Part 2

FORMATION AND EVOLUTION OF GALAXY CLUSTERS

Section A

Diffuse baryons

Outskirts of Galaxy Clusters: Intense Life in the Suburbs
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The warm-hot intergalactic medium

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Abstract. The warm-hot intergalactic medium contains a major part of all baryons in the universe. Despite this, it is very hard to observe in X-rays due to its relatively low temperature and the poor spectral resolution of most instruments. The high sensitivity and good spectral resolution of XMM-Newton allowed for the first time to show the presence of the warm-hot intergalactic medium in the outskirts of several nearby clusters of galaxies. In this contribution these results are presented. The physical state of the gas such as temperature, density, mass and chemical composition are discussed.

1. Introduction

Recent observational studies (e.g. using WMAP, Spergel et al. 2003) have brought us in the era of high accuracy cosmology. It has become now clear 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 (Rauch et al. 1998; Weinberg et al. 1997). 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) finds only $\Omega = 0.0124$ (Fukugita et al. 1998), to be compared to the total baryon density $\Omega_b = 0.044$. Even accounting for the local Lyα forest (29% of all baryons, see the contribution by Stocke in these proceedings), these findings imply that currently we do not see a major fraction of all baryons.

Theoretical and numerical work (for example Cen & Ostriker 1999) has predicted 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 towards these clusters. They dubbed this component the Warm-Hot Intergalactic Medium (WHIM). Due to its low temperature and low density, it is difficult to observe in X-ray emission; observing it by means of absorption line studies requires high spectral resolution and sensitivity as well as bright background sources. In this paper I summarize the main results from observational studies of the WHIM using both emission and absorption techniques.

2. Emission (line) studies

2.1. *Cluster soft excess emission*

For a long time the hard X-ray spectra of clusters of galaxies have been modeled successfully with a thermal plasma emission model. The hot gas (10^7–10^8 K) is in hydrostatic equilibrium in the deep cluster potential well. It constitutes the major part of the baryonic mass contents of clusters (only the dark matter contribution is larger). With the advent of more sensitive low energy X-ray instrumentation (ROSAT PSPC, EUVE DS detector) it was found that some clusters contained soft excess emission above the predicted hard X-ray emission from the cluster (Virgo, Lieu et al. 1996a; Coma, Lieu et al.

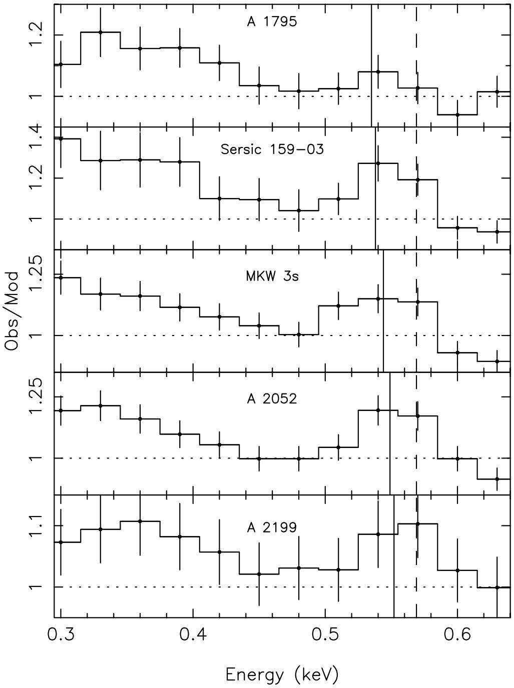

Figure 1. Fit residuals with respect to a two temperature model for the outer 4–12 arcmin part of six clusters. The position of the O VII triplet in the cluster restframe is indicated by a solid line and in our Galaxy's rest frame by a dashed line at 0.569 keV (21.80 Å). The instrumental resolution at 0.5 keV is ∼60 eV (FWHM).

1996b). Later a few other cases were found using either EUVE, ROSAT or BeppoSAX (see for instance Durret et al. 2002 for more references). Several different interpretations have been given, for example thermal emission from warm plasma (Lieu et al. 1996a, 1996b; Fabian 1997), or nonthermal emission, for instance inverse-Compton scattering between the cosmic microwave background (CMB) and intracluster relativistic electrons (Hwang 1997; Ensslin & Biermann 1998; Sarazin & Lieu 1998).

There has been a long debate in the literature and on conferences on this work, arguing about issues like proper background subtraction, modeling of the hot gas distribution, the physical implications etc. This is due to the fact that at the relevant low energies the above mentioned instruments have almost no spectral resolution, and calibration at these energies has always been a difficult task. The reality of the soft excess has been demonstrated recently, however, using the large sensitivity and moderate spectral resolution of XMM-Newton.

2.2. *XMM-Newton observations*

Using previous instrumentation, it was hard or impossible to demonstrate that the soft excess found in clusters has a thermal origin, due to the lack of spectral resolution. At the expected temperatures of the WHIM, the soft X-ray emission of a warm plasma is dominated by line radiation. A particular strong line blend is the O VII triplet near 22 Å (0.57 keV). This triplet is well isolated from other lines using CCD spectral resolution and is rather strong, since oxygen is the most abundant metal.

Table 1. XMM-Newton detection of the WHIM

Cluster	A 1795	Sérsic 159−03	MKW 3s	A 2052	A 2199
L_X [a]	4.7	0.78	0.83	0.71	1.5
Redshift	0.064	0.057	0.046	0.036	0.030
R (arcmin)	80	60	60	80	60
R (Mpc)	5.7	3.8	3.1	3.3	2.1
$n_{\mathrm{H}}(0)$ [b]	45	80	120	140	120
$N_{\mathrm{H}}(0)$ [c]	16	19	23	28	16
kT (keV) [d]	0.200±0.008	0.180±0.006	0.230±0.012	0.208±0.007	0.195±0.013
Abundance O	0.08±0.05	0.08±0.03	0.09±0.03	0.12±0.03	0.16±0.05
$N_{\mathrm{O}\,VII}(0)$ [e]	4	4	6	9	7
I_{triplet} [f]	1.3	2.8	3.4	7.7	7.1

[a] 2–10 keV luminosity of the cluster, in 10^{37} W (10^{44} erg s^{-1}), taken from David et al. (1993).

[b] Hydrogen density (assuming constant density sphere with radius R), in units of m^{-3} (10^{-6} cm^{-3}).

[c] Hydrogen column density through the core in units of 10^{24} m^{-2} (10^{20} cm^{-2}).

[d] Temperature of the WHIM component.

[e] O VII column density through the core in units of 10^{20} m^{-2} (10^{16} cm^{-2}).

[f] Total intensity of the O VII triplet (r+f+i line combined), in units of photons cm^{-2} s^{-1} sr^{-1}.

We have performed an extensive study of the presence of soft excess emission in a large sample of clusters using XMM-Newton data. Here we summarize the results of our work. A full account and details about the analysis are given in Kaastra et al. (2003a) for a sample of 14 clusters. This sample was extended to 20 clusters in Kaastra et al. (2003b), and the cluster A 2199 was added in Kaastra et al. (2004a). Our Table 1 is adapted from the last paper. In 7 out of 21 clusters there is evidence for a soft X-ray excess, in 5 of them there are signatures of a WHIM origin (the presence of O VII line emission plus the corresponding soft excess, Fig. 1), while in the remaining two (Coma, A 3112) the soft excess may have a non-thermal origin. The presence of soft excess in these last two clusters as well as in A 1795 was confirmed using a different analysis by Nevalainen et al. (2003).

The spatial extent of the soft excess emission is of the order of 1 degree in radius for these clusters (2–6 Mpc). The surface brightness drops only slowly toward the outer regions of the structure. In our study of Coma mentioned above we focussed on the central part. An extensive study of the outer parts was performed by Finoguenov et al. (2003). They found evidence for extended soft X-ray emission ($kT = 0.2$ keV), from plasma with 0.1 times solar metallicity, from a filamentary structure with a width of 3 Mpc and length 20 Mpc, seen in front of Coma (distance 90 Mpc). The presence of this filament is also evident from the redshift and spatial distribution of galaxies near Coma.

Stimulated by these findings, other studies using archival ROSAT PSPC data have been performed. Bonamente et al. (2002) did a statistical study of 38 clusters observed with ROSAT. Excess soft X-ray radiation, above the contribution from the hot intracluster medium, is evident in a large fraction of sources and is clearly detected with large statistical significance in the deepest observations. Zappacosta et al. (2004) studied archival PSPC data in the region around the Sculptor supercluster, and found a clear correlation between the 1/4 keV flux and the galaxy distribution, with indications for diffuse, filamentary structures sometimes connecting the known clusters of Sculptor.

3. Absorption line studies

3.1. *The Local Group ($z = 0$)*

X-ray absorption lines towards bright background sources have been reported now for several sources. A Chandra LETGS observation of PKS 2155-304 (Nicastro et al. 2002) showed unresolved O VII, O VIII and Ne IX lines (FWHM<800 km s^{-1}). Contrary, a FUSE observation showed O VI absorption consisting of a narrow (FWHM=100 km s^{-1}) and broader (FWHM=160 km s^{-1}) component. Nicastro et al. argue that the broad UV component as well as the X-ray component originate from low-density intergalactic plasma collapsing toward our Galaxy, consistent with the predictions of a warm-hot intergalactic medium from numerical simulations. The structure has a density of 6×10^6 cm^{-3}, overdensity δ of 60, temperature of 0.5 MK and ~3 Mpc size.

In several other Seyfert 1 galaxies and quasars, in particular the ones at higher redshift, it is now easy to see the $z = 0$ absorption component in long exposed grating spectra (3C 273, Fang et al. 2003; NGC 5548, Steenbrugge et al. 2003; NGC 4593, McKernan et al. 2003a). In other cases it is not clear if absorption is due to the WHIM or due to an ionized outflow of the background source, for example 3C 120 (McKernan et al. 2003b).

The number of lines of sight studied in X-rays up to now is very limited, due to the limited spectral resolution and sensitivity of the current X-ray spectrometers (but see Sect. 4). Using FUSE, Savage et al. (2003) studied 100 lines of sight in O VI (λ1032, λ1038 Å) absorption. Similar results using halo stars were obtained by Zsargó et al. (2003). However, with data from a single ion only it is hard to distinguish nearby absorption (Galactic halo) from distant absorption (Local Group). For example, Nicastro et al. (2003) argue, based upon the spatial distribution of high-velocity O VI absorbers, that this component originates from the Local Group and not the Galactic halo.

3.2. *Low redshift ($z > 0$) absorbers*

Absorption lines from $z > 0$ gas have now been found in FUSE spectra of a few bright quasars using O VI lines (H 1821+643 Tripp et al. 2000, Oegerle et al. 2000; PG 0353+415, Savage et al. 2002; PHL 1811, Jenkins et al. 2003). In the X-ray band, the results sofar have not been very convincing.

Fang et al. (2002) report the 4.5σ detection of O VIII Lyα absorption at $z = 0.055$ toward PKS 2155-304, utilizing a Chandra LETG/ACIS observation. Since there is also a small group of spiral galaxies at the same redshift, Fang et al. identified this with the first X-ray detection of O VIII from the WHIM.

However, these results have not been confirmed in both XMM-Newton RGS spectra with much longer exposure time and sensitivity (Paerels et al. 2003, Cagnoni et al. 2003), neither in a long observation using the LETG/HRC-S configuration.

Mathur et al. (2003) claim the detection of O VII and O VIII X-ray absorption lines at the redshifts of 6 intervening UV absorption systems (in particular at $z = 0.12$ and $z = 0.24$) toward the quasar H 1821+643 in a 500 ks Chandra observation. However, the significance of these detections is rather low and should best be regarded as upper limits until more sensitive data become available.

An exception to this lack of significance is the recent discovery of absorbers at $z = 0.011$ and $z = 0.027$ toward Mrk 421 (see Nicastro, these proceedings).

4. New X-ray instrumentation

The problem with detecting the WHIM in X-ray emission is its weakness in the filaments between the clusters. This is due to the fact that the X-ray emission scales with n^2

and the density is low ($< 10\ \mathrm{m}^{-3}$). Moreover, this emission is seen against the extragalactic background and a strong Galactic X-ray foreground. In particular the spectrum of the foreground is due to plasma at the same temperatures as the WHIM and therefore with similar spectra. As we showed in Sect. 2, with the present day CCD spectral resolution it is possible but non-trivial to disentangle foreground from (super)cluster emission near the brightest parts of the WHIM, where it connects to the clusters. Going beyond this requires high spectral resolution, high sensitivity and large field of view.

This last instrumental property (large field of view) is not present in the currently planned high resolution imaging X-ray missions (Astro-E2, Constellation-X, XEUS). These instruments will be able to investigate the properties of the WHIM both using absorption and emission studies, but only in "pencil-beam" regions of the sky. Good overviews of the capabilities of XEUS, the most powerfull of these instruments, are given by Paerels et al. (2003), Barcons (2003), and Kaastra & Paerels (2004b).

In order to map the WHIM, wide-field imaging is needed. Currently there is a Japanese proposal for such a mission, named DIOS (Yoshikawa et al. 2003; see also Suto et al. 2004). A similar proposal with smaller grasp (MBE, see Fang et al. 2004) was not awarded funding by NASA in 2003. Also our group is currently studying a concept for such a WHIM mission (Den Herder et al. 2004). More details will be given in that paper.

5. Conclusions

The presence of X-ray emission from the WHIM is now well established using XMM-Newton observations near bright clusters of galaxies. For the WHIM component in the filaments between the clusters, we currently rely upon a few UV and X-ray absorption measurements. In the coming years this situation is expected to improve, due to the launch of more sensitive X-ray observatories as well as dedicated WHIM missions.

References

Barcons, X. 2003 *MPE Report* **281**, 77

Bonamente, M., Lieu, R., Joy, M.K., & Nevalainen, J. 2002 *ApJ*, **576**, 688

Cagnoni, I., Nicastro, F., Maraschi, L., Treves, A., & Tavecchio, F. 2003 *New Astr. Rev.*, **47**, 561

Cen, R., & Ostriker, J.P. 1999 *ApJ*, **514**, 1

David, L.P., Slyz, A., Jones, C., Forman, W., Vrtilek, S.D., & Arnaud, K.A. 1993 *ApJ*, **412**, 479

Den Herder, J.W.A., Paerels, F.B.S., Kaastra, J.S., et al. 2004 *Proc. SPIE*, submitted

Durret, F., Slezak, E., Lieu, R., Dos Santos, S., & Bonamente, M. 2002 *A&A*, **390**, 397

Ensslin, T. A., & Biermann, P. L. 1998 *A&A*, **330**, 90

Fabian, A. C. 1997 *Science*, **275**, 48

Fang, T., Marshall, H.L., Lee, J.C., Davis, D.S., & Canizares, C.R. 2002 *ApJ*, **572**, L127

Fang, T., Sembach, K.R., & Canizares, C.R. 2003 *ApJ*, **586**, L49

Fang, T., Croft, R.A.C., Sanders, W.T., et al. 2004 *ApJ*, submitted (astro-ph/0311141)

Finoguenov, A., Briel, U.G. & Henry, J.P. 2003 *A&A*, **410**, 777

Fukugita, M., Hogan, C., & Peebles, P.J.E. 1998 *ApJ*, **503**, 518

Hwang, C.-Y. 1997 *Science*, **275**, 48

Jenkins, E.B., Bowen, D.V., Tripp, T.M., et al. 2003 *AJ*, **125**, 2824

Kaastra, J.S., Lieu, R., Tamura, T., Paerels, F.B.S., & den Herder, J.W.A., 2003a, *A&A*, **397**, 445

Kaastra, J.S., Lieu, R., Tamura, T., Paerels, F.B.S., & den Herder, J.W.A., 2003b, *Adv. Space Research*, in press.

Kaastra, J.S., Lieu, R., Tamura, T., Paerels, F.B.S., & den Herder, J.W.A. 2004a In *Soft X-ray emission from clusters of galaxies and related phenomena*, (ed. R. Lieu), Kluwer, in press (astro-ph/0305424)

Kaastra, J.S., & Paerels, F.B.S. 2004a In *Soft X-ray emission from clusters of galaxies and related phenomena*, (ed. R. Lieu), Kluwer, in press

Lieu, R., Mittaz, J.P.D., Bowyer, S. 1996a *ApJ*, **458**, L5

Lieu, R., Mittaz, J.P.D., Bowyer, S. 1996b *Science*, **274**, 1335

Mathur, S., Weinberg, D.H., & Chen, X. 2003 *ApJ*, **582**, 82

McKernan, B., Yaqoob, T., George, I.M., & Turner, T.J. 2003a *ApJ*, **593**, 142

McKernan, B., Yaqoob, T., Mushotzky, R., George, I.M., & Turner, T.J. 2003b *ApJ* **598**, L83

Nevalainen, J., Lieu, R., Bonamente, M., & Lumb, D. 2003 *ApJ*, **584**, 716

Nicastro, F., Zezas, A., Drake, J., et al. 2002 *ApJ*, **573**, 157

Nicastro, F., Zezas, A., Elvis, M., et al. 2003 *Nature*, **421**, 719

Oegerle, W.R., Tripp, T.M., Sembach, K.R., et al. 2000 *ApJ*, **538**, L23

Paerels, F.B.S., Rasmussen, A., Kahn, S., den Herder, J.W., de Vries, C.P. 2003 *MPE Report* **281**, 57

Rauch, M. 1998 *ARA&A*, **36**, 267

Sarazin, C. L., & Lieu, R. 1998 *ApJ*, **494**, L177

Savage, B.D., Sembach, K.R., Tripp, T.M., & Richter, P. 2002 *ApJ*, **564**, 631

Savage, B.D., Sembach, K.R., Wakker, B.P., et al. 2003 *ApJS*, **146**, 125

Spergel, D.N., Verde, L., Peiris, H.V., et al. 2003 *ApJS*, **148**, 175

Steenbrugge, K.C., Kaastra, J.S., de Vries, C.P., & Edelson, R. 2003 *A&A*, **402**, 477

Suto, Y., Yoshikawa, K., Yamasaki, N.Y., et al. 2004 In *proc. VI International Conference on Gravitation and Astrophysics of Asian-Pacfic Countries* (astro-ph/0402389)

Tripp, T.M., Savage, B.D., & Jenkins, E.B. 2000 *ApJ*, **534**, L1

Yoshikawa, K., Yamasaki, N.Y., Suto, Y., et al. 2003 *PASJ*,**55**, 879

Weinberg, D.H., Miralda-Escude, J., Hernquist, L., & Katz, N. 1997 *ApJ*, **490**, 564

Zappacosta, L., Maiolino, R., Mannucci, F., Gilli, R., & Schuecker, P. 2004 *MNRAS*, submitted (astro-ph/0402575)

Zsargó, J., Sembach, K.R., Howk, J.C., & Savage, B.D. 2003 *ApJ*, **586**, 1019