XMM-NEWTON DISCOVERY OF O VII EMISSION FROM WARM GAS IN CLUSTERS OF GALAXIES

Jelle S. Kaastra\(^1\), R. Lieu\(^2\), T. Tamura\(^1\), F.B.S. Paerels\(^3\) and J.W.A. den Herder\(^1\)

\(^1\)SRON National Institute for Space Research, Utrecht, The Netherlands
\(^2\)University of Alabama at Huntsville, USA
\(^3\)Columbia University, New York, USA

Abstract
XMM-Newton recently discovered O VII line emission from \(\sim 2\) million K gas near the outer parts of several clusters of galaxies. This emission is attributed to the Warm-Hot Intergalactic Medium. The original sample of clusters studied for this purpose has been extended and two more clusters with a soft X-ray excess have been found. We discuss the physical properties of the warm gas, in particular the density, spatial extent, abundances and temperature.

1. Introduction

Soft excess X-ray emission in clusters of galaxies was first discovered using EUVE DS and Rosat PSPC data in the Coma and Virgo cluster (Lieu et al. 1996a,b). It shows up at low energies as excess emission above what is expected to be emitted by the hot intracluster gas, and it is often most prominent in the outer parts of the cluster. However, a serious drawback with the old data (either EUVE or Rosat) concerns their spectral resolution, which does not exist for the EUVE DS detector, and is very limited for the Rosat PSPC at low energies where the width of the instrumental broadening causes a significant contamination of the count rate by harder photons.

The forementioned reasons render it very difficult for firm conclusions about the nature of the soft excess emission to be deduced from the original data alone. For example, already in the first papers it was suggested that the emission may have a thermal origin, but is also consistent with it having a power law spectrum caused by Inverse Compton scattering of the cosmic microwave background on cosmic ray electrons (Sarazin & Lieu 1998).

With the launch of XMM-Newton it is now possible to study the soft excess emission with high sensitivity and with much better spectral resolution using the EPIC camera’s of this satellite. The high resolution Reflection Grating...
Spectrometer (RGS) of XMM-Newton has proven to be extremely useful in studies of the central cooling flow region, but due to the very extended nature of the soft excess emission, the RGS is not well suited to study this phenomenon.

2. XMM-Newton observations

XMM-Newton has by now observed a large number of clusters. We investigated the presence of soft excess emission in a sample of 14 clusters of galaxies. This work has been published by Kaastra et al. (2003a). In that paper the details of the data analysis are given. Briefly, much effort was devoted to subtracting properly the time-variable soft proton background, as well as the diffuse X-ray background. We made a carefull assessment of the systematic uncertainties in the remaining background, since a proper background subtraction has been one of the contentious issues in the discussion around the discovery of the soft excess in EUVE and Rosat data. In a similar way, the systematic uncertainties in the effective area and instrumental response of the EPIC camera’s were carefully assessed and quantified. In the spectral fitting procedures, both the systematic uncertainties in the backgrounds and the instrument calibration were taken into account. Spectra were accumulated in 9 concentric annuli between 0 and 15 arcmin from the center of the cluster.

The original sample used by Kaastra et al (2003a) has been extended to 21 clusters using archival data (see also Kaastra et al. 2003c). These additional clusters were analyzed in exactly the same way as the original 14 clusters. The spectra were initially analyzed using a two temperature model for the hot gas, with the second temperature of the component fixed at half that of the first component. From experience with cooling flow analysis (Peterson et al. 2003; Kaastra et al 2003b) we learnt that such a temperature parameterization is sufficient to characterize fully the cooling gas in the cores of clusters, while in the outer regions it is an effective method to take the effects of eventual non-azimuthal variations in the annular spectra into account. We note that the temperature of the coolest "hot gas" component in all cases where we detect a soft excess is much higher than the (effective) temperature of the soft excess. This is due to the now well-known fact that the emission measure distribution of the cooling flow drops off very rapidly. In fact, our models for the cooling flow predict no significant emission from O VII ions in the cooling plasma (at least below the detection limit of XMM-Newton).

The presence of a soft excess in this sample of clusters was tested by formally letting the Galactic absorption column density be a free parameter in the spectral fitting. Of the 21 clusters, 5 have apparent excess absorption. All these 5 clusters are located in regions where dust etc. is important, or they have a very compact core radius such that the temperature gradients in the core
Figure 1. Soft excess in the 0.2–0.3 keV band as compared with a two temperature model (data points with error bars). The solid histogram is the predicted soft excess based upon scaling the sky-averaged XMM-Newton background near the cluster with the relative enhancement of the soft X-ray background derived from the 1/4 keV PSPC images. For the $k$th cluster the values for annulus $j$ are plotted at bin number $10(k - 1) + j$.

are not fully resolved by XMM-Newton and therefore the spectra are highly contaminated.

While the excess absorption in 5 clusters can be fully explained, the absorption deficit in 7 of these clusters cannot be explained by uncertainties in the calibration, background emission or foreground absorption, but only by the presence of an additional emission component. In fact, in several of the clusters the best-fit column density is zero!

In Fig. 1 we show the soft excess in the 0.2–0.3 keV band for the seven clusters with a significant soft component. These clusters are Coma, A 1795, Sersic 159–03, MKW 3s, A 2052 (see also Kaastra et al. 2003a); A 3112 (see also Nevalainen et al. 2003 and Kaastra et al. 2003c) and A 2199 (paper in preparation).

The field of view of XMM-Newton is relatively small (~15 arcmin radius) and therefore all these relatively nearby clusters fill the full field of view. For this reason, only a sky-averaged soft X-ray background (obtained from deep fields) as well as the time variable soft proton background (which is relatively small at low energies) were subtracted from the XMM-Newton data. Using the 1/4 keV Rosat PSPC sky survey data (Snowden et al. 1995), maps at 40 arcmin resolution were produced to estimate the average soft X-ray background in an annulus between 1–2 degrees from the cluster. Most of these seven clusters show an enhanced 1/4 keV count rate in this annulus (as compared to the typical sky-averaged 1/4 keV count rate). This, combined with the decreasing density of the hot gas in the outer parts of the cluster causes the apparent soft
excess with increasing relative brightness at larger radii in Fig. 1. The figure shows complete consistency of the XMM-Newton data with the PSPC 1/4 keV data in this respect for A 1795, Sersic 159–03, MKW 3s, A 2052 and A 2199. We show below that in these clusters this large-scale soft X-ray emission is due to thermal emission from the (super)cluster environment.

However, there is an additional soft component in Coma, A 3112, Sersic 159–03 and perhaps A 1795. The fact that this component is above the prediction from the large scale PSPC structures implies that its spatial extent is at most 10–60 arcmin. We shall return to this component in Sect. 5.

3. Emission from the Warm-Hot Intergalactic Medium

In the previous section we found that five clusters show a soft excess in the 0.2–0.3 keV band at a spatial scale of at least 1–2 degrees, combining our XMM-Newton spectra with PSPC 1/4 keV imaging. It is not obvious a priori whether this excess emission is due to emission from the cluster region or whether it has a different origin, for example galactic foreground emission. Here the spectral resolution of the EPIC camera’s is crucial in deciding which scenario is favoured. In Fig. 2 we show the fit residuals of the fit with two hot components and Galactic absorption only, in the outer 4–12 arcmin region combining all three EPIC camera’s. The fit residuals show two distinct features: a soft excess below 0.4–0.5 keV, and an emission line at \( \sim 0.56 \) keV. This emission line is identified as the O VII triplet, and detailed spectral fitting shows that both phenomena (soft excess and O VII line) can be explained completely by emission from a warm plasma with a temperature of 0.2 keV (see Kaasstra et al. 2003a for more details). Thus, the soft excess has a thermal origin. Moreover, the centroid of the O VII triplet (which is unresolved) agrees better with an origin at the redshift of the cluster than with redshift zero. This clearly shows that the thermal emission has an origin in or near the cluster, although a partial contribution from Galactic foreground emission cannot be excluded in all cases. We also note that in A 1795 and A 2199 the O VII line is relatively weak and needs more confirmation.

Taking this additional soft thermal component into account in the spectral fitting yields fully acceptable fits. In fact, in the energy band below 1 keV, the soft component contributes 20–40 % of the X-ray flux of the outer (4–12 arcmin) part of the cluster.

We identify this component as emission from the Warm-Hot Intergalactic Medium (WHIM). Numerical models (for example Cen & Ostriker 1999, Fang et al. 2002) show that bright clusters of galaxies are connected by filaments that contain a significant fraction of all baryonic matter. Gas falls in towards the clusters along these filaments, and is shocked and heated during its accretion onto the cluster. Near the outer parts of the clusters the gas reaches its highest
Figure 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 restframe is indicated by a solid line and in our Galaxy’s rest frame by a dashed line at 0.569 keV (21.80 Å). The fit residuals for all instruments (MOS, pn) are combined. The instrumental resolution at 0.5 keV is $\sim$60 eV (FWHM).
temperature and density, and it is here that we expect to see most of the X-ray emission of the warm gas.

4. Properties of the warm gas

The temperature of the warm gas that we find for all our clusters is 0.2 keV. The surface brightness of the warm gas within the field of view of the XMM-Newton telescopes is approximately constant, with only a slight enhancement towards the center for some clusters (a stronger increase towards the center for Sersic 159−03 is discussed in the next section). In Table 1 we list the central surface brightness $S_0$ as estimated from our XMM-Newton data, expressed as the emission measure per solid angle. We use $H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$ throughout this paper. Using the known angular distance to the cluster we estimate the same quantity in units of $\text{m}^{-5}$ (see also Table 1). We then use a simplified model for the geometry of the emitting warm gas, namely a homogeneous sphere with uniform density. The radius $R$ of this sphere is estimated from the radial profile of the Rosat PSPC 1/4 keV profile around the cluster, and is also listed in Table 1. We find typical radii of 2–6 Mpc, i.e. the emission occurs on the spatial scale of a supercluster. From this radius and the emission measure, the central hydrogen density $n_H(0)$ is estimated. We find typical densities of the order of 50-150 m$^{-3}$. Assuming a different density profile (for example $n(r) = n(0)[1 + (r/a)^2]^{-1}$ for $r < R$ and $n = 0$ for $r > R$) yields central densities that are only 20–50 % larger. These densities are 200–600 times the average baryon density of the universe. We also estimate the total hydrogen column density, which is typically $1.6 - 2.8 \times 10^{25}$ m$^{-2}$. Using then the measured oxygen abundances from our XMM-Newton data (essentially determined by the ratio of the O VII triplet to the soft X-ray excess), which are typically 0.1 times solar, we then derive total O VII column densities of the order of $0.4 - 0.9 \times 10^{21}$ m$^{-2}$. These column densities and the typical sizes of the emitting regions are similar to those as calculated for the brightest regions in the simulations of Fang et al. (2002). We have taken here a solar oxygen abundance of $8.5 \times 10^{-4}$ and an O VII fraction of 32 %, corresponding to a plasma with a temperature of 0.2 keV.

Finally, we determined the total mass of the warm gas ($M_w$, Table 1). This mass is for most clusters comparable to the total cluster mass $M_A$ within the Abell radius (2.1 Mpc for our choice of $H_0$) as derived by Reiprich & Böhringer (2002) for the same clusters.

We make here a remark on MKW 3s and A 2052. These clusters are separated by only 1.4 degree and both belong to the southernmost extension of the Hercules supercluster (Einasto et al. 2001). A 2199, at 35 degrees to the North, is at the northernmost end of the same supercluster. The redshift distribution of the individual galaxies in the region surrounding MKW 3s ($z = 0.046$) and
A 2052 \((z = 0.036)\) shows two broad peaks centered around the redshifts of these clusters, but galaxies with both redshifts are found near both clusters. Therefore this region has a significant depth (43 Mpc) as compared to the projected angular separation (4.3 Mpc). The relative brightness of the warm gas near these clusters (as seen for example from the value of \(S_0\)) is then explained naturally if there is a filament connecting both clusters. In that case we would see the filament almost along its major axis.

5. **Non-thermal emission?**

Apart from the large scale, extended emission from the warm gas some clusters also exhibit a centrally condensed soft excess component (Fig. 3). In MKW 3s, A 2052 and A 2199 this central enhancement is relatively weak. It could be a natural effect of the enhanced filament density close to the cluster centers. In A 1795 and Sersic 159–03 the enhancement is much larger. It is unlikely that this emission component for the latter two clusters also originates from projected filaments in the line of sight - the high surface brightness would necessitate filaments of length far larger than a cluster’s dimension. Another possibility is warm gas within the cluster itself. In order to avoid the rapid cooling which results from this gas assuming a density sufficient to secure pressure equilibrium with the hot virialized intracluster medium, it should be magnetically isolated from the hot gas. Yet another viable model for the central soft component is non-thermal emission. We note that the soft excess in the center of Coma and A 3112 also possibly has a non-thermal origin, as there is no clear evidence for oxygen line emission in their spectra. Clearly, deeper spectra and in particular a higher spectral resolution is needed to discriminate
Figure 3. Emission measure integrated along the line of sight for five clusters of galaxies.

models. At this conference, several new mission concepts have been presented that may resolve these issues in the near future.

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). SRON is supported financially by NWO, the Netherlands Organization for Scientific Research.

References

Cen, R., & Ostriker, J.P. 1999, ApJ, 514, 1
Einasto, M., Einasto, J., Tago, E., Muller, V., & Andernach, H. 2001, AJ, 122, 2222
Fang, T., Bryan, G.L., & Canizares, C.R., 2002, ApJ, 564, 604
Kaastra, J.S., Lieu, R., Tamura, T., Paerels, F. B. S., & den Herder, J. W., 2003a, A&A, 397, 445
Kaastra, J.S., Tamura, T., Peterson, J.R., et al., 2003b, A&A, submitted
Kaastra, J. S., Lieu, R., Tamura, T., Paerels, F. B. S., & den Herder, J. W., 2003c, Adv. Sp. Res., in press
Lieu, R., Mittaz, J.P.D., Bowyer, S., et al. 1996a, ApJ, 458, L5
Lieu, R., Mittaz, J.P.D., Bowyer, S., et al. 1996b, Science 274, 1335
Nevalainen, J., Lieu, R., Bonamente, M., & Lumb, D., 2003, ApJ, 584, 716
Peterson, J.R., Kahn, S.M., Paerels, F.B.S., et al., 2003, ApJ, in press
Reiprich, T.H., & Bohringer, H., 2002, ApJ, 567, 716
Sarazin, C.L., & Lieu, R., 1998, ApJ, 494, L177
Snowden, S.L., Freyberg, M.J., Plucinsky, P.P., et al., 1995, ApJ, 454, 643