et al. 2004).

4. XIS analysis

4.1. Spectrum fitting

The XIS spectrum in high energy band is functional for searching non-thermal emission in clusters of galaxies since the XIS achieves the lowest NXB among the existing CCD detectors. Here, we present the results from XIS spectral analysis only for WR region, where the detection possibility of non-thermal X-ray is higher in the HXD spectrum (§3). We estimated the XIS NXB by means of background generator xisntebgdgen, in which the NXB data is created along the COR history in each observation. The reproducibility of the XIS NXB seems to be different among four sensors (XIS0–3), and it distributes...
5–10%. We fitted the NXB subtracted spectra (within central 7') with the five component model; the ICM, the CXB, point sources, Galactic emission, and possible non-thermal hard X-ray. The CXB, point sources, and possible non-thermal component are described by powerlaw as shown §3. Galactic component is modeled by APEC with 1 solar abundance. For thermal emission of the ICM, we use thin plasma model, MEKAL. Furthermore, 20% systematic error is included for each spectrum in order to consider uncertainty of responses. All the spectra of four sensor are fitted simultaneously and fitting parameters are linked among four spectra. Figure 3 shows the NXB subtracted spectrum of the XIS0 from Abell 3376 WR region. The best fit parameter is shown in table 1.

The ICM temperature seems to be somewhat higher than that of the central region, which is measured to be about 4.6 keV (this observation). The metal abundance is consistent with the ASCA result of 0.24 solar (Fukazawa et al. 2004) within the error. Following the approach of the HXD, the non-thermal flux containing the systematic fluctuation of each component is derived as \((9.2 \pm 0.4 \pm 3.9) \times 10^{-13} \text{erg s}^{-1} \text{cm}^{-2}\) in 4–8 keV. Here, the contribution against systematic error is 35%, 51%, 8%, 6%, and <1% for the NXB, the ICM, the CXB, point sources, and Galactic component, respectively. The detection significance is not high enough, and we just get an upper limit again; \(<1.3 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2}\).

4.2. X-ray distribution

Since we could get an upper limit of possible non-thermal emission from the XIS spectra, we next investigate its distribution to confirm if the emission is associated with the synchrotron radio of WR. The background subtracted XIS image in 4–8 keV is shown in figure 4 left. The 1.4 GHz radio contour is superposed on together. As the background data (NXB and CXB), we used second Lockman Hole observation. As reported by Bagchi et al. (2006), the elongated thermal emission by merger event can be seen even in 4–8 keV band. Moreover, there is no correlation with radio emission of WR. In order to compare the emission distribution among different energy bands, we investigate the count rate distribution around WR as shown in figure 4 right. This is extracted from the white square region of figure 4 left. The count rate is arbitrarily normalized so as to distinguish the difference among profile easily. The position of two point sources (magenta circle in 4 left) correspond to ~1750 and ~1970

<table>
<thead>
<tr>
<th>spectral component</th>
<th>parameter</th>
<th>value</th>
</tr>
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<tbody>
<tr>
<td>Galactic</td>
<td>(kT)</td>
<td>0.243±0.011</td>
</tr>
<tr>
<td>ICM thermal</td>
<td>(kT)</td>
<td>4.57±0.30</td>
</tr>
<tr>
<td></td>
<td>(A_{Fe}^i)</td>
<td>0.30±0.07</td>
</tr>
<tr>
<td></td>
<td>(N_{H}^i)</td>
<td>3.43±0.68</td>
</tr>
<tr>
<td></td>
<td>flux(^i)</td>
<td>5.6\times10^{-13}</td>
</tr>
<tr>
<td>non-thermal</td>
<td>flux(^i)</td>
<td>&lt;1.4\times10^{-11}</td>
</tr>
</tbody>
</table>

\(^s\): The plasma temperature in the unit of keV.
\(\dagger\): The metal abundance in the unit of solar.
\(\ddagger\): The absorption column density in the unit of \(10^{20} \text{cm}^{-2}\).
\(\ddagger\): The X-ray flux in 4–8 keV band in the unit of \(\text{erg s}^{-1} \text{cm}^{-2}\).
pixel on the profiles, and the count rate seems to be enhanced around these points. The X-ray distributions are very similar among all the energy bands. Thus, the profile in 4–8 keV band is considered to reflect the thermal photon distribution. These results suggest that the excess hard X-ray does not coincide with the WR radio, and has no spatially characteristic deflection.

5. Discussion

Suzaku has observed Abell 3376 twice successfully in order to search the non-thermal hard X-ray emission from clusters of galaxies. With the use of independently estimated NXB, an excess hard X-ray emission is found in Abell 3376 WR region. Although the large systematic fluctuation does not allows us to detect the non-thermal X-ray emission, we could give the excess emission upper limits from the HXD and XIS spectrum analysis; \(<1.4 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} (15–50 \text{ keV})\), and \(<1.3 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2} (4–8 \text{ keV})\), respectively. X-ray profile in 4–8 keV indicates that the excess emission is not associated with the radio synchrotron from WR.

The XIS upper limit of possible non-thermal emission is obtained from the area whose major part is occupied by WR radio emission. However, it is hard to distinguish if it associated with the WR. Then, we firstly discuss the distribution of possible non-thermal emission, combining the HXD upper limit. Assuming the photon index of 1.8, the XIS limit is converted to \(<3.2 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}\) in the 15–50 keV band. If there is non-thermal emission as strong as the HXD upper limit, the XIS upper limit above is much smaller. Such situation could be defused by assuming uniform distribution of X-ray. In this case, taking account of the difference of spectral integration area, the XIS limit is enhanced up to \(<2.4 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}\) (15–50 keV). This approximately suits with the HXD upper limit. Considering that there is no sign of excess X-ray emission in Center/ER region, we can tentatively conclude that the possible non-thermal emission, roughly as strong as that observed with BeppoSAX, expands over the area comparable to the HXD field of view rather uniformly.

We next calculate magnetic filed separately for the HXD and the XIS since their systematic fluctuation are not same origin. The synchrotron luminosity in Abell 3376 WR is reported to be \(L_{\text{sync}} = 9.84 \times 10^{40} \text{ erg s}^{-1}\) (10 MHz–100 GHz) from VLA 1.4 GHz observation by Bagchi (2002). The energy density of CMB is \(U_{\text{CMB}} = 4.2 \times 10^{-13} (1+z)^4 = 5.0 \times 10^{-13} \text{ erg cm}^{-3}\). Meanwhile, X-ray luminosity of excess hard X-ray are derived from the obtained upper limits as \(L_{\text{HXR}} < 1.3 \times 10^{44} \text{ erg s}^{-1}\) for the HXD (15–50 keV), and \(L_{\text{HXR}} < 2.3 \times 10^{43} \text{ erg s}^{-1}\) for the XIS (2–10 keV). The photon index is assumed to 1.8 again. By means of a relation \(L_{\text{HXR}}/L_{\text{sync}} = U_{\text{CMB}}/U_{B}\) (where \(U_{B} = \frac{1}{2} B^2\)), the magnetic field is estimated to be \(>0.1 \mu G\) (HXD) and \(>0.5 \mu G\) (XIS), which are roughly consistent when the equipartition is assumed \((\sim 0.4 \mu G)\). It will get close to the typical magnetic field of ICM (a few \(\mu G\)) according to the NXB improvement.

The improvement of NXB estimation accuracy is still key to detect non-thermal emission. In addition, multi-wavelength observations together with the high energy detectors in MeV–TeV must play an important roll to resolve non-thermal view of clusters of galaxies.

References

Boldt, E., IAU Symp. 124, 611, 1987