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X-RAY EMISSION FROM THE WARM-HOT INTERGALACTIC MEDIUM

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ABSTRACT

In this paper I give an overview of the detection of emission from the warm-hot intergalactic medium (WHIM) in the outer parts of clusters of galaxies. The evidence for the presence of soft excess X-ray emission in 7 out of 21 clusters is summarized, and it is demonstrated that several of these clusters show the signatures of thermal emission in the outer parts. A strong signature is the presence of redshifted O VII emission at 0.57 keV. In the central parts, several clusters show also a soft excess, but in this case the observations cannot well discriminate between a thermal or non-thermal origin of the soft X-ray excess.

Key words : clusters of galaxies – X-rays

I. INTRODUCTION

Recent cosmological studies have shown now clearly that matter constitutes only 27 % of the mass density of the universe, and baryons even less: only 4 %. At high redshift, all baryons are found, predominantly in the Lyα forest. However, at low redshifts, a census of the baryons (in stars of different types, atomic and molecular gas, dust, hot plasma in clusters and warm plasma in groups) shows that between 25–60 percent of all baryons are unaccounted for (Fukugita *et al.* 1998, 2004; Penton *et al.* 2004). Although the uncertainty in the precise amount of "missing" mass is rather large, mainly due to the uncertainties in the detected baryonic components but also due to the exact definitions of certain baryonic components, it is still clear that there is a significant component of missing baryons.

Of course, baryons do not disappear, and the most common idea is that a major part of these missing baryons are to be found in the so-called warm-hot intergalactic medium (WHIM, Cen & Ostriker 1999). Theoretical and numerical work by these authors and several other groups has shown that most of these missing baryons should be in a plasma phase with temperatures between 10^5 and 10^7 K, in filaments connecting the clusters and with on average higher density and temperature toward these clusters. Due to the low temperature and low density of this WHIM, it is difficult to observe in X-ray emission. However, near the knots of this cosmic web (clusters of galaxies), the density may be high enough to detect this baryonic component in emission. The weaker parts can only be seen in emission using future instrumentation with high spectral sensitivity, large effective area X-ray telescopes (for example the Missing Baryon Explorer (MBE), Fang *et al.* 2004; the Diffuse Intergalactic Oxygen Surveyor (DIOS), Suto *et al.* 2004), or alternatively in absorption toward bright background sources.

The observational evidence for detecting the WHIM in emission and absorption in general has been summarized recently in more detail in another paper (Kaastra 2004); in this contribution, I will focus upon the detection of the WHIM near clusters of galaxies.

II. EUVE AND ROSAT OBSERVATIONS

As outlined above, current models for the formation of large scale structure predict that matter residing in the filaments that connect clusters of galaxies will be accelerated toward those clusters; shocks will form and the gas will be heated. The highest in-fall velocities and densities are obviously expected to occur near the clusters of galaxies, and therefore this is the most obvious place to look for emission from this medium that should have sub-keV temperatures. Plasma with low temperature will emit thermal emission at low energies. The signatures of WHIM emission is therefore a diffuse soft X-ray component in the outskirts of galaxy clusters. Since there is also hot gas present in the outer parts of a cluster, the WHIM inter-cluster emission will be seen as a soft X-ray excess above the thermal emission of the hot intra-cluster gas.

Historically, such a soft excess component has been seen first in the Virgo and Coma clusters of galaxies (Lieu *et al.* 1996a, 1996b). It was found in both EUVE DS detector observations as well as in Rosat PSPC observations. However, this discovery has been a subject of controversy ever since the time of the first reports. As a result, a large number of papers on both theoretical and observational aspects appeared.

Concerning the data analysis, papers have debated issues like background subtraction and low-energy calibration. At the energies where the soft excess produces most photons ($E < 0.3$ keV), the PSPC of Rosat has effectively almost no intrinsic spectral resolution, and the EUVE DS detector, which is more sensitive

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to even softer photons, lacks spectral resolution at all. Moreover, response matrix calibration at these energies is extremely difficult. The best that could be done with these data from a spectroscopic point of view is to compare radial profiles obtained with EUVE with the slightly higher energy radial profiles obtained by Rosat (Mittaz *et al.* 1998; Durret *et al.* 2002). In several cases such an analysis revealed a relatively larger importance of the soft excess in the outer parts.

The lack of spectral resolution of EUVE and Rosat prevented to prove whether the emission has a non-thermal or thermal nature. The most natural explanation of thermal emission is emission from the WHIM near the clusters, while for non-thermal emission one of the most popular models is Inverse-Compton scattering between the cosmic microwave background (CMB) and intra-cluster relativistic electrons (Hwang 1997, Ensslin & Biermann 1998, Sarazin & Lieu 1998).

III. XMM-NEWTON OBSERVATIONS

Thanks to the launch of XMM-Newton, it is now possible to study clusters of galaxies at low energies with moderate (~ 60 eV) spectral resolution and good sensitivity. A number of studies have been performed now using the XMM-Newton EPIC detectors. Here we mention the following work.

Kaastra *et al.* (2003) studied a sample of 14 clusters with XMM-Newton. In five of these clusters a significant soft excess is evident. These clusters are A 2052 and MKW 3s in the southern part of the Hercules supercluster, Coma, A 1795 and Sérsic 159-03 (alias A S1101). The sample of Kaastra *et al.* was extended from 14 to 21 clusters (Kaastra *et al.* 2004a, 2004b). Two additional cases of a soft excess were found: A 3112 and A 2199, bringing the detection rate of a soft excess to 7 out of 21.

The soft excess in A 3112 was found earlier in the XMM-Newton data by Nevalainen *et al.* (2003). These authors studied Coma, A 1795 and A 3112 and found a soft excess in all of these clusters. Both Kaastra *et al.* (2003) and Nevalainen *et al.* (2003) find that the observed surface brightness of the soft excess is in general in good agreement with earlier PSPC observations, showing that (instrumental) background subtraction does not cause major problems.

Both groups of Kaastra *et al.* (2003) and Nevalainen *et al.* (2003) studied only the central part of the Coma cluster. The Coma outskirts were investigated in detail by Finoguenov *et al.* (2003). These authors studied 5 fields at a radial distance of 0.5–1.0 degree from the center of the Coma cluster. They found evidence for the presence of a filament with a width of 3 Mpc and a length of ~20 Mpc, seen more or less along the axis and in projection in front of the Coma cluster (distance 90 Mpc). This filament is also evident from the spatial and redshift distribution of galaxies in front of the Coma cluster, and here again the surface brightness is consistent with the measured low energy flux of the Rosat PSPC detector.

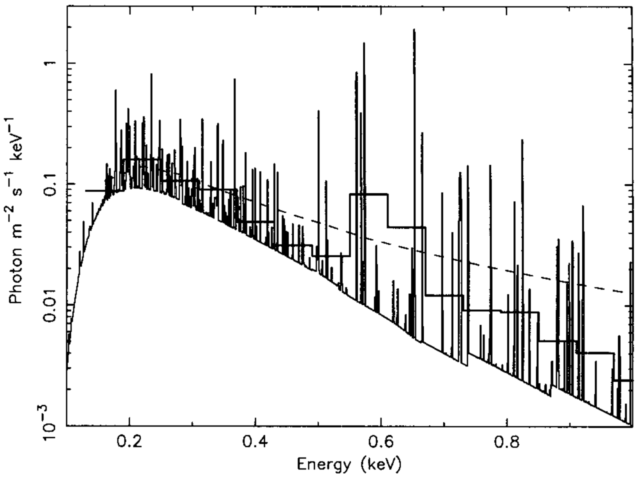

Fig. 1.— This figure shows an isothermal spectrum (kT = 0.2 keV, metallicity 0.1 times solar), similar to the soft component found in the outskirts of some clusters of galaxies. The spectrum is shown at two resolutions: a bin size of 1 eV, as is in principle possible with the new generation of Transition Edge Sensor (TES) detectors and a bin size of 60 eV, similar to the CCD resolution of the XMM-Newton EPIC cameras. The figure shows that the strongest emission lines for this plasma are the O VIII Lyα line at 0.65 keV and the O VII triplet around 0.57 keV. At CCD resolution, the triplet is not resolved. Finally, the dashed line shows a power law with photon index 2 with the same flux as the isothermal spectrum; at 60 eV resolution or better, the power law can be well distinguished from a thermal spectrum.

IV. DETECTION OF LOW-TEMPERATURE THERMAL EMISSION FROM CLUSTERS

As shown in the previous section, the presence of a soft excess in several clusters of galaxies is now a well established fact. It seems to be present in approximately 1/3 of all clusters (the sample of Kaastra *et al.* 2004a,b was not selected for studying soft excess emission but mainly for studying cooling flows, hence it is not biased toward likely soft excess candidates). Also in low-spectral resolution surveys, a significant fraction of all clusters show indications for the presence of a soft excess (Rosat PSPC survey of Bonamente *et al.* 2002).

Thanks to the spectral resolution of XMM-Newton (approximately 60 eV at E = 600 eV), it is now possible to determine the nature of the emission: thermal or non-thermal (see Fig. 1). When a spectral fit is made to the XMM-Newton X-ray spectrum of the outer parts of those clusters containing a soft excess, and when only the hot gas is taken into account, the fit residuals clearly show the signature of thermal emission in five out of seven cases (A 1795, Sérsic 159-03, A 2052, MKW 3s and A 2199). In the other two clusters with a soft excess, these thermal signatures are not clearly

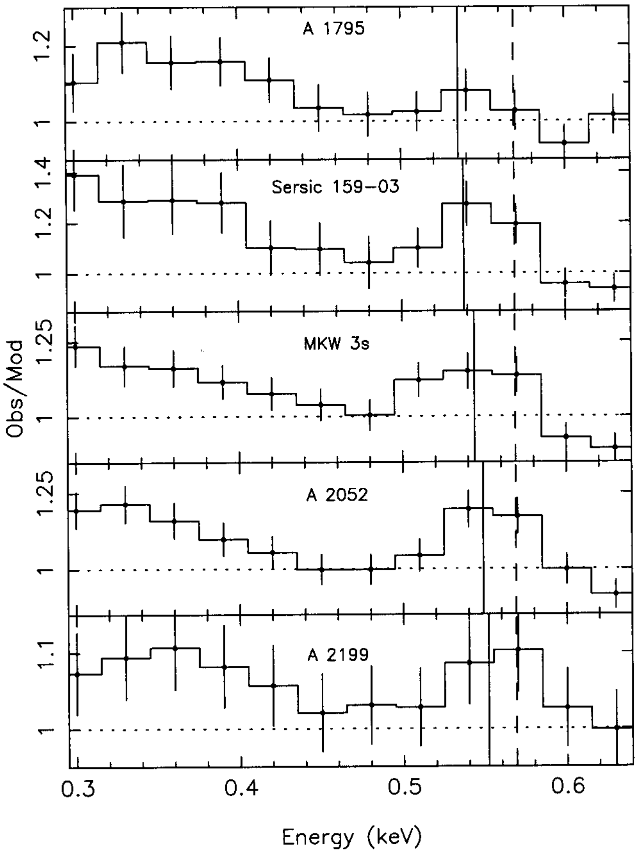

Fig. 2.— Fit residuals with respect to a two temperature model for the outer 4–12 arcmin part of six clusters. The position of the O VII triplet in the cluster rest frame is indicated by a solid line and in our Galaxy's rest frame by a dashed line at 0.569 keV. The instrumental resolution at 0.5 keV is ~60 eV (FWHM).

present (Coma, A 3112).

This thermal signature is present in the form of an emission line at 0.57 keV, in addition to an unresolved soft excess below an energy of 0.3 keV (see Fig. 2). This line can be identified with the (unresolved) triplet of O VII (resonance, inter-combination and forbidden line, at energies of 574, 569 and 561 eV, respectively). Under collisional ionisation conditions, the centroid of this triplet is at 569 eV. From the measured line centroid in the 4–12 arcmin annular range, we find for the best three cases the following average redshifts (with in brackets the true redshift of the cluster): Sérsic 159-03: 0.045±0.018 (0.058), MKW 3s: 0.079±0.025 (0.045), and A 2052: 0.034±0.018 (0.035).

Important here is that these measured redshifts are all consistent with the cosmological redshifts of the clusters, and that this implies that the line centroids differ by 2–3σ from the expected centroids if the emission was produced at $z = 0$. Although we cannot exclude that there may be still a contribution of a few tenth to these oxygen lines from residual Galactic foreground emission (the EPIC resolution corresponds to $\Delta z = 0.10$, hence we really depend upon centroiding), it is clear that the major part of the line emission comes from the (super)cluster environment.

It is further clear that additional observations with higher spectral resolution are needed to confirm this discovery. Astro-E2, to be launched in 2005, will have an energy resolution of 6 eV, ten times better than EPIC at these low energies, and hence Astro-E2 will probably the first satellite to confirm the cluster origin of the O VII emission with high precision.

However, there is more evidence than just the O VII line (centroid) for thermal low energy emission in clusters. This additional evidence stems from the spatial distribution of the emission. The soft excess emission shows a broad distribution, often extending beyond the XMM-Newton field of view (15 arcmin radius), and is less centrally peaked than the hot gas emission. As it has a strong soft X-ray contribution below 0.3 keV (see for instance Fig. 2), we can use the monochromatic Rosat PSPC maps at 1/4 keV to map the spatial distribution. As we indicated earlier, the surface brightness distribution of the soft excess is in good agreement with the Rosat measurements. The Rosat maps show in general extended emission out to about a degree, corresponding to this soft excess. It is very unlikely that the soft excess found in 7 out of 21 clusters would all originate in foreground Galactic clouds with a size of a degree, that would be centered around those clusters. Of course, we cannot exclude that in a few individual cases there is some amount of Galactic contamination, but we do not expect this to be the case for all the soft excess clusters. Again, higher spectral resolution observations with for example Astro-E2 will be able to measure quantitatively any amount of galactic foreground contamination.

The properties of the warm gas (Kaastra *et al.* 2003, 2004ab; Finoguenov *et al.* 2003) can be summarized as follows. For five clusters in the redshift range of 0.03–0.06 we find a typical radius of 1 degree, corresponding to a physical size of 2–6 Mpc. The hydrogen density of the gas, which has a temperature of 2×10^6 K, is between 50 and 150 m^{-3}, and the oxygen abundance is between 8–16 percent of the solar oxygen abundance. The total hydrogen column density through the cluster is of the order of a few times 10^{25} m^{-2}. All these numbers are in agreement with predictions from numerical simulations.

V. THERMAL OR NON-THERMAL EMISSION?

Of course the discovery of O VII line emission in cluster outskirts (Kaastra *et al.* 2003, Finoguenov *et al.* 2003) caused much excitement as it proofs that the soft excess around clusters is real and in several cases is due to thermal emission with temperatures of 0.2 keV, and it may be the first evidence for the "top of the iceberg" emission from the warm-hot intergalactic medium.

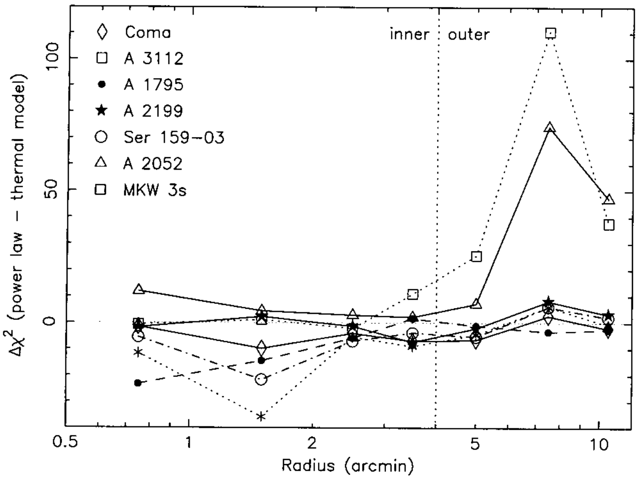

Fig. 3.— Best-fit χ^2 difference for a fit to the soft excess with a power law as compared to a fit with a thermal component, as a function of the radial distance to the center of the cluster. Positive values correspond to clusters where a thermal model gives the best fit, negative values to clusters where a power law model gives the best fit. The number of degrees of freedom in all fits was 234.

However, it has been misunderstood that we claim as if all soft excess emission would be purely thermal (for instance Bowyer *et al.* 2004; also at this conference). There are definitely some clusters where we cannot exclude that the soft excess has a non-thermal origin. We discuss this in more detail below.

In Fig. 3 we compare for the seven clusters with a significant soft excess the goodness of fit for a model with a power law or a thermal soft excess. In all these cases, the addition of a soft component (either power law or ∼0.2 keV thermal emission) improves the fit significantly as compared to a model with only thermal emission from the hot component.

Looking first to the outer parts (4–12 arcmin radius, we combine the three annuli in this range of Fig. 3), in the four clusters MKW 3s, A 2052, A 2199 and Sérsic 159-03 we find a significantly better fit with a thermal soft excess than with a power law (as indicated by the positive $\Delta\chi^2$ in the figure). These clusters show strong O VII emission in the same region (Fig. 2) and are our favoured candidates for WHIM emission in the cluster outskirts. On the other hand, A 1795 does not show very strong O VII emission and may be an intermediate case; Coma and A 3112 do also show no evidence for strong line emission *in the 4-12 arcmin range*; note that Finoguenov *et al.* (2003) did detect line emission in the outer parts of Coma at 0.5–1 degree from the center.

Looking next to the central parts (0.5–4 arcmin radius), there is evidence for weak O VII emission in A 2052 and MKW 3s only; in the other clusters it cannot be significantly detected. In several cases, from a statistical point of view a power law model works as good or even better than a thermal model in the inner parts. It should be noted that in the cluster cores the emission from the hot gas dominates, and therefore it is much harder to disentangle the superimposed soft excess emission, as the hot gas emission works as a "background" to be subtracted and is therefore effectively a source of additional noise in the detection of the soft component.

In the specific case of the central part of Coma, Kaastra *et al.* argued that the soft excess as detected by XMM-Newton is consistent with the BeppoSAX detected hard X-ray tail, if a single power law component is fit to both the soft and hard excess emission. The thermal model can only not be excluded if the metallicity of the gas is very low: the best-fit oxygen abundance would be as low as 0.07 times solar.

In summary, we find a rather complex behaviour of the soft excess: in the outer parts of several clusters, thermal emission dominates, most likely due to the hottest and densest parts of the WHIM in the cluster outskirts (A 2052 and Coma are good examples of this). In the central parts, we cannot exclude that there is (at least in some cases, like Coma) also a non-thermal component. Again, for the central parts high-spectral resolution measurements like expected from Astro-E2 are urgently needed to put much stronger constraints on the thermal/non-thermal issue.

VI. CONCLUDING REMARKS

Recently, Cheng *et al.* (2004) have made a detailed hydrodynamical simulation of a concordance ΛCDM model, to investigate the possible thermal origin for a soft excess in a set of 20 simulated clusters having temperatures in the range 1–7 keV. They detect a significant excess in most of the simulated clusters, whose relative amount changes from cluster to cluster and, for the same cluster, by changing the projection direction. In about 30 per cent of the cases, the soft X-ray flux is measured to be at least 50 per cent larger than predicted by the one-temperature plasma model. These results are in good agreement with our findings of a soft excess in 7 out of 21 clusters. Interestingly, Cheng *et al.* find that the excess is generated in the virialized regions. Its main contributor is low entropy and high density gas associated with merging sub-halos, rather than diffuse warm gas.

Further theoretical and observational work in this field is very important. On the observational side, Astro-E2 with its calorimeter will be the next obvious step; this will open the era of high-resolution spectroscopy of extended sources. However, the imaging capabilities of Astro-E2 are limited and a dedicated wide-field, high resolution mission such as MBE (Fang *et al.* 2004) or DIOS (Suto *et al.* 2004, see also these proceedings) is a mandatory requirement to proceed.

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