Constructing the Universe with Clusters of Galaxies, IAP 2000 meeting, Paris (France) July 2000
Florence Durret & Daniel Gerbal eds.

WHAT DO WE GAIN WITH XMM-NEWTON EPIC/MOS CAMERAS?

S. DOS SANTOS, G.C. STEWART and L. E. SPURGEON
Department of Physics & Astronomy,
University of Leicester,
1, University Road,
Leicester LE1 7RH
UK

1 Introduction

With the launch of a new generation of X-ray observatories, namely Chandra and XMM-Newton, it is worth to quantify, now that real data are available, the gain in information these satellites will bring. Some of these gains are obvious, like the unprecedent spatial resolution of Chandra (e.g. allowing to compare meaningfully X-ray with radio data of galaxy jets [?]) or the very high sensitivity together with a good spatial resolution of XMM-Newton(e.g. allowing to detect clusters and groups of galaxies up to high redshifts [?]). Moreover, the availability of high spectral resolution gratings (like the RGS [?] onboard XMM-Newton) alows a fine detection of a great number of elemental lines, and thus a precise diagnostic of the temperatre and density conditions of the emitting plasma. In these proceedings, however, we will concentrate on the MOS [?] cameras onboard XMM-Newton, and see that they allow significant improvements on the amount of information available, improvements which clearly allow us to address questions unanswerable with previous satellites.

In fact, as we will see, the basic answer to the question of the title could be stated in one very short sentence : *more photons*. Compared to the ROSAT PSPC detector (apart from the much higher sensitivity of course), the MOS cameras provide an extended energy band (0.2-10.0 keV instead of 0.2-2. keV for the PSPC) with as good a spatial resolution[a]. Moreover, the latter, represented by the PSF, is much less variable onboard XMM-Newton, compared to ROSAT. Compared to ASCA, MOS's energy coverage extends softer and the spatial resolution is an

[a] In fact, the mirror efficiency is comparable in both satellites, but the different technology of the detectors (proportional counter vs. CCDs) allows the MOS cameras to provide sharper images than the PSPC.

order of magnitude better, the PSF being much less dependent on energy (and thus avoiding many problems in the data reduction process).

We will illustrate these facts by three examples in the following : first, on the observation of a compact group of galaxies, namely HCG 16, and in particular on the galaxy classification that can be achieved with XMM-Newton. Second, on a rich cluster of galaxies, Abell 496, to show the possibility of separating the whole image in several energy bands. Finally, we will address the issue of serendipitous extended source detection, and show that the extended spectral coverage can be crucial for this task.

2 Hickson 16

HCG-16 is a compact group of galaxies[?] (hereafter HCG) which comprises seven galaxies, with a mean recession velocity of 3959 ± 66 km s^{-1} and a velocity dispersion of 86 ± 55 km s^{-1}[?]. This HCG is very unusual, being comprised only of spiral galaxies, which seem all to be active, either harboring an active nucleus or a starburst. Moreover, the X-ray properties of HCG 16 are still a matter of debate, some teams arguing that only galactic emission is present[?], while others find a diffuse extended emission[?]. Latter, a careful reanalysis of the same data showed that this diffuse component was indeed present, but heavily contaminated by foreground and background sources[?], thus reducing its luminosity by a facter greater than 2. Apart from this controversy about its diffuse medium, the real nature of the galaxies was still puzzling : all the four central galaxies, originally discovered by Hickson[?] showed clear signs of interaction and a strong ionising continuum, but the nature of this continuum was still unclear. X-ray observations can directly see this ionising continuum, thus giving useful constraints on its nature. However, as we will see, a broad energy band is needed for this task, which ROSAT lacked.

The observations of HCG 16 were taken in orbit 23 as part of the XMM-Newton EPIC first-light. Exposures of 50 ks were taken with EPIC. Standard screening was applied using the XMM-Newton SAS (Science Analysis Software) and a low energy cut of 200 eV was applied to the data, due to remaining calibration uncertainties at softer energies. The first 10 ks of the observation were removed, due to a high count-rate background particle flare.

2.1 Soft and Hard band images

The screened photon list obtained was then used to produce images in two different bands : a soft band, comprising the photons which energy was between 0.2 and 2 kev (and thus mimicking a ROSAT observation of the group); and a hard band, between 2 and 10 keV. These images were denoised and reconstructed using a wavelet technique[?], which allows to retain only the significant features at a certain threshold in different spatial scales. The threshold was chosen to be 4σ.

Figure 1 shows the reconstructed image of the central CCD of the MOS1 detector. It contains the four central galaxies of the group : three of them (hcg16-A, C and D) are clearly visible, while the fourth one is much fainter in this band (HCG16-B).

Figure 2 shows the same type of reconstruction, but for the hard band (2-10 keV). ROSAT could not observe this part of the energy band, and ASCA's PSF allowed only to see a blob of extended emission (associated with the four galaxies and, if present, diffuse emission) coincident with the group center. With XMM-Newton, on the contrary, all the four galaxies are well separated. The surprising fact is the height of the hard X-ray peak associated with the galaxy HCG16-B : it is by far the most luminous galaxy of the group in this energy range, which shows that its spectrum is very hard. It is here obvious that a restricted energy band (like the one of ROSAT) can lead to wrong interpretations on the nature of these galaxies : in fact, most of the flux of HCG16-B could not be observed before XMM-Newton, and we could think that this

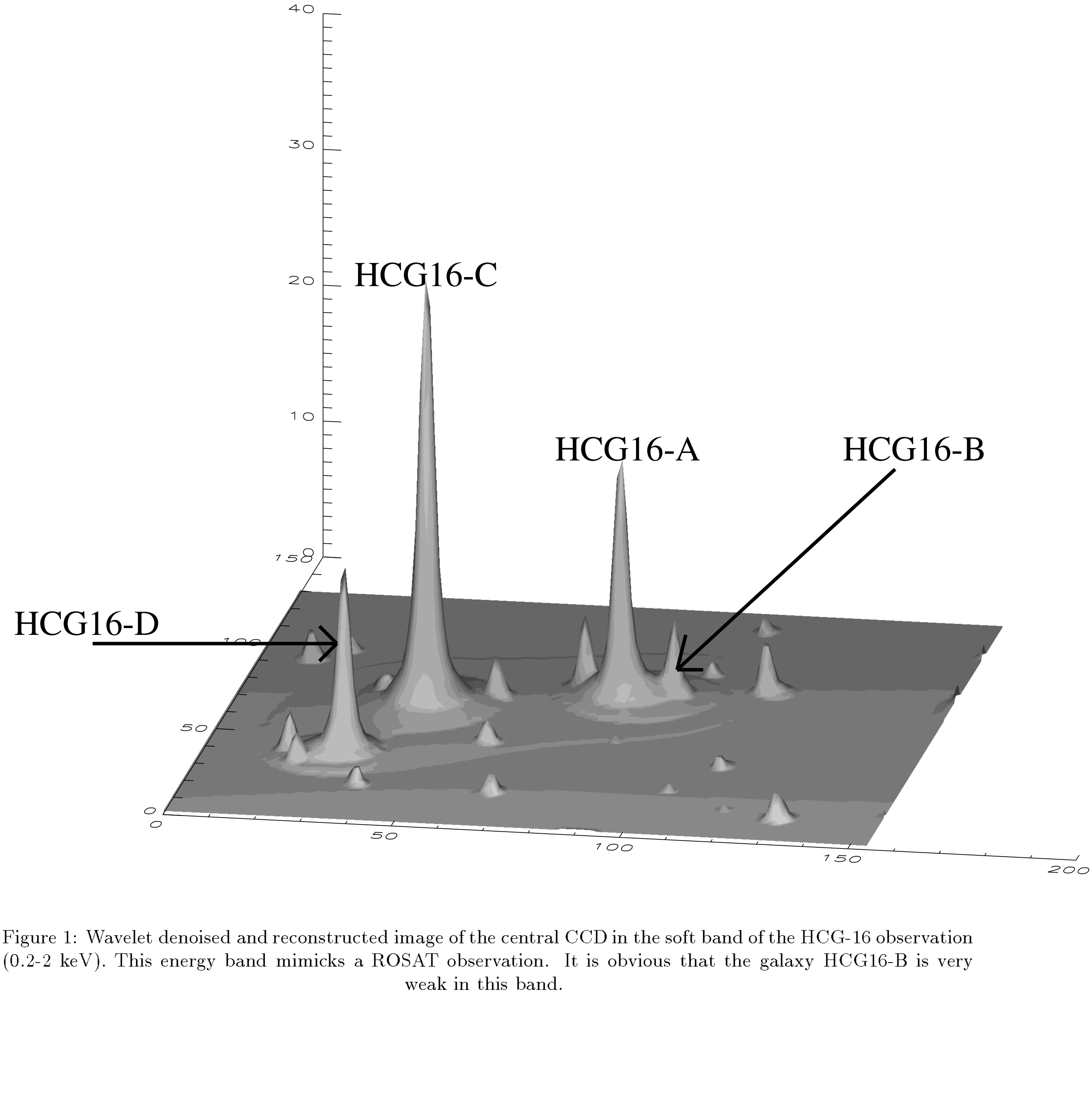

Figure 1: Wavelet denoised and reconstructed image of the central CCD in the soft band of the HCG-16 observation (0.2-2 keV). This energy band mimicks a ROSAT observation. It is obvious that the galaxy HCG16-B is very weak in this band.

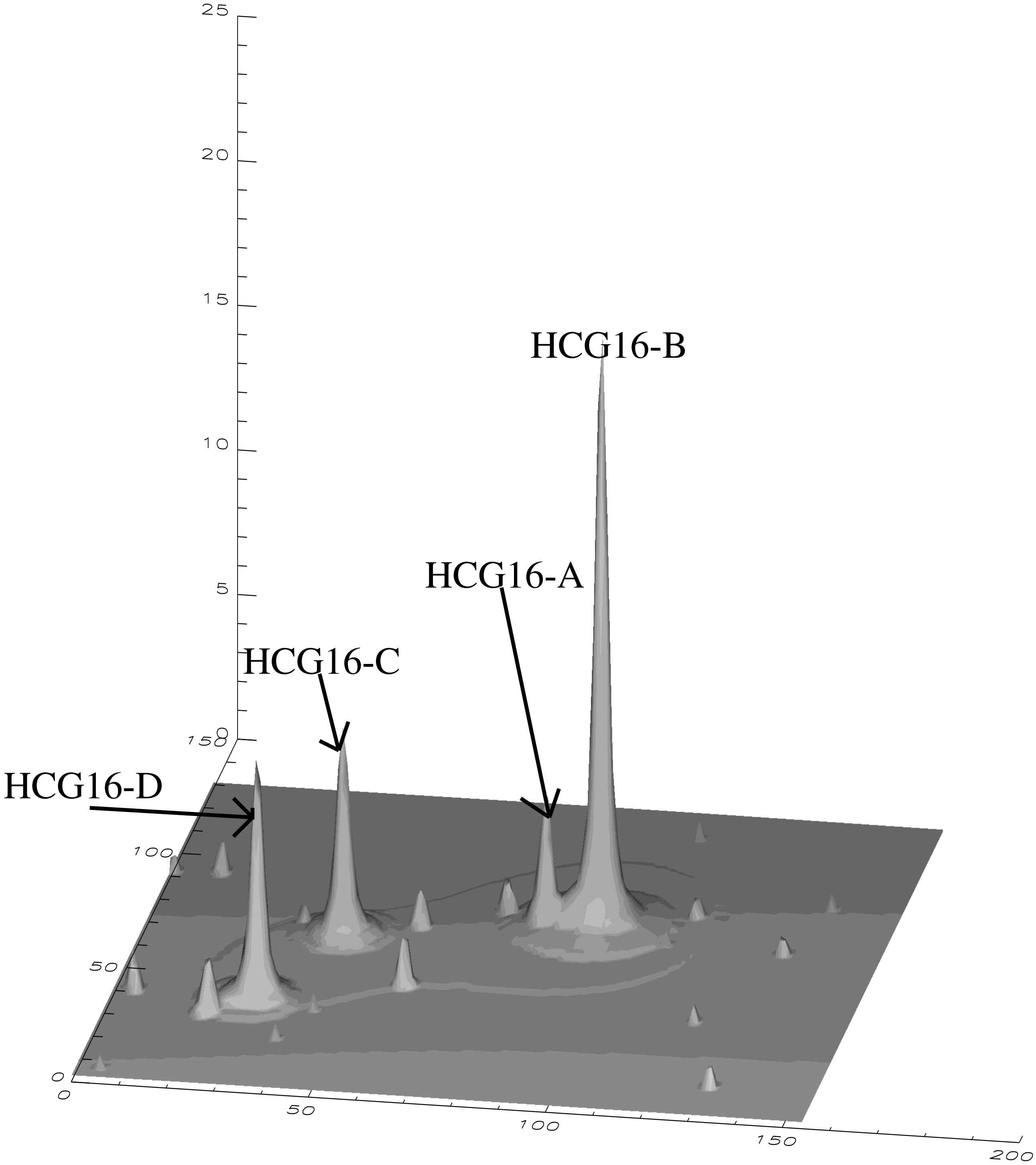

Figure 2: Wavelet denoised and reconstructed image of the central CCD in the hard band of the HCG-16 observation (2-10 keV). This energy band could not be observed by ROSAT, and ASCA did'nt have enough spatial resolution to give useful results. Here, the galaxy HCG16-B is, by far, the dominant source in the group, showing that a restricted bandpass can lead to wrong conclusions about the nature of the galaxies.

object was intrinsically faint.

2.2 Detailed spectra

The restrictions seen in the last section are even worse when one wants to fit a detailed model to a particular galaxy spectrum. This, in theory, allows to disentangle between a thermal emission due to an on-going starburst and a power-law emission due to an active nucleus. We will not here review the spectral results for the four galaxies, this is done elsewhere [?]. We will instead focus on HCG16-B (also called NGC833). The figure 3 shows the whole band spectrum from the inner $20''$ of the galaxy. The spectrum was fitted in XSPEC v11.0 and required three components to obtain a good fit (the three components were required at a confidence level higher than 99.99 %) : the most obvious is the peak at high energies from an obscured AGN; this emission is in the form of a power-law of index $\Gamma = 1.8 \pm 0.5$, absorbed by material of column density equal to $N_H = 2.4 \pm 0.4 \times 10^{23}\,\mathrm{cm}^{-2}$. The second component is an un-absorbed power-law, resulting from radiation scattered into our line of sight, by thin, hot, plasma directly illuminated by the AGN. The third component is radiation from an optically-thin thermal plasma, with a temperature of $kT = 470$ eV. The improvement in the fit upon adding the thermal emission is $\Delta\chi^2 = 36.7$. This complex X-ray spectrum amply confirms the presence of an AGN in HCG16-B of luminosity $1.4 \pm 0.6 \times 10^{42}\,\mathrm{erg\,s}^{-1}$, it is, remarkably, the dominant source of power in the galaxy. In contrast, the thermal X-ray emission, is more than 100 times weaker ($8.9 \pm 3.0 \times 10^{39}$ erg s^{-1}).

The restricted ROSAT band can obviously not produce the same detailed results : below 2 keV, the obscured AGN is invisible because of the very high column density of the central active nucleus. Moreover, because of the poor statistics, the soft spectrum could be fit by an optically-thin thermal plasma, without any need for a power-law component. It is thus obvious that such an analysis was biased and couldn't elucidate the ionising continuum nature of the galaxies of the group, as XMM-Newton has done.

3 Abell 496

We will illustrate now directly the adavantage of having a high sensitivity and thus a high number of collected photons from a given source. Abell 496 is a moderately rich cluster of galaxies ($T \sim 5$ keV), observed by XMM-Newton as part of the calibration phase. We will not review here the results on A496 obtained on the central part and the cooling flow (see Tamura et al. in these proceedings) and the large-scale temperature profiles (see Arnaud et al. in these proceedings). Instead, we can take advantage of the number of photons collected by XMM-Newton, and separate the whole energy band into 4 sub-bands and look at the morphology of the cluster in these four bands. We thus divided the whole 0.2-10 keV band into : 0.2-1.5 keV, 1.5-4 keV, 4-6 keV and 6-10 keV. From the screened photon list, we constructed images in these four bands, which were denoised and reconstructed using the same wavelet-based method as in the last section.

Figure 4 shows the reconstructed images (with a threshold of 4σ) in these four bands. The differences in morphology are obvious : the main one is that the two softer bands (0.2-1.5 and 1.5-4 keV) are much more peaked than the harder ones. The surface brightness maximum region in the latter is extended and has an elliptical shape. On the contrary, in the two softer bands, the maximum is very peaked and the position of the peak is off-centered, compared to the center of the ellipse mentioned above.This is typically the type of morphology we expect from a cooling-flow, since most of the emission, in the cooling region, will come from low temperature cooling gas. Moreover, the twisting of the isophotes between the two softer bands is not the same, the softer being the rounder (which is still probably an effect of the central cooling-flow).

The last results can be used in two interesting ways : first, if enough photons are present,

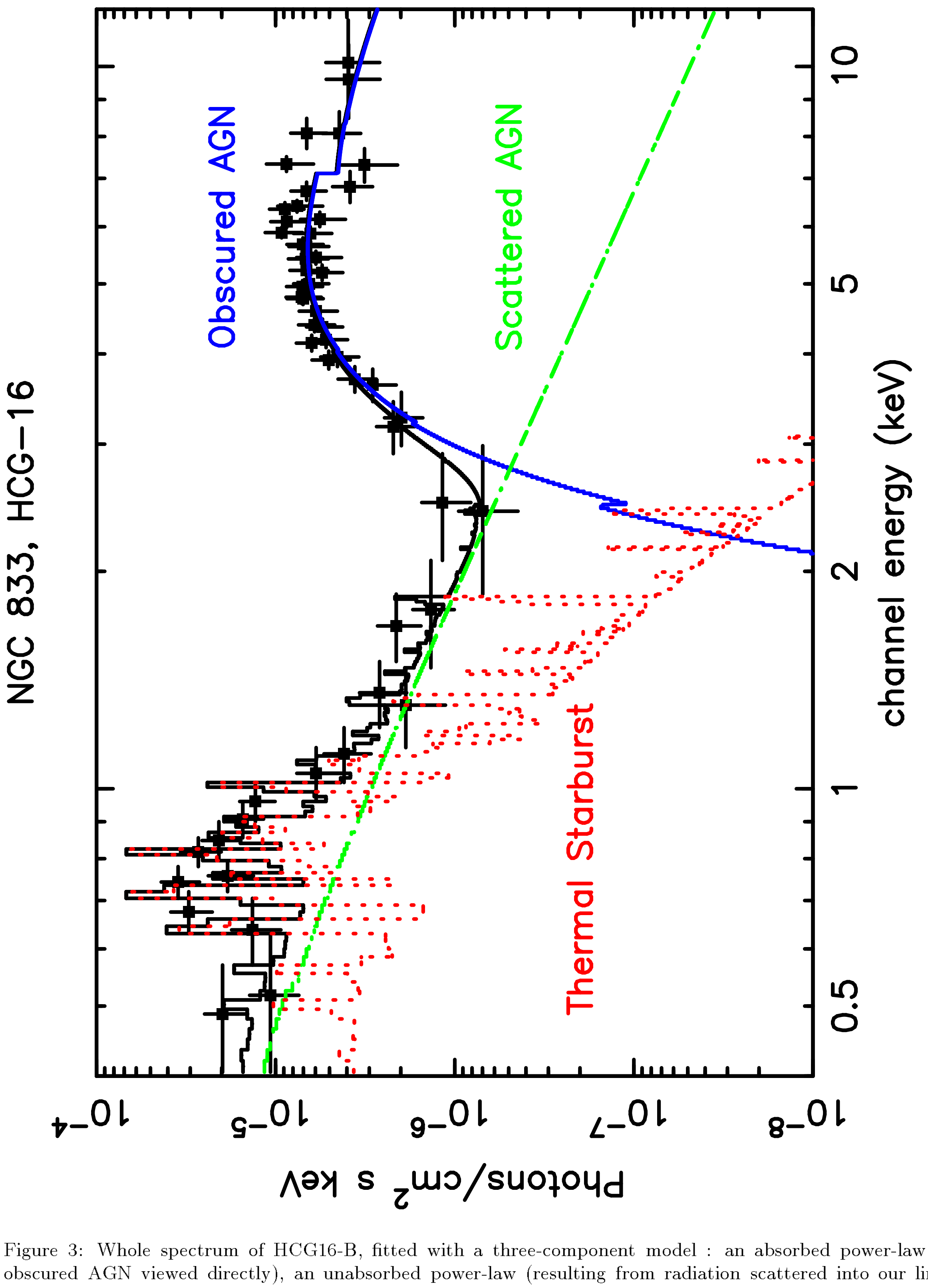

Figure 3: Whole spectrum of HCG16-B, fitted with a three-component model : an absorbed power-law (the obscured AGN viewed directly), an unabsorbed power-law (resulting from radiation scattered into our line of sight, by thin, hot, plasma directly illuminated by the AGN and an optically-thin thermal plasma (see text).

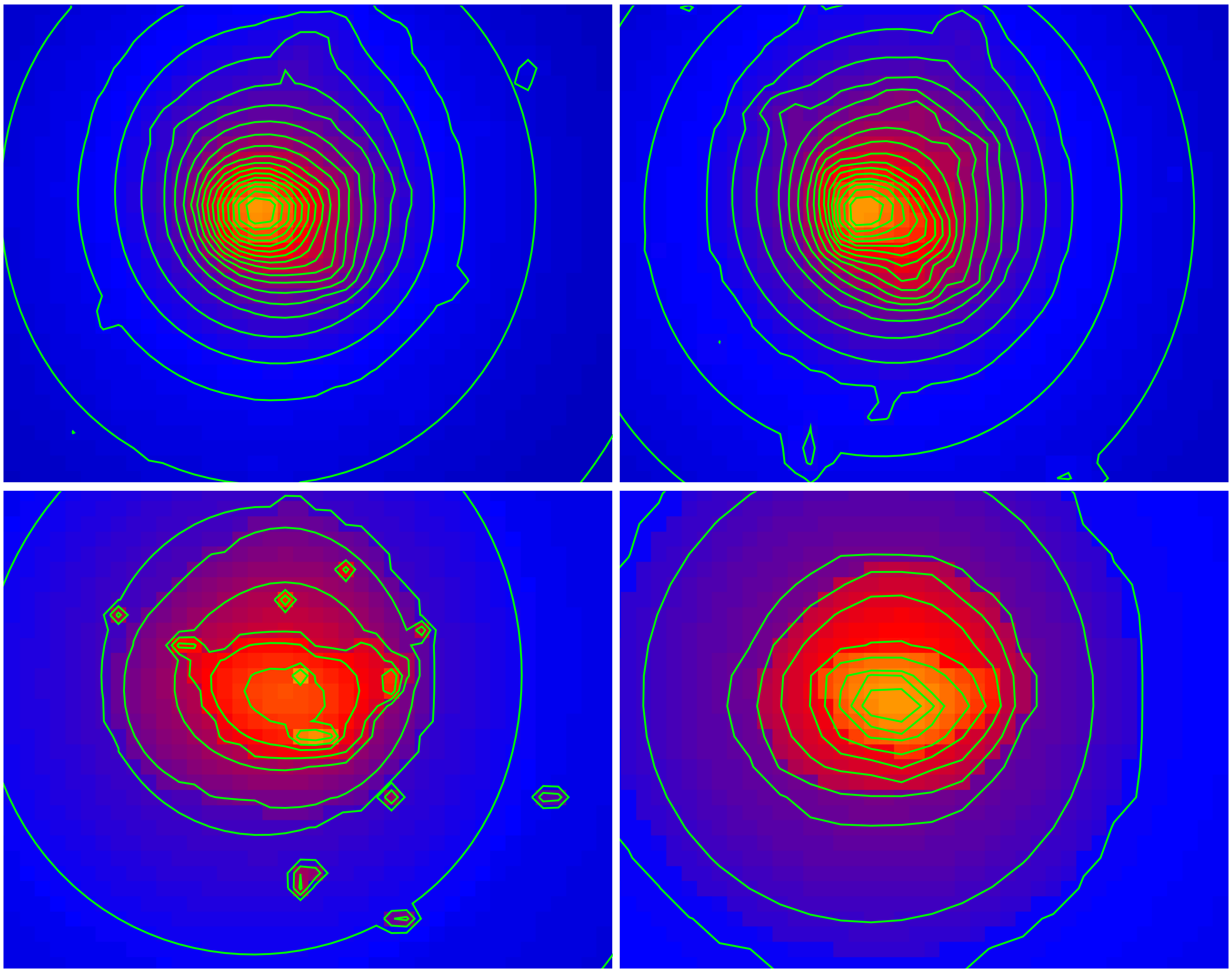

Figure 4: Wavelet-denoised and reconstructed images (with a threshold of 4σ) of four different bands of Abell 496. From left to right and top to bottom : 0.2-1.5 keV, 1.5-4 keV, 4-6 keV, 6-10 keV. The ability to separate the whole band in four sub-bands and having enough photons to reconstruct an image can be very important in the case of a spectro-imaging fit to the surface brightness. The soft bands are obviously more peaked than the hard ones, witnessing the presence of a moderate cooling-flow.

one can isolatea small region of the spectrum, say for example the region of the Fe complex at 6.4 keV (rest energy). If an estimation of the continuum in this region is available (through the mean temperature of the cluster, for example), one can have a precise idea of the spatial variation of the Fe equivalent width. To our knowledge, this has not yet been done for clusters, but has been tried for an XMM-Newton observation of Cas A [?]. In some region of the nebula, this equivalent width was higher than 4 keV, which means that these regions could quite be seen as pure iron regions (in the sense that the great majority of the X-ray emission comes from Fe)! The second way the different bands can be used (which is more appropriate for clusters of galaxies) is when fitting the surface brightness profiles of clusters : one technique often used [?] consists in fitting a 2-dimensional model to the surface brightness in different bands in order to recover the gas density profile. This has been done with ROSAT data and will of course be even more useful with XMM-Newton data, separated in different bands. The fact that spectral information is available up to 10 keV should allow to reconstruct the temperature profile as well as the gas density profile.

4 Serendipitous cluster detection

During all the years of life of the observatory, XMM-Newton will observe a non-negligible part of the sky with deep pointings. These pointings will contain the object for which the observation was accepted, but also a great number of serendipitous sources. A scientific analysis of this harvest of sources will be of great interest, and is the main task of the SSC consortium [?]. XMM-Newton provides obviously unrivaled capabilities for serendipitous X-ray surveys by virtue of the large field of view of the X-ray telescopes with the EPIC X-ray cameras and the high throughput afforded by the heavily nested telescope modules. We present here the first detection of a serendipitous cluster and show that the extended energy band of the telescope as well as its high sensitivity were very important in the detection, as well as the determination of the redshift of the cluster.

4.1 The observation

The Supernova remnant G21.5-09 was observed 5 times between revolutions 60 and 65 at different positions on the detector in order to assess the vignetting function of the telescope. During one of the four offaxis pointings, an extended object was detected at $\sim 10'$ of the center of the field of view. The figure 5 shows the 0.2-10 keV band MOS2 image of this observation. The left extended source is the Supernova remnant, while the right one is a serendipitous source. G21.5-09 is situated in the plane of the Galaxy, and so, is heavily absorbed. It is thus interesting to look at the soft band image of the same observation. The 0.2-2 keV image is displayed in figure 6 : the serendipitous source has disappeared, while G21.5-09 is still there! This means obviously that either the source has a very hard spectrum (which is difficult to understand) or it is situated on the other side of our galaxy. From these two images, it is obvious that ROSAT was unable to observe this source, because it doesn't cover the energy band where it is visible. Once again, one sees the great advantage of having an extended energy band!

4.2 Spectral study

The photons inside a circle of radius $1.5'$ centered on the brightness maximum were collected in order to pursue a detailed spectral study. The figure 7 shows this spectrum between 2 and 10 keV (no photons were detected below 2 keV). The red points indicate MOS2 data and the black MOS1 data. Both instruments were fitted simultanously, and it was obvious, from a visual inspection, that the spectrum was not well fit by a power-law. A prominent emission line can be seen near 6 keV, which seems to be indicative of an optically-thin thermal enriched plasma.

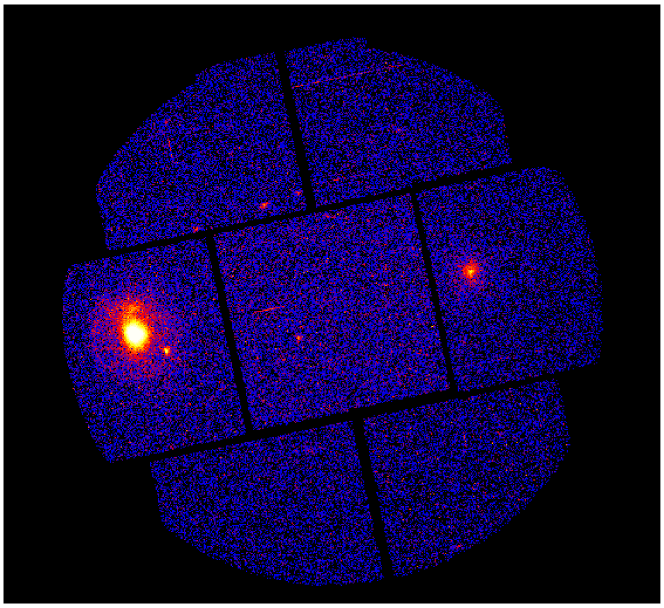

Figure 5: 0.2-10 keV band MOS2 image of an offaxis G21.5-09 observation. The left extended source is the Supernova remnant, while the right one is a serendipitous source.

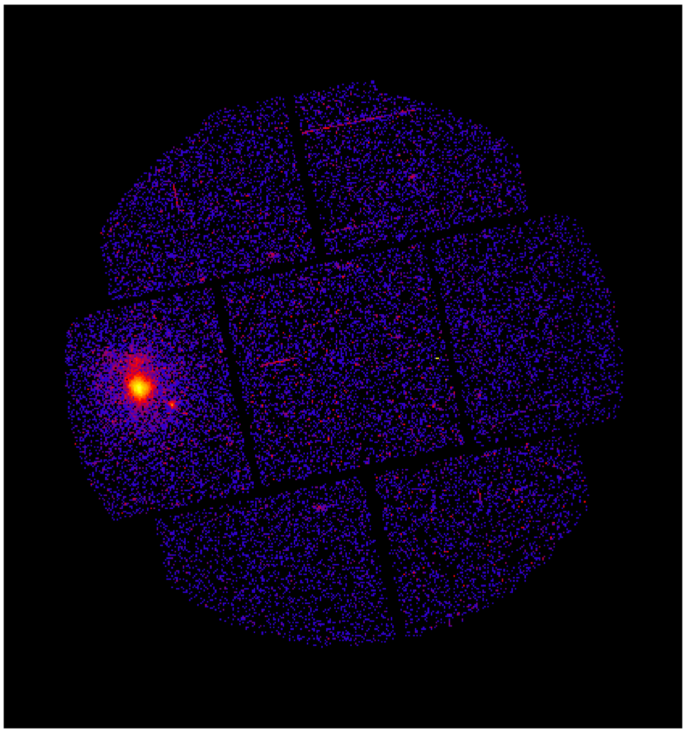

Figure 6: 0.2-2 keV band MOS2 image of an offaxis G21.5-09 observation. The serendipitous source has disappeared, due to the heavy absorption of our galaxy!

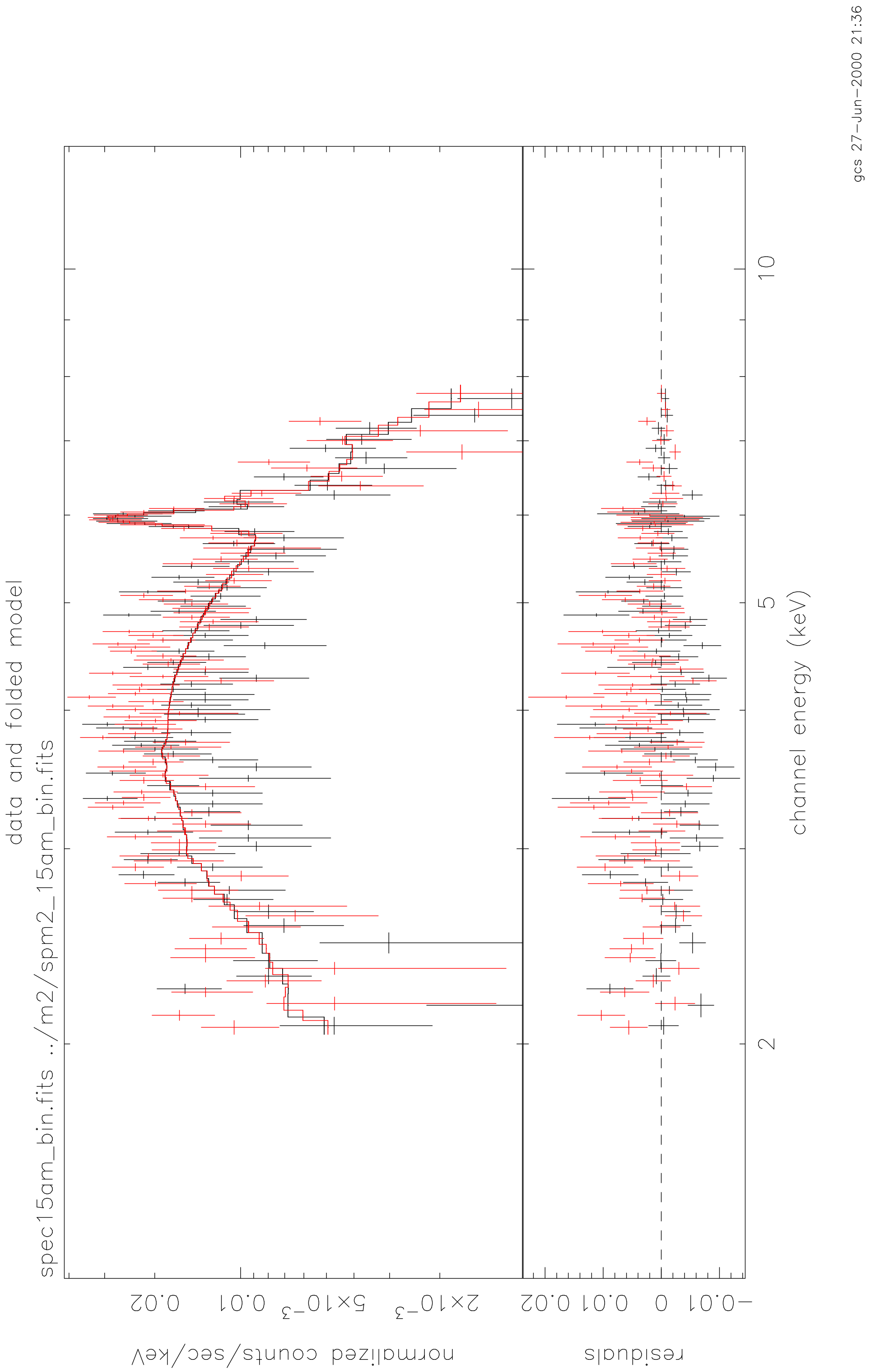

Figure 7: cluster spectrum in the 2-10 keV energy band with residuals to the fit. Red croses are MOS2 data and black crosses are MOS1.oth instruments were simultanously fit.

Figure 8: thank you, thank you very much ...

Thus we fit the data with an absorbed MEKAL model with variable temperature, abundance and absorption column. We also let the redshift of the source vary in order to reproduce the Fe line energy peak. The fit (as the residuals witness) is fairly good and gives the following results : $T = 5.4 \pm 0.8$ keV, $Z = 0.51\, Z_{\odot} \pm 0.09$ and $nH = 8 \pm 0.6 \times 10^{22}$ cm^{-2}. This hydrogen column compares very well with DIRBE-FIRAS obtained values and the Luminosity was computed to be $L_X = 4 \times 10^{44}$ erg s^{-1}.

The redshift, due to the great number of photons in the Fe line, was estimated with a great precision : $z = 0.12 \pm 0.002$ (all the errors quoted are 90 % confidence intervals). This is very interesting for the prospects of clusters serendipitous detections, since the determination of the redshift should be fairly easy for the brightest clusters discovered.

No cooling-flow in the central arcminute was required to fit the spectral data, and the inclusion of a cooling-flow model or a second thermal model did not improve the fit. Please note that this can not be stated as evidence of lack, but should be viewed as lack of evidence! The soft photons are heavily absorbed and this could bias our result.

There was also a lack of direct spectral evidence for a change in temperature betwen $1.5'$ and $3'$, but the profile softness ratio seems to increase with radius (from -0.22 to -0.07), which can be explained by a temperature change or a metallicity change.

Finally, it is woth noticing that this cluster fits very well in the commonly observed $L_X - T$ relation.

5 Conclusions

In summary, we have shown here that the high-throughput of XMM-Newton, its extended energy band and its good spatial resolution contribute to enhance enormously the amount of physical information one can derive from one observation. XMM-Newton seems very well suited for the observation of moderate and high-redshift clusters (from the resolved spectroscopy for the local ones to a good determination of the redshift for the most luminous) and for the serendipitous source detection. Obviously, this X-ray observatory will revolutionize the way we study X-ray clusters.

Acknowledgments

This work is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA). EPIC was developed by the EPIC Consortium led by the Principal Investigator, Dr. M. J. L. Turner. The consortium comprises the following Institutes: University of Leicester, University of Birmingham, (UK); CEA/Saclay, IAS Orsay, CESR Toulouse, (France); IAAP Tuebingen, MPE Garching, (Germany); IFC Milan, ITESRE Bologna, OAPA Palermo, (Italy). EPIC is funded by: PPARC, CEA, CNES, DLR and ASI.