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Hard X-ray emission from galaxy clusters observed with INTEGRAL

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Abstract. Some galaxy clusters are known to contain a large population of relativistic electrons, which produce radio emission through synchrotron radiation. Therefore, it is expected that inverse Compton scattering of the relativistic electrons with the CMB should produce non-thermal emission in addition to the well-known thermal plasma in the X-ray domain. We focus on the recent results by INTEGRAL in the Coma, Perseus and Ophiuchus clusters, which shed a new light on the non-thermal emission thanks to its angular resolution and sensitivity in the hard X-ray range.

Key words. Galaxies: clusters: general – X-ray: galaxies: clusters

1. Introduction

Since the detection of diffuse emission from the Coma cluster of galaxies in radio wavelengths in the 1970s (Willson 1970), it is well-known that galaxy clusters contain a large population of relativistic particles and large-scale magnetic fields, which produce low-frequency radio emission through the synchrotron process (e.g., Feretti & Giovannini 2007). In this framework, inverse-Compton (IC) processes between relativistic electrons and the Cosmic Microwave Background (CMB) occur (Sarazin 1999), which is expected to produce a hard tail in the X-ray spectrum. In the cases where non-thermal emission can be detcted both in radio and X-rays, a direct measurement of the cluster magnetic field can be achieved, and the population of non-thermal electrons can be fully solved. As a result, the total energy and pressure of the non-thermal electrons can be measured.

To the present day, several claims of non-thermal emission have been made, in particular from *BeppoSAX* (Fusco-Femiano et al. 1999) and *RXTE* (Rephaeli & Gruber 2002) (see Rephaeli et al. 2008, for a review). However, these results are still controversial (Rossetti & Molendi 2004), so observations by other instruments are important. Moreover, the hard X-ray instruments on board *BeppoSAX* and *RXTE* are non-imaging, so the results could have been contaminated by obscured AGN.

In this proceeding, we present the results of observations of the Coma, Perseus and Ophiuchus clusters with *INTEGRAL*. Thanks to a good angular resolution and sufficient sensitivity, the IBIS/ISGRI and JEM-X instruments on board the *INTEGRAL* observatory (Winkler et al. 2003) provide a good opportunity to search for a hard tail in the X-ray spectrum of a few bright, nearby clusters. In view of the results from *INTEGRAL*, we also describe the prospects for the next generation of hard

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X-ray telescopes (*NuSTAR*, *ASTRO-H*) on this topic.

2. *INTEGRAL* observations of galaxy clusters

2.1. The Coma cluster

Coma is the first cluster for which detection of non-thermal hard X-ray emission has been claimed (Fusco-Femiano et al. 1999), although this result is still controversial (Rossetti & Molendi 2004). Therefore, an independent confirmation of the result by other experiments would be important.

INTEGRAL performed dedicated observations of the cluster for a total of 800 ksec (see Eckert et al. 2007; Lutovinov et al. 2008, for the detailed results). The cluster was clearly detected by IBIS/ISGRI up to ~ 40 keV with a significance of 11σ. Analyzing the 18-30 keV image in detail, we found that the emission is displaced compared to the 1-10 keV profile derived from archival *XMM-Newton* data. Subtracting the scaled *XMM-Newton* profile from the *INTEGRAL* profile, significant residuals (~ 6σ) are found ~ 10 arcmin SW of the cluster core. However, this feature is probably not associated with non-thermal emission. Indeed, it can be explained by a higher temperature of $kT = 12 \pm 2$ keV in this region, in agreement with *XMM-Newton* data (Neumann et al. 2003).

Recently, a shock front has been detected in this region of the cluster (Markevitch 2010). *INTEGRAL* is detecting the shocked gas in the downstream region. Observations of the shock region with the future generation of hard X-ray telescopes could lead to the detection of non-thermal emission in this region. This result was recently confirmed by an analysis of the *Swift*/BAT data, which also noted a similar shift of the morphology towards the SW, and set an upper limit to the non-thermal emission a factor of ~ 3 below the *BeppoSAX* detection by Fusco-Femiano et al. (1999).

2.2. The Perseus cluster

Detection of non-thermal emission from the core of the Perseus cluster has been claimed using a very long *Chandra* observation (Sanders et al. 2005; Sanders & Fabian 2007). The extrapolation of this component to the hard X-ray range would lead to a flux firmly detectable by *INTEGRAL*/ISGRI. Perseus was the target of a 500 ksec observation by *INTEGRAL*/ISGRI and JEM-X. The results of this observation were published in Eckert & Paltani (2009).

Although there is evidence for an excess hard X-ray emission compared to the thermal component in the *INTEGRAL* spectrum, we have firm evidence that above ~ 30 keV the spectrum is dominated by the emission of the active nucleus at the centre of NGC 1275. Indeed, we observe significant variations of the hard X-ray flux in this energy range, which can only be explained by the presence of a compact source, i.e. the central nucleus of NGC 1275. Moreover, the extrapolation of the non-thermal flux detected by *Chandra* exceeds the *INTEGRAL* spectrum at 50 keV by a factor of 3-4. Overall, the broad-band (3-120 keV) *INTEGRAL* spectrum is well-described by a two-temperature thermal component to describe the large temperature variations observed in X-rays, plus the emission from the central AGN under the form of a power law. Therefore, *INTEGRAL* data do not support the *Chandra* result.

2.3. The Ophiuchus cluster

Thanks to its location in the galactic bulge, where *INTEGRAL* spends a significant amount of its observing time, the total exposure time on this object is large (> 3 Msec). Therefore, we were able to extract a high signal-to-noise spectrum with both ISGRI (17-80 keV) and JEM-X (3-20 keV). See Eckert et al. (2008) for the detailed analysis.

Fitting the 3-20 keV spectrum with a thermal model, we measure a temperature $kT = 8.5 \pm 0.5$ keV. Extrapolating this model to higher energies, a significant excess ($4.0 - 6.4\sigma$) is found above 25 keV. This indicates the presence of non-thermal emission at a robust confidence level.

After the early results from *INTEGRAL*, we started a campaign to observe the cluster at other wavelengths (X-rays, *XMM-Newton*, and

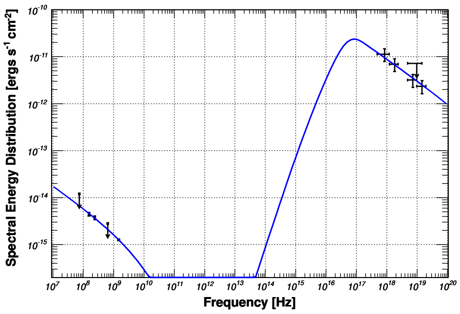

Fig. 1. Spectral Energy Distribution (SED) of the non-thermal emission in the Ophiuchus cluster (from Murgia et al. 2010). The solid line shows the best-fit model with a synchrotron/IC model with $B_V = 0.31\,\mu G$.

radio, GMRT). Our analysis of a 50 ksec observation of the Ophiuchus cluster with *XMM-Newton* (Nevalainen et al. 2009) confirms the existence of non-thermal emission. Combining the *XMM-Newton* and *INTEGRAL* spectra in the central region (radius of 7 arcmin from the center), we find a clear excess at the highest energies, at the level of 5.7σ. *XMM-Newton* measures a mean temperature of 9.1 ± 0.1 keV for Ophiuchus, in agreement with previous results. Except for the existence of a very compact cool core, the *XMM-Newton* data do not give any evidence for temperature variations above ~ 1 arcmin from the center. Therefore, unlike the case of Coma (see above) the hard X-ray excess cannot be explained by the presence of a hotter region.

In addition to X-rays, the Ophiuchus cluster was also observed in the radio band by VLA (Murgia et al. 2009) and GMRT (Murgia et al. 2010). Archival VLA data demonstrate the existence of diffuse radio emission, which confirms the existence of a population of non-thermal electrons. The spectrum of the radio source is steep ($\alpha = 1.4 \pm 0.3$), in agreement with the typical spectra of radio halos. Combining the radio (VLA, GMRT) and X-ray (*XMM-Newton*, *INTEGRAL*) data, we constructed a Spectral Energy Distribution (SED) of the non-thermal emission (see Fig. 1). Fitting the SED with a model consisting of synchrotron (radio) and IC-CMB (hard X-ray) components, we are able to fully solve the population of electrons (see Murgia et al. 2010, for details). Our best-fit model gives a volume-averaged magnetic field of $B_V = 0.31\,\mu G$, which is a rather low value compared to the typical values measured from Faraday rotation (e.g., Carilli & Taylor 2002). However, it should be kept in mind that the magnetic field computed in this way is volume-averaged, while Faraday rotation measures the magnetic field along a specific line of sight.

Our modeling of the SED allows us to compute other important properties of the electron population. Using the curvature of the radio spectrum, we estimate a maximum Lorentz factor of $\sim 3.8 \times 10^4$ for the electrons. On the other hand, we have no handle on the low-energy cutoff of the electron. Below $\gamma \simeq 700$, the radiative losses are dominated by Coulomb collisions with the thermal plasma, so it is reasonable to expect a break in the electron spectrum around this value. If we use a minimum Lorentz factor of $\gamma = 300$, the total pressure of the electron population is $P_{nt} = 2.5 \times 10^{-12}$ ergs cm^{-3}, which represents around 3% of the thermal pressure (Nevalainen et al. 2009), so the dynamics of the thermal gas is unaffected by the non-thermal electron population.

In conclusion, Ophiuchus will be a good target for the next generation of hard X-ray telescopes, which could be able to map the magnetic field and the relativistic electron population throughout the clusters thanks to their much improved angular resolution and sensitivity .

3. Conclusions

Thanks to a good angular resolution and sensitivity in the hard X-ray range, *INTEGRAL* has played a significant role in the past few years in the search for non-thermal emission, allowing us to detect a hard tail in the Ophiuchus at a robust confidence level and to set important constraints on the hard X-ray emission in Coma and Perseus. In the near future, the *NuSTAR*[1] and *ASTRO-H*[2] missions will bring

[1] http://www.nustar.caltech.edu/
[2] http://astro-h.isas.jaxa.jp/

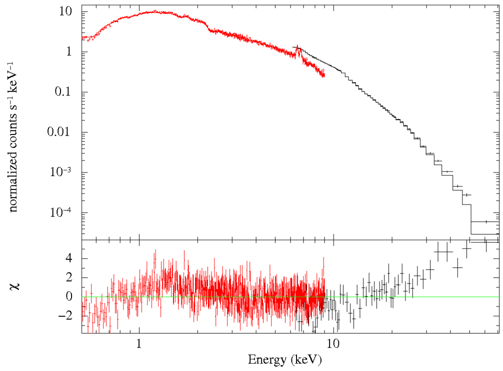

Fig. 2. Simulated 100 ksec ASTRO-H observation of the Ophiuchus cluster fitted with a single-temperature thermal model. The bottom panel shows the deviations to the model in units of σ.

the focusing technique to the hard X-ray range ($E \lesssim 80$ keV), improving the sensitivity in this energy range by more than two orders of magnitude and the angular resolution by a factor of 20 compared to existing missions. In bright clusters, non-thermal emission will be detected with high signal-to-noise. In Fig. 2 we show a simulated 100 ksec *ASTRO-H* spectrum of the Ophiuchus cluster, fitted with a single thermal component. A clear excess is found at the highest energies, indicating the presence of non-thermal emission at a confidence level $> 12\sigma$. It will be possible to split the signal into several regions, allowing us to map the magnetic field throughout the cluster.

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