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Swift BAT search for non-thermal emission in HIFLUGCS clusters

D. Wik

NASA Goddard Space Flight Center, Astrophysics Science Division, Code 662, Greenbelt, MD 20771, USA, e-mail: daniel.r.wik@nasa.gov

Abstract. Detections of diffuse inverse Compton (IC) emission at hard X-ray energies have typically been controversial and/or of low significance. Consistency of the existing limits and detections may be possible only for very extended IC spatial distributions. To test this idea, we apply a method to characterize extended, hard X-ray emission from the *Swift* BAT survey. Spatially coincident spectra from *XMM-Newton* and *Swift* are jointly fit to simultaneously constrain both thermal and non-thermal components, but no significant IC spectral component is seen in any of the clusters in the sample. For the Coma cluster, our upper limits exclude the most recently detected fluxes, regardless of the IC spatial distribution. Spectra from all clusters are summed, to enhance marginal IC emission possibly present in many clusters, but no aggregate non-thermal excess is found, although a hint of an excess is seen in the radio halo/relic subset.

Key words. Galaxies: clusters: general – Intergalactic medium – Magnetic fields – Radiation mechanisms: non-thermal – X-rays: galaxies: clusters

1. Introduction

While a non-thermal phase is known to exist in the intracluster medium (ICM) of galaxy clusters, as evidenced by Mpc-scale structures called radio halos and relics, its detailed state is poorly constrained. The relativistic electron population emitting synchrotron radiation in these halos and relics requires a magnetic field, but its strength, B, cannot be determined from radio observations – of the synchrotron emission at least – alone, because the radio flux depends on both B and the number density of relativistic electrons. A promising way to break this degeneracy is by independently observing the electron population via inverse Compton (IC) emission produced by their interactions with cosmic microwave background photons (Rephaeli 1979). This IC emission is primarily present at X-ray energies and should dominate the spectrum of galaxy clusters below ($\lesssim 0.5$ keV) and above ($\gtrsim 10$ keV) the energies where thermal bremsstrahlung primarily emits. Co-spatial flux measurements of radio synchrotron and IC emission therefore allow the volume-averaged value of B, and thus the energy content in magnetic fields, to be determined. While the energy, and similarly the pressure, in B fields should not be large relative to the thermal gas in galaxy cluster interiors, the same may not be true in cluster outskirts (Finoguenov et al. 2010).

At hard X-ray energies (> 10 keV), the exponential decline in the thermal spectrum and the lack of Galactic and solar wind

Send offprint requests to: D. Wik

charge exchange foregrounds provides a relatively straightforward means for detecting a non-thermal, IC spectral component. Various searches completed at these energies have found marginal or controversial evidence for such non-thermal excesses, perhaps most notably in the Coma cluster where $\sim 4\sigma$ detections (Rephaeli & Gruber 2002; Fusco-Femiano et al. 2004) have been difficult to reproduce (Rossetti & Molendi 2004; Eckert et al. 2007; Wik et al. 2009, 2011). Also, stacking the hard energy spectra from many clusters (e.g., Nevalainen et al. 2004) can increase the significance of individually marginal IC detections, yielding a more clear, if average, IC flux. In these proceedings, we present a search for IC excesses in the *Swift* BAT spectra of a flux-limited sample of galaxy clusters, using lower energy spectra from *XMM-Newton* to accurately determine the thermal component present in the BAT energy bands.

2. Data and methodology

The *Swift* BAT all sky survey (Tueller et al. 2010) provides a deep map of hard energy (14–195 keV) emission; its uniform coverage and impressive sensitivity makes it the most complete dataset from which to study the brightest objects in a given class. To take full advantage of this capability, we have chosen the flux-limited HIFLUGCS sample (Reiprich & Böhringer 2002), which contains the brightest clusters in the sky outside the Galactic plane. A selection of the brightest clusters provides the greatest opportunity to detect IC emission, given that the IC signal could reasonably be thought to be similarly bright and that good quality, lower energy X-ray data, critical for assessing the thermal contribution at high energies, is more likely to exist. Also, the fact that HIFLUGCS is a complete flux-limited survey allows one to discuss the statistical properties of hard excesses through an analysis of the stacked spectrum.

Previous analyses of *Swift* BAT observations of galaxy clusters (Ajello et al. 2009, 2010) have focussed on only those detected by the BAT and were limited to the central regions of those clusters; in all of these cases,

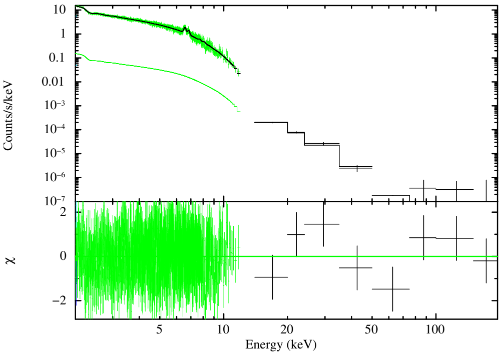

Fig. 1. Single temperature (APEC) fit to the *XMM-Newton* EPIC-pn (E < 12 keV) and *Swift* BAT (E > 12 keV) spectra. This single temperature model (kT = 8.24 keV) is sufficient to describe the 2–200 keV emission from the central 30 arcmin^2 of the Coma cluster.

the BAT signal is consistent with having a thermal origin. Here, we apply the method developed by Renaud et al. (2006) to extract the total extended flux detected by the BAT, which is then combined with spatially coincident *XMM-Newton* EPIC data (Zhang et al. 2006, 2009) to produce wide band spectra that are simultaneously fit to thermal and non-thermal models. The calibration of BAT fluxes are carefully matched to the EPIC calibration, in both normalization and spectral shape, via fits to the Crab. The resulting single temperature fit to the joint spectrum of the Coma cluster is shown in Fig. 1. Only EPIC data with energies above 2 or 3 keV are considered in order to isolate the highest temperature components, which produce proportionately more emission at hard energies, and thus not mistake the spectrum of a multi-temperature ICM as due to an IC excess. The full data analysis procedure is detailed in Wik et al. (2011).

3. Results

The spectra in Fig. 1, extracted from a 1 degree square region, are well fit by an APEC thermal model with $kT = 8.24 \pm 0.19$ keV, in good agreement with previous global measurements. The addition of a non-thermal spectral component to account for excess emission at hard

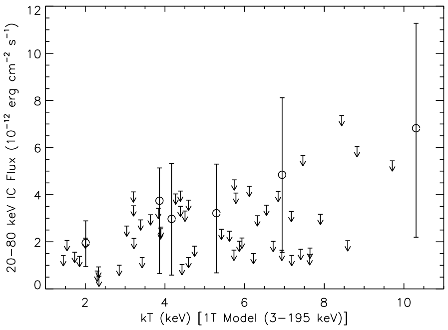

Fig. 2. Upper limits and measurements of the non-thermal spectral component in the 3–195 keV joint fits as a function of cluster temperature. Limits and error bars indicate the 90% confidence interval without considering the impact of systematic uncertainties. In general, an excess attributable to IC emission is not observed, and the few detections have marginal statistical significance.

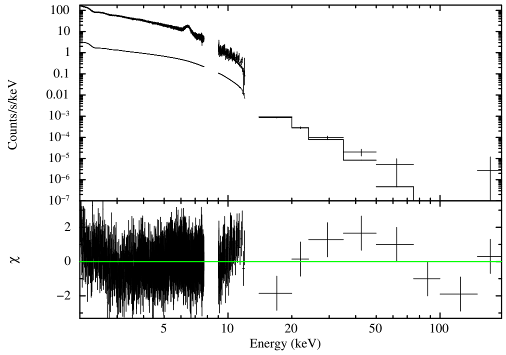

Fig. 3. The stacked spectrum of all 58 clusters with the combined single temperature model fit. The CXB contribution appears below the EPIC-pn data. The problems between 2–3 keV (described in the text) clearly show up in the residuals. The combined single temperature model determined from the 2–12 keV fits is sufficient to explain the summed BAT spectrum; no non-thermal excess is obvious.

energies, as detected with *RXTE* (Rephaeli & Gruber 2002) and *Beppo-SAX* (Fusco-Femiano et al. 2004), appears unwarranted and supports the analysis of a *Suzaku* HXD-PIN observation that finds an IC upper limit below that expected from those detections (Wik et al. 2009). However, the smaller FOV of the HXD-PIN detector relative to that of the other observatories' detectors allows the possibility that the IC emission originates from a large, diffuse source extending beyond the HXD's FOV. The *Swift* BAT survey, on the other hand, has no such limitation and should be able to detect such degree-scale non-thermal emission if it is present. In Wik et al. (2011), upper limits for a suite of extended IC spatial distributions are computed, all of which are inconsistent with the previous detections and imply $B > 0.2\mu$G.

The strong upper limits to non-thermal emission in Coma, comparable to the *Suzaku* upper limit of 6×10^{-12} ergs cm^{-2} s^{-1} (20–80 keV), imply an unprecedentedly sensitive search for a sample as large as HIFLUGCS. Unfortunately, due to incomplete coverage and flared-out *XMM-Newton* data, 5 clusters had to be excluded from this analysis. The remaining 58 clusters' EPIC pn and MOS spectra, extracted from circular regions in single-pointing observations, are jointly fit with similarly extracted BAT spectra to single temperature (1T), 2T, and 1T plus non-thermal (T+IC) models. These fits are performed over both the 2–195 keV and 3–195 keV ranges; including 2–3 keV data during T+IC fits turned out to be problematic, as the non-thermal power law component often tended to account for an incompletely characterized gold edge at 2.2 keV or additional, low temperature gas emitting mainly at the lowest energies and imperfectly fit by the APEC component. The 90% upper limits/fluxes, without including systematic effects, for the sample clusters are presented in Fig. 2 as a function of their 1T best-fit temperature. The 6 clusters with non-thermal indications are A1367, A1651, A2142, A2589, A3112, and Fornax, but in none of these cases does an IC interpretation stand up to the effects of systematic uncertainties and/or a reasonable 2T description of the spectra.

While no clear IC signal is apparent in individual cluster spectra, a low level excess present in many of these clusters may be enhanced to a statistically significant level by summing or stacking the spectra. The stacked spectrum of all 58 clusters is shown in Fig. 3, along with the summed 1T models deter-

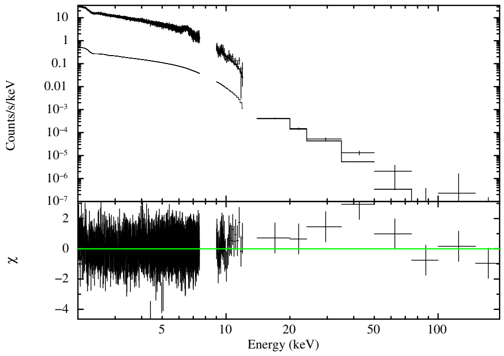

Fig. 4. The stacked spectrum of all clusters with large-scale, diffuse radio halos or relics with the combined single temperature model. A slight excess is apparent in the BAT spectrum, due to either a non-thermal spectral component or a significant multi-temperature structure in the individual clusters.

mined only from fits to the *XMM-Newton* data (2–12 keV). The BAT fluxes, which are not included in the derivation of the thermal model, are nonetheless completely consistent with it. Adding a non-thermal component fails to significantly improve the fit. However, many of the clusters in HIFLUGCS are relaxed, have cool cores, or simply have a low mass, while the clusters we expect to exhibit a non-thermal excess are hot, merging, massive systems hosting radio halos and/or relics. Dividing up the clusters into various subsamples of shared properties, such as by temperature, central cooling time, or the presence of a radio halo/relic, we find that only the radio halo/relic subsample shows some evidence of a non-thermal excess – at a level of 2.3σ–3.5σ before including systematic uncertainties. Although it is encouraging that the subsample we expect to have IC emission has the strongest evidence for it, these clusters are undergoing mergers, which are capable of creating higher temperature regions that can also produce hard energy excesses.

4. Conclusions

The electrons generating radio halos and relics produce IC emission at a level that depends on the global average value of B in galaxy clusters, which may play an important role in the dynamics and equilibrium state of the ICM. The coarse imaging capability and deep observations of the *Swift* BAT survey allow some of the most sensitive measurements at hard X-ray energies to date, but even so we are unable to definitively detect diffuse IC emission from any of the clusters in the survey. Happily, upcoming missions with focussing hard X-ray optics, *NuSTAR* and *Astro-H*, have the potential to achieve even higher sensitivities that may clearly resolve the issue of non-thermal X-ray emission in clusters once and for all.

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