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X-RAYING LARGE-SCALE STRUCTURE

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ABSTRACT

We review the observational evidence for the existence of a warm-hot intergalactic medium (WHIM). We expect that the morphology of this material is similar to that of cosmic rays and magnetic fields in large-scale structure, *i.e.,* filaments connecting clusters of galaxies. Direct evidence for the WHIM, either in emission or absorption, is weak.

Key words : cosmology: large scale structure – intergalactic medium

I. INTRODUCTION

The topic of this conferecne is cosmic rays and magnetic fields in large-scale structure. Numerical simulations (*e.g.,* Ryu *et al.* 2003) show that the morphology of the regions with these fields are filamentary with the filaments centered on clusters of galaxies. The topic of this paper is warm baryons. Numerical simulations (*e.g.,* Davé *et al.* 2001) show that the morphology of these baryons is similar to the nonthermal material. The reason for the simularity is, of course, because both are responding to the underlying and gravitationally dominant dark matter. So by studying one, we can learn something about the other.

The simulations indicated that the properties of the baryons distributed over large scales are: temperature of $10^5 - 10^7$ K, corresponding to kT = 8.6 - 860 eV, and overdensity with respect to the mean density of the universe of $10 - 10^4$. Such material has been dubbed the Warm-Hot Intergalactic Medium or WHIM. About 35% of all baryons at z = 0 are thought to be in this state.

The WHIM may simultaneously solve two problems in astrophysics: Where are the local baryons seen already at high redshift? Why do clusters not obey classical scaling relations? (Evrard & Henry, 1991; Kaiser, 1991).

II. SEARCH FOR THE WHIM

The WHIM is a key component for the evolution of baryons in the universe. Up until now it has been mainly a theoretical concept. Is there any evidence that it exists?

The dominant ions produced by collisions in the WHIM containing elements with abundances at the cosmic ratios are expected to be OVII (574 eV), OVIII (654 ev) and NeIX (923 eV) (Peterson, 2004), where the energies are the resonance transitions of each ion. Thus searches for the WHIM often concentrate on searches for emission or absorption of photons at these soft X-ray energies.

(a) Absorption against Random Bright AGN

The advent of grating spectrometers onboard the Chandra and XMM-Newton X-ray observatories has enabled these searches and many have been made. Theoretical calculations show that these measurements are at the limits of current sensitivities with only a few percent of random sight lines producing detectable absorption with 100 ks Chandra exposures (Kravtsov, Klypin, & Hoffman 2002). Actual data fully support that conclusion! Some of the more recent results are contained in the following papers: Nicastro *et al.* (2002); Kaspi *et al.* (2002); Rasmussen, Kahn, & Paerels (2003); Fang, Sembach, & Canizares (2003); Mathur, Weinberg, & Chen (2003); McKernan *et al.* (2003a); McKernan *et al.* (2003b); Cagnoni *et al.* (2004).

Absorption at z = 0 is detected against five AGNs. The measured equivalent widths are 0.4 - 0.7 eV (for OVII corresponding to a column density of $0.5 - 2.5 \times 10^{16}$ cm^{-2} for b = 200 - 420 km s^{-2}), 0.1 - 0.4 eV (for OVIII), and 0.0 - 0.2 eV (for NeIX).

Since the absorption redshift is zero (or occasionally that of the background AGN), are these detections really of the WHIM or some material in our galaxy or the galaxy hosting the AGN? In additions to these two explanations, absorption by material in the Local Group has also been proposed. We know that there is more than sufficient material in the Milky Way to do the absorbing. Futomoto *et al.* (2004) have detected absorption against the source 4U1820-303 in the globular cluster NGC 6624 at 7.6 ± 0.4 kpc. The measured equivalent widths are 1.19 ± 0.24 eV (for OVII corresponding to a column density of $3.5 \pm 1.9 \times 10^{16}$ cm^{-2} for b = 200 - 420 km s^{-2}), 0.54 ± 0.15 eV (for OVIII), and 0.50 ± 0.13 eV (for NeIX). At least some and maybe all of the purported WHIM signal comes from the Milky Way.

The only way to be sure the signal is from the WHIM is to detect absorption neither at z = 0 nor at the z of the background AGN. Nicastro (2003) had the good

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idea to wait until one of the bright AGN became even brighter in an outburst. OVII at z = 0.0116 was detected in a 200 ks Chandra LETG exposure against Mkn 421 in outburst. The measured equivalent width is 0.08 ± 0.02 eV (corresponding to a column density of $0.12 \pm 0.03 \times 10^{16}$ cm^{-2} independent of b).

We may summarize this section as there is now at least one sight line that exhibits absorption of an ion appropriate to the WHIM, which is located at a redshift different from zero and the redshift of the background AGN.

(b) Emission near Galaxy Clusters

Searching for emission from the WHIM near galaxy clusters has two advantages. First we expect the WHIM to be the densest, hence produce the strongest signal, at these positions. Second the filament containing the WHIM may point at us, *i.e.,* the sight line is not random. Yasuda, Fukugita, & Okamura (1997) have shown that the Virgo cluster itself has such a geometry. Of course the measrured WHIM properties may not then be representative. Yoshikawa *et al.* (2004) show that the WHIM material will have a velocity width comparable to the virial velocity of its cluster.

Over the past decade there have been many attempts to image WHIM material using the ROSAT, ASCA, Beppo-SAX, and EUVE satellites. Some papers describing this work are: Briel & Henry (1995); Wang, Connolly, & Brunner (1997); Kull & Böhringer (1999); Scharf *et al.* (2000); Berghöfer, Bowyer, & Korpela (2000); Tittley & Henriksen (2001); Zappacosta *et al.* (2002, 2004); Soltan, Freyberg, & Hasinger (2002); Bonamente *et al.* (2002, 2003); and Bowyer *et al.* (2004). Most of these results were reports of detections at specific locations with various levels of believability. Briel & Henry (1995) gave an upper limit on the overdensity from stacked emission between clusters of $\delta < 375$, assuming a rather hot temperature of 1000 eV.

The EPIC detector on XMM-Newton is a big improvement on the above work, since it has good spectral resolution, no scattered light, and large collecting area. It is possible to search for the OVII, OVIII and NeIX emission lines with this instrument. These lines are the unambiguous signature of warm gas. Kaastra *et al.* (2003), Finoguenov, Briel & Henry (2003), and Fujimoto *et al.* (2004) report this type of observation.

OVII and OVIII mission lines are clearly detected against five clusters (Virgo, Coma, Ser 159-03, MKW 3s, and A2052), showing that warm gas is present somewhere along the line of sight. In three cases (Ser 159-03, MKW 3s, and A2052) the redshift of the lines is nonzero and agrees with that of the cluster assuming the lines are collisionally excited. ASTRO-E2, with its greatly increased spectral resolution for diffuse objects, can make a major contribution in this area.

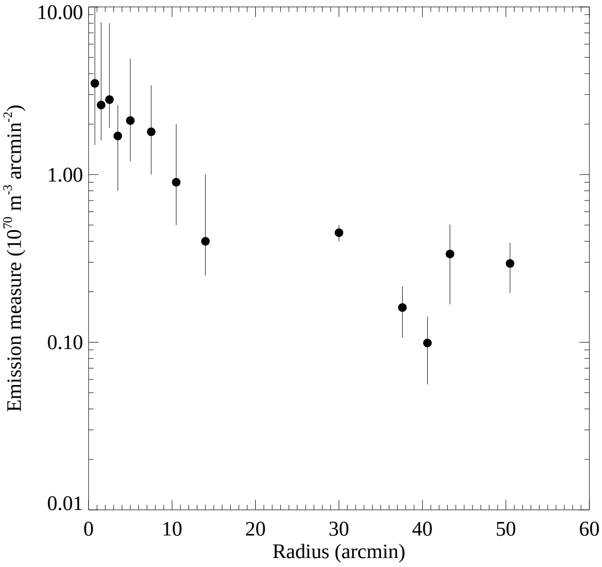

Fig. 1.— Emission measure per solid angle of the warm component against the Coma cluster as a function of angle from the bright Coma galaxy NGC 4874. The inner eight points are from Kaastra *et al.* 2003 while the outer five points are from Finoguenov *et al.* 2003. Both data sets seem to describe emission from a single component that decreases with radius.

The intensity of the lines is model dependent with many model components, primarily because the known local warm gas producing the soft X-ray background has properties similar to the WHIM, which makes it difficult to subtract it off. All three of the above papers utilize the "unlimited field of view" of the ROSAT All-Sky Survey (RASS) to assess the amount of soft X-ray background near their objects. The comparison of models for the EPIC data with actual RASS data shows good agreement with no adjustable parameters. We have compared the Finoguenov *et al.* (2003) model of the Milky Way emission with actual measurements by McCammon *et al.* (2002). In units of ph cm^{-2} s^{-1} sr^{-1}, the model and observed line intensities for OVII and OVIII are 5.6 ± 1.0, 4.8 ± 0.8 and 1.8 ± 0.2, 1.6 ± 0.4, respectively. The agreement is excellent.

The Coma cluster was observed both near the center (Kaastra *et al.* 2003) and on its outskirts (Finoguenov *et al.* 2003). Fig. 1 shows the relation of these two data sets. A single component with emission measure decreasing from the center appears consistent with all data.

(c) Absorption against AGN behind Galaxy Clusters

This techniques has all the advantages and disadvantages as searching for emission near galaxy clusters. It has one additional disadvantage: there must be a relatively bright source, *i.e.,* an AGN, behind a galaxy cluster. Generally there are no such AGNs or if one is there it is not so bright. But the technique has one additional advantage: widths that are expected to be comparable to the cluster velocity dispersion should be easily resolved with the current grating spectrometers.

To date there have been two observations of this type: against LBQS 1228+1116 (z = 0.237) for the Virgo cluster (Fujimoto *et al.* 2004) and against X Comae (z = 0.09) for the Coma cluster (Takei *et al.* 2004), both using the XMM-Newton RGS. Both observations did not receive their requested exposure due to time lost to background flares.

In Virgo, OVII absorption is not detected while OVIII absorption is detected at the 2.1σ level. The redshift of the line is cz = 1253^{+881}_{-369} km s^{-1} consistent with the Virgo cluster redshift of 1307 km s^{-1}. The column density is $6.2^{+3.3}_{-4.4} \times 10^{16}$ cm^{-2}.

Krolik & Raymond (1988) and Sarazin (1989) noted that observations of both emission and absorption from the same line may be combned to yield the density n_e and path length L of the emitting material. This result is because the absorption is proportional to n_eL while emission is proportional to n_e^2L. Both emission and absorption lines from OVIII are now seen toward the Virgo cluster. Taking the absorption measurement as an upper limit gives L$\geq$ 9 Mpc and $n_e \leq 6 \times 10^{-5}$ cm^{-3}, that is a low density filament.

Our analysis of the Coma RGS data is ongoing. OVII and NeIX absorption are detected at the $2-3\sigma$ level. The widths of both lines are about twice the Coma cluster velocity dispersion, centered on the Coma systemic velocity.

We summarize this section as these measurements are difficult because the background AGNs are not among the brightest. Consequently, without additional exposure, the results are only marginally significant. It therefore seems prudent not to overinterpret them.

III. SUMMARY — HAVE WE DETECTED THE WHIM?

The short answer is probably, although there are large systematic and statistical errors. One absorption line from an ion expected to be present in the WHIM and not associated with either local or source material has been seen. Definite emisson lines from appropriate ions toward clusters of galaxies have been seen, but the fraction of their emission from local material is model dependent. The redshifts of the emission is consistent with the parent cluster in three cases. Finally, possible WHIM absorption lines at the redshifts of two different clusters, which also have emission lines from the same ions, have been seen in the spectra of AGN background to the clusters.

Prospects of characterizing the WHIM with current X-ray instrumentation are unfortunately small. The current sensitivities are just too poor to permit more than only a few firm detections. This situation should be contrasted with the wide range of expected WHIM properties. These likely run from dense collisionally ionized to tenuous photoionized plasmas coupled with inhomogeneous metal abundances and very long equilibration times. There will probably be more free parameters than observables for the forseeable future.

However all is not lost. It should be possible to show unequivocally that the WHIM is more than a theoretical construct. We seem to be well along towards that goal.

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