Coma revealed as an extended hard X-rays source by INTEGRAL IBIS/ISGRI

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ABSTRACT

Aims. We report the *INTEGRAL*/IBIS observations of the Coma Cluster in the hard X-ray/soft γ-ray domain.
Methods. Since the Coma Cluster appears as an extended source, its global intensity and significance cannot be directly extracted with standard coded mask analysis. We used the method of imaging the extended sources with a coded mask telescope developed by Renaud et al. (2006).
Results. The imaging capabilities and the sensitivity of the IBIS/ISGRI coded mask instrument allows us to identify for the first time the site of the emission above $\sim 15\,\mathrm{keV}$. We have studied the Coma Cluster morphology in the 18-30 keV band and found that it follows the prediction based on X-ray observations. We also bring constraints on the non-thermal mechanism contribution at higher energies.

1. Introduction

Clusters of galaxies are the largest bound structures in the visible universe, and amongst the most luminous ones. This makes them important cosmological probes. The intercluster medium (ICM) is heated to high temperatures by the initial collapse. In addition, it is believed that as groups and smaller clusters of galaxies merge to form larger ones, violent shocks compress and heat the intercluster medium to X-ray emitting temperatures (10^7–10^8 K). These shocks could also drive the acceleration of ions and electrons to relativistic energies, thereby producing a spectrum extending from the radio to the γ-ray domains through processes such as synchrotron emission and inverse Compton (hereafter, IC) scattering.

The observations of diffuse radio halos from cluster cores (Giovannini et al. 1993), and the more recent reported detection of extreme ultraviolet (EUV) and hard X-ray (HXR) emission from clusters (Bowyer et al. 1999; Fusco-Femiano et al. 1999; Rephaeli et al. 1999) seem to point to the possible presence of non-thermal and/or supra-thermal particles. Although the origin of the radio halos is most probably synchrotron emission from high energy electrons, that of the EUV photons and hard X-rays has been the source of much debate and is still uncertain. Sarazin (1999) suggested that the extreme UV and hard X-rays could arise from IC scattering of the energetic, synchrotron producing electrons off the cosmic microwave background radiation (see also Bykov

et al. 2000 for a detailed discussion of nonthermal high energy emission in galaxy clusters). Alternatively, this emission could also be due to bremsstrahlung radiation of supra-thermal electrons accelerated by turbulent gas dynamics in the ICM (Ensslin et al. 1999; Sarazin & Kempner 2000). If the HXR cluster component is confirmed, then the question remains: is it thermal or non-thermal in origin?

Thus far, X-ray imaging observations of clusters such as Coma, have shown that the emission in the X-ray range is predominantly thermal, originating from bremsstrahlung in the hot ICM. *BeppoSAX* and *RXTE* detected a hard X-ray excess that extends beyond 10 keV and apparently deviates from the steep thermal spectrum expected from pure bremsstrahlung emission (Fusco-Femiano et al. 1999; Fusco-Femiano et al. 2004; Rephaeli et al. 1999; Rephaeli & Gruber 2002). Given that these observations were carried out with non-imaging instruments, contamination from point sources contained in their field of view is not unlikely. Moreover, a recent second look at the *BeppoSAX* data on Coma seems to show that there is no evidence of a HXR excess (Rossetti & Molendi 2004). This debate can only be convincingly resolved and put to rest through sensitive imaging observations at high energies beyond the thermally dominated X-ray emission.

In this letter, we report on hard X-ray/soft γ-ray observations of the Coma Cluster with the IBIS/ISGRI (Ubertini et al. 2003; Lebrun et al. 2003) coded mask instrument onboard *INTEGRAL* (Winkler et al. 2003). A large field of view ($29° \times 29°$, $8° \times 8°$ fully coded), fine imaging capabil-

ities (PSF of 12′ FWHM, Gros et al. 2003), and an unprecedented 3σ broadband sensitivity of ~ 1 mcrab at 20 keV (10^5 s, $\Delta E = E/2$), make IBIS/ISGRI ideal for probing the nature of the HXR excess in the Coma Cluster: **the first extended source detected with this instrument**.

2. Observations and Data Reduction

The Coma Cluster was observed with *INTEGRAL* in 2003 during revolutions 36, 71 and 72. Almost 250 pointings aiming within 13° of Coma amount to ~500 ks. Using these data, Krivonos et al. (2005) demonstrated the ability of IBIS/ISGRI to detect faint extra-galactic sources, and established a catalog of 12 serendipitous sources ($\geq 4\sigma$) in addition to the Coma Cluster. The authors noted that the source corresponding to the latter was extended, and hence, its flux and significance calculated with the standard analysis were likely inaccurate. Renaud et al. (2006) presented a general method to determine the flux and the total detection significance for any extended celestial source observed through a coded mask. We here apply this method to the study of the spatial and spectral features of the Coma Cluster.

Reconstructed sky images with coded mask telescopes are correlation maps between the detector image and a decoding array derived from the mask pattern. The deconvolution algorithm implemented in the *INTEGRAL* Off-Line Scientific Analysis (OSA, Goldwurm et al. 2003) is optimized for point-sources and the flux of any source is given by the peak of the SPSF at its position in the correlation map. For this reason, the intensity of an extended source cannot be derived directly using the standard processing. This limitation can be overcome by constructing images of flux per solid angle (*i.e.* per sky pixel), in which the global flux is given by the sum of intensities over the emissive region. The details of this method are presented in Renaud et al. (2006).

We analyzed the Coma Cluster data with OSA v. 5.0 and obtained individual sky images in the 18–30, 30–50, 50–100 and 100–150 keV energy bands, directly from the standard analysis. We evaluated their quality by measuring the noise given by the width of the distribution of significance values, and then constructed images in flux per sky pixel which were combined to make mosaics in the four energy ranges.

3. Results

3.1. Morphology of the emission

The IBIS/ISGRI significance map of the Coma Cluster in the energy range 18–30 keV is shown in Figure 1. We have overlaid the instrument's response to a point-like source of comparable intensity in the bottom right corner of the image. This serves as a morphological comparison, and strongly suggests that the Coma Cluster is indeed an extended source for IBIS/ISGRI. The maximal pixel value within the extended emission is at the ~8σ confidence level, consistent with Krivonos et al. (2005) who noted that it was likely unresolved.

In the X-ray domain, the spectrum of the Coma Cluster is dominated by thermal bremsstrahlung from hot intercluster
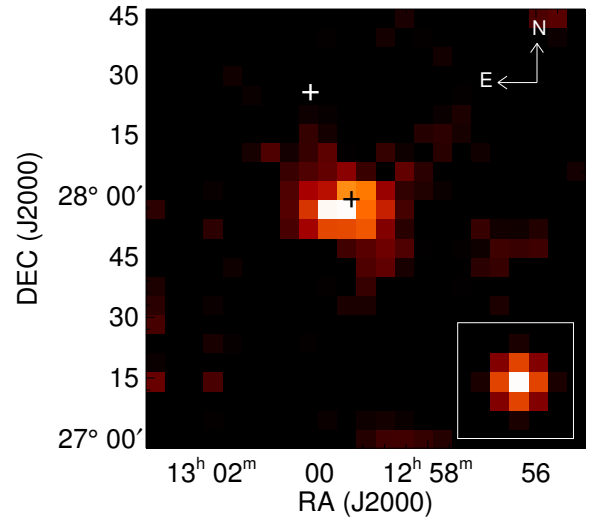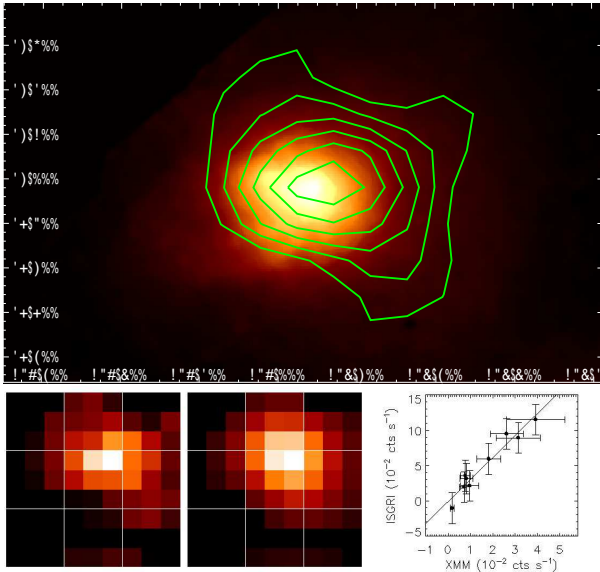

Fig. 1. IBIS/ISGRI significance image of the Coma cluster in the 18–30 keV energy range. The black cross indicates the position of NGC 4874, near the center of the X-ray emission from Coma (Briel et al. 2001). The white cross shows the location of X Comae, a bright Seyfert galaxy at ~30′ from the cluster. The colour scale is linear, with black corresponding to 1σ and white to 8σ. The IBIS SPSF is also shown in the lower right corner.

gas. *RXTE* observations (Rephaeli & Gruber 2002) yielded values from which we can derive the expected ratio of non-thermal to thermal emission at higher energies. These are 0.2 and 1.0 in the 18–30 keV and 30–50 keV energy ranges respectively. *XMM-Newton* observations revealed marked temperature variations (from 4 to 11 keV) at distances >10′ from the centre of the cluster (Arnaud et al. 2001, Briel et al. 2001, Neumann et al. 2003). A hot front in the southwest (kT ~ 11 keV) was interpreted as an adiabatic compression due to recent accretion of matter. Within the core, centered on NGC 4874, these authors found a homogeneous temperature distribution of ~8.25 keV.

Given that the X-ray emission between 0.3 and 2 keV depends only slightly on the plasma temperatures in the range of those measured in the ICM (Fig. 1 of Arnaud 2005), the *XMM-Newton* map in this energy range is a good estimate of the ICM gas emissivity. Therefore, we can use the 0.3–2 keV EPIC MOS mosaic image, shown in the top panel of Figure 2 and overlaid with the IBIS/ISGRI 18–30 keV contours, in conjunction with the temperature map of Arnaud et al. (2001) to construct a map of the expected thermal emission in the 18–30 keV band. Moreover, for best accuracy, we computed correction factors, which account for the temperature variations across the cluster, using the `mekal` model in XSPEC v.11.3. The redshift and abundances were set to $z = 0.0231$ and 0.25, respectively (Arnaud et al. 2001). The relative intensity of each region was weighted with the corresponding correction factor. The final 18–30 keV map, convolved with the IBIS/ISGRI PSF, is shown in the middle bottom panel of Figure 2. The IBIS/ISGRI image shown in Figure 1 is reproduced in the bottom left panel for reference.

To calculate the correlation coefficient between the IBIS/ISGRI mosaic in the 18–30 keV range and the expected map for the emission in this energy band constructed in the

Fig. 2. *Top panel: XMM-Newton* 0.3-2 keV mosaic image (Neumann et al. 2003) with IBIS/ISGRI significance contours in the 18–30 keV energy range, going from 2σ to 10σ. *Bottom panel:* IBIS/ISGRI image of flux per pixel in the 18–30 keV band centered on the Coma Cluster (left), the predicted morphology based on the *XMM-Newton* images in intensity and inferred temperature (middle), and the correlation between the 18–30 keV and 0.3–2 keV images (right). The white squares delineate the regions over which the flux was summed for the purpose of correlation study.

manner described above, the sky pixels over which the flux is summed have to be independent. This is very nearly the case at all scales larger than the size of the SPSF, which is 12′ or 2.5 sky pixels. The white squares in the bottom left and middle panels of Figure 2 correspond to regions that are 3 pixels (14.′5) by 3 pixels in size, and thus regions that we can consider independent from one another as far as the flux and variance are concerned. By summing the flux per pixel over the nine regions in each map, we obtained two sets of nine intensities. The uncertainties associated with the IBIS/ISGRI map were derived according the prescription of Renaud et al. (2006), and those of the interpolated map were calculated based on an uncertainty of 1 keV on the plasma temperature (Arnaud 2006, priv. comm.).

We found a linear correlation coefficient of $\rho = 0.95$, and show the correlation plot in the bottom right panel of Figure 2. The probability that a random sample of 9 uncorrelated data points yield a linear correlation coefficient of 0.95 or larger is 8.7×10^{-5}. This close agreement between the morphologies of the detected and expected thermal emission from the Coma Cluster at energies between 18 and 30 keV brings us to conclude that what is seen in this energy range by IBIS/ISGRI is compatible with an emission of pure thermal origin with no indication of a non-thermal component having a significantly different morphology. A distinction between thermal and non-thermal emission components could be detected only through a fine spectro-imaging analysis on small spatial scales and over the entire emissive region. It is interesting to note that this result adds weight to the temperature variations seen in X-rays by *XMM-Newton*.

3.2. Reconstructed global intensity

We now turn to the question of the global intensity of this emission when the source is considered to be extended. Since instruments such as *BeppoSAX*/PDS and RXTE are only capable of recording the total emission within their ~1° FOV, their detection of a HXR tail from the Coma Cluster could not definitively and exclusively be attributed to it. This uncertainty is substantiated by the presence of other sources present in the FOV like X Comae, a bright Seyfert galaxy discovered by *ROSAT*/PSPC ~30′ northeast of the Coma Cluster (Dow & White 1995). Even if X Comae may experience flux variability, Fusco-Femiano et al. (1999) demonstrated that because of its steep spectral index, an unusually strong variability would be necessary in order to have a significant effect on the total detected flux. Hence, its hard X-ray emission would be blended into the global flux and not detected as variable. Nonetheless, since IBIS/ISGRI does not detect an excess above 3σ at the position of X Comae in either of the four energy bands defined in § 2, we assume that the spectra obtained by *RXTE* and *BeppoSAX* are truly representative of the emission from Coma and that there really exists a HXR tail, despite the ongoing dispute on this issue (Rossetti & Molendi 2004).
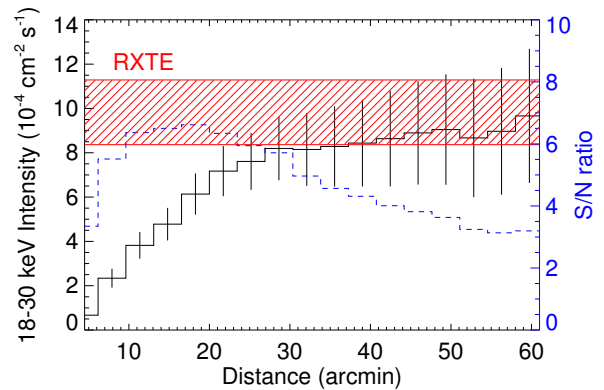

Fig. 3. The 18–30 keV IBIS/ISGRI integrated intensity (left scale, solid line with error bars) and corresponding significance calculated on concentric circles and expressed as a function of radius (right scale, dashed line). The shaded area shows the intensity within the 1σ error derived from *RXTE* observations (Rephaeli & Gruber 2002; Rossetti & Molendi 2004).

Figure 3 shows the intensity in 18–30 keV range, integrated over circular areas with increasing radii centred on the pixel of maximum intensity located at RA(J2000) = $12^h59^m31.7^s$ and DEC(J2000) = 27°57′ 07.″6. The intensity is shown as the monotonically increasing black curve with error bars. The dashed blue curve represents the total statistical significance (S/N ratio) calculated on the basis of each circular area. This analysis is done without any a priori assumption on the size of the emitting region. The shaded area shows the *RXTE* flux taken from Rephaeli & Gruber (2002, Table 1) and Rossetti & Molendi (2004), whose results are consistent with one another. The best agreement is found for $R = 30′$. This value is also in line with the extent of the X-ray surface brightness

observed by *ASCA*/GIS (Honda et al. 1996). The IBIS imaging sensitivity was deduced from Crab Nebula observations in each of the four energy bands assuming a Crab spectrum of $9.7\,E^{-2.1}\,cm^{-2}s^{-1}keV^{-1}$ (Krivonos et al. 2005).

The treatment in the 30–50 keV energy range was performed in the same way as for the 18–30 keV range, and the flux was summed over the same region but no significant excess was found. Although we expect that at least half of the global intensity in the 30–50 keV band arises from thermal processes, the emission above 50 keV is purely non-thermal. However, no imaging telescopes have observed the Coma at energies >10 keV and thus the morphology of the yet undetected non-thermal emission above 30 keV is unknown. We derived upper limits for the flux in the 50–100 keV and 100–150 keV ranges in the standard way, relying on the assumption that the source is point-like ($\Phi \lesssim 8'$). Even though we have shown that this is not so, these upper limits are a good estimate in the case of a non-detection. The 18–150 keV ISGRI spectrum is shown in Figure 4. For comparison, we have plotted the *RXTE* best-fit spectrum of this source (Rephaeli & Gruber 2002; Rossetti & Molendi 2004) as the shaded area (1σ errors), and find that the spectra agree.
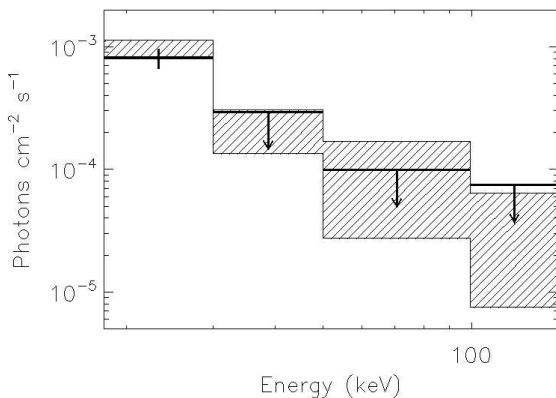
Fig. 4. IBIS/ISGRI spectrum of the Coma Cluster. The upper limit in the 30–50 keV range is calculated assuming that the source has the same shape as it does in the 18–30 keV energy range. At higher energies, the upper limits are derived as for a point-source. The best-fit *RXTE* spectrum within its 1σ uncertainties, is shown as the dashed area. Upper limits are given at the $3\,\sigma$ confidence level.

4. Conclusion

The unequalled imaging capabilities and sensitivity of the IBIS/ISGRI telescope on *INTEGRAL* give us the opportunity of imaging extended sources in the hard X-ray and soft γ-ray domains for the first time. We have shown that the morphology of the emission from the Coma Cluster in the 18–30 keV energy range is akin to that in X-rays when the temperature variations measured by *XMM-Newton* across the cluster's emission are taken into account. There is no evidence for the presence of non-thermal emission arising from a region with the same morphology as that associated with the thermal emission. We find that the integrated intensity is in good agreement with previous *RXTE* and *BeppoSAX* observations of Coma.

Future *INTEGRAL* observations will surely reveal more details about the morphology and nature of the emission from Coma. Our analysis was based on the assumption that the morphology of the emission is the same in the 30–50 keV range as it is between 18 and 30 keV. Given that the upper limit we quote for the 30–50 keV flux is only a factor of 1.5 above the mean *RXTE* spectrum, and that non-thermal mechanisms such as IC scattering and non-thermal bremsstrahlung are expected to contribute half the flux in this range, deeper *INTEGRAL* observations ($\sim$1.5 Ms) will permit a fine morphological study of the emissive region. This will provide the opportunity to definitively determine whether there is or not a HXR tail, and if so to identify the site of particle acceleration in the Coma Cluster for the first time.

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