A DIFFERENTIAL X-RAY GUNN-PETERTON TEST USING A GIANT CLUSTER FILAMENT

MAXIM MARKEVITCH
Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138; maxim@head-cfa.harvard.edu

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ABSTRACT

Using CCD detectors onboard the forthcoming X-ray observatories Chandra and XMM, it is possible to devise a measurement of the absolute density of heavy elements in the hypothetical warm gas filling intercluster space. This gas may be the largest reservoir of baryonic matter in the Universe, but even its existence has not been proven observationally at low redshifts. The proposed measurement would make use of a unique filament of galaxy clusters spanning over $700 h_{100}^{-1} \text{ Mpc}$ ($0.1 < z < 0.2$) along the line of sight in a small area of the sky in Aquarius. The surface density of Abell clusters there is more than 6 times the sky average. It is likely that the intercluster matter column density is enhanced by a similar factor, making its detection feasible under certain optimistic assumptions about its density and elemental abundances. One can compare photoabsorption depth, mostly in the partially ionized oxygen edges, in the spectra of clusters at different distances along the filament, looking for a systematic increase of depth with the distance. The absorption can be measured by the same detector and through the same Galactic column, hence the differential test. A CCD moderate energy resolution ($\Delta E \sim 100$ eV) is adequate for detecting an absorption edge at a known redshift.

Subject headings: cosmology: observations — intergalactic medium

1. INTRODUCTION

Simulations suggest that at present, most of the baryons in the Universe should reside in the diffuse medium filling intergalactic space (e.g., Miralda-Escudé et al. 1996; Cen & Ostriker 1999a). Indeed, the observed baryonic matter in low-redshift galaxies and clusters is only a fraction of the amount predicted by Big Bang nucleosynthesis (Persic & Salucci 1992; Fukugita, Hogan, & Peebles 1998). Observationally, however, little is known about intergalactic medium (IGM) outside the relatively small confines of galaxy clusters where it is sufficiently hot to emit detectable radiation. UV and optical studies show that intercluster hydrogen is almost completely ionized and therefore practically undetectable (Gunn & Peterson 1965), with only a small fraction of it residing in Ly$\alpha$ forest clouds (e.g., Rauch et al. 1997; Giallongo, Fontana, & Madau 1997). IGM may be enriched with heavy elements that originate in supernovae and are transported to IGM by supernova-generated winds (e.g., De Young 1978). The amount of heavy elements in the IGM carries important information on the cumulative number of supernova explosions integrated over time, which is inaccessible by other means. Heavy elements with a relative abundance of order 1% solar were detected in Ly$\alpha$ absorbers (e.g., Burles & Tytler 1996 and references therein). However, these measurements are restricted by design to the small fraction of high-$z$ gas that is in dense clouds, and are unlikely to tell about the IGM on average.

At present, there is no direct information on the amount and composition of the diffuse IGM at low $z$ — possibly the largest reservoir of baryons around us — although there are plausible conjectures. At low redshifts, gas in galaxies has roughly solar heavy element abundances and gas in clusters exhibits quite a universal relative iron abundance of 1/3 solar (e.g., Edge & Stewart 1991; Fukazawa et al. 1998). The apparent lack of iron abundance evolution in clusters out to $z \sim 0.3$ and possibly beyond puts the epoch of cluster gas enrichment at $z \gtrsim 1$ (Mushotzky & Loewenstein 1997). Today’s clusters should have formed later than that, and there is no obvious reason for the enrichment of IGM to occur preferentially in the regions of space that later became clusters. Therefore, as argued by, e.g., Renzini (1999), cluster metallicity can be taken as representative of the low-$z$ universe as a whole. Simulations by Cen & Ostriker (1999b) predict a present-day universal abundance of 0.2 solar with a higher metal concentration around clusters. On the other hand, clusters, unlike the field population, contain mostly ellipticals and few spirals, suggesting that the dense cluster environment provides for an effective stripping of the enriched galaxy gas (e.g., Sarazin 1988). If so, the IGM may have much lower heavy element abundances than the cluster gas. Note that if heavy elements are detected in intercluster space, this would also set a lower limit on the total hydrogen density (and therefore the baryon density $\Omega_b$) as well, since the intercluster relative abundances are unlikely to be higher than the cluster values.

Unlike hydrogen and most helium, heavy elements in the diffuse IGM outside clusters are not expected to be strongly ionized and can in principle be detected via X-ray absorption in an X-ray analog of the Gunn-Peterson test (Shapiro & Bahcall 1980; Aldcroft et al. 1994; Fang & Canizares 1997; Perna & Loeb 1998; Hellsten, Gnedin, & Miralda-Escudé 1998). Such an absorption (mostly due to oxygen and iron) has never been observed. Indeed, the above authors estimate that for an IGM that is uniform on large linear scales, the expected resonant absorption lines in a random direction towards a distant quasar are very weak.

Fortunately, the Universe is not uniform and there is one place in the sky where such a test, using not quasars but galaxy clusters as background candles, may be feasible with the forthcoming Chandra and XMM observatories, as described below.

2. LOOKING THROUGH A GIANT CLUSTER FILAMENT

Figure 1 shows the sky distribution of the most distant galaxy clusters from the catalog by Abell, Corwin, & Olowin (1989). Besides the Galactic plane shadow, the most prominent feature of the distribution is a concentration of clusters in Aquarius at
\[ \alpha = 348^\circ, \delta = -23^\circ, \] with the surface density of clusters about 6 times higher than average over the Southern Galactic hemisphere. This concentration was first noted by Abell (1961) and listed among the most likely candidates of rich distant superclusters. Later spectroscopic data (Ciardullo, Ford, & Harms 1985) showed that members of this concentration in fact form a giant filament along the line of sight, spanning a range of redshifts between 0.08 and 0.21 or about 700 \( h_{700}^{-1} \) Mpc (Fig. 2).

One can reasonably assume that the overdensity of the IGM in this volume is proportional to that of clusters, since a bias on such a large linear scale is unlikely (forthcoming cosmological simulations of the Hubble volume will address this issue, e.g., Colberg et al. 1998). Therefore, this filament should also provide an enhancement in the IGM column density by a factor of about 6. This enhancement makes the absorption detectable in the X-ray spectra of clusters located at the far end of the filament that are seen through the filament.

There are distant and nearby members of the filament that are close in projection (Fig. 2). This enables a “differential” test by measuring a difference in absorption in the nearby and distant cluster spectra and looking for its systematic increase with the cluster distance along the filament. Such a differential measurement can significantly reduce systematic errors due to (a) uncertainty of the Galactic column density and (b) unavoidable instrument calibration inaccuracy. Since the hypothetical absorbing gas is located within the small interval of known and low redshifts, its detection and interpretation can be straightforward.

### 2.1. Expected absorption column density

Big Bang nucleosynthesis predicts a baryonic (plausibly, dominated by IGM) density parameter of \( \Omega_b \simeq 0.05 h_{700}^{-2} \) (Walker et al. 1991) \( \pm \) a factor of 2 from the uncertainly of the measured deuterium abundance (e.g., Steigman 1996). Simulations of the observed Ly\( \alpha \) forest by Rauch et al. (1997) and the detection of high-\( z \) helium by Davidsen, Krauss, & Wei (1996) are consistent with the upper bound of the above value. Here we would like to get an upper limit estimate of the possible absorbing column, for which we assume the above upper bound as an IGM density, \( \Omega_{\text{IGM}} \simeq 0.1 h_{700}^{-2} \). The difference in hydrogen column density between the nearest and farthest clusters in the filament is

\[
N_H (0.1 < z < 0.2) \approx 2.5 \times 10^{21} \text{ cm}^{-2} h_{50}^{-1} \frac{\Omega_{\text{IGM}}}{0.1 h_{50}^{-2}} \frac{\Delta}{6 b_{700}},
\]

where \( \Delta \) is the surface overdensity of clusters in that region of the sky and \( b_{700} \) is the cluster bias on the 700 Mpc scale (if there is any). For comparison, the Galaxy has \( N_H \approx 2 \times 10^{20} \text{ cm}^{-2} \) in that direction. In the redshift interval in front of the filament (\( z < 0.1 \)) and assuming no IGM overdensity, \( N_H \approx 2 \times 10^{20} \text{ cm}^{-2} \), negligible compared to that in the filament. Another useful quantity for comparison is a possible column density of warm gas on a line of sight crossing the outskirts of a rich galaxy cluster. For example, extrapolating the X-ray gas density profile for the Coma cluster beyond its virial radius (\( r \approx 3 \text{ Mpc} \)) to 10 Mpc, one obtains \( N_H \approx 3 \times 10^{20} \text{ cm}^{-2} \) (excluding the hot, weakly absorbing gas within the virial radius). Again, it is negligible compared to the column density.
that accumulates along the 700 Mpc overdense filament. Thus the proposed test can indeed probe the absorbing medium far from cluster confines.

2.2. Expected conditions in the gas

Simulations predict that a large fraction of all baryons at low redshifts is in the form of “warm” gas with temperatures between $10^5$ and $10^7$ K (e.g., Cen & Ostriker 1999a). Although these temperatures are low for a complete collisional ionization of heavy elements such as oxygen and iron, the low-density regions outside clusters, photoionization by Cosmic X-ray Background (CXB) dominates the ionization rate (e.g., Aldcroft et al. 1994). Unlike the uncertain ionizing UV background at high redshifts that is involved in the interpretation of Lyα data, the present-day CXB is directly measurable (e.g., Chen, Fabian, & Gendreau 1997). The ionizing radiation is stronger in the immediate vicinity of an X-ray-bright cluster, but CXB dominates beyond a few Megaparsecs from the cluster. The diffuse IGM is optically thin with respect to photoabsorption. For the expected density, the recombination timescales of interest are short compared to the Hubble time, thus the medium should be close to ionization equilibrium. For an estimate of the ionization balance expected in the gas filling our filament and subjected to photoionization by CXB, we used XSTAR code by T. Kallman and J. Krolik. For a range of temperatures $(3 - 30) \times 10^5$ K and an IGM density $n_H \approx 2 \times 10^{-4}$ cm$^{-3}$ (six times the assumed $\Omega_{\text{IGM}}$), oxygen is mainly in the form of OVII and OVIII ions with an increasing fraction of the completely ionized species for increasing temperature. If the IGM is clumpy (which is most likely, e.g., Cen & Ostriker 1999a), plasma in the denser regions would have lower ionization states, for a given temperature. For illustrative purposes of this paper, we use the ionization balance calculated for $T = 3 \times 10^5$ K and the above average gas density; qualitative conclusions are similar for other temperatures and densities in the expected range. For a consistently optimistic estimate, relative abundances of heavy elements in the IGM are assumed to be 0.3 solar. To calculate absorption depth for the obtained mixture of ions, atomic data from Verner et al. (1996ab) were used. Figure 3 shows an example absorbed spectrum. As noted in earlier works, of all elements, oxygen causes the strongest absorption features and has the best chance to be detected.

3. DISCUSSION

3.1. Absorption lines vs. absorption edges

Earlier work addressing the practical possibility of detecting the IGM has concentrated on resonant absorption lines in the spectra of distant quasars. In the random direction in the sky, the column density of the absorbing material is expected to be low and absorbers spread over a large redshift interval. For such random searches, it is indeed optimal to look for easily identifiable spectral features such as lines. The lines are expected to have very low equivalent width, $\Delta \lambda \sim 0.1$ eV, and their detection requires high spectral resolution instruments and large-area telescopes such as the future calorimeter onboard Constellation-X$^2$, or impractically long observations with grating spectrometers onboard the forthcoming Chandra$^3$ and XMM$^4$ observatories.

It is often overlooked, however, that equivalent width of the photoionization edges for oxygen ions is comparable to or greater than the width of the resonant lines. Detection of an edge does not require high spectral resolution. For example, Figure 3 shows the absorbed spectrum from Fig. 3a smoothed with a 100 eV resolution (FWHM) that can be achieved with a CCD. To emulate a realistic situation when the exact Galacti- c column density is unknown and is fitted as a free parameter, the figure also shows a model spectrum without the IGM absorption but with an increased Galactic $N_H$ to reproduce the flux at low energies (dotted line). Also shown by dashed line is an IGM-absorbed spectrum in which line absorption is not included (only edges are included). It is apparent that with such energy resolution, edge absorption in the interval $E = 0.6 - 1$ keV (observer frame) is a dominant feature. This absorption is “warm” and cannot be mimicked by increasing the assumed neutral Galactic column density. Note, however, that because weak, broad edges are not so easily identifiable as lines, one can hope to find them only if the redshift of the absorber is known a priori, as in the Aquarius filament. In this filament, the width of the redshift interval containing the absorber, $0.1 < z < 0.2$, corresponds to an energy interval smaller than the spectral resolution of the CCD detector and is therefore unimportant.

3.2. Feasibility with forthcoming observatories

The spectrum in Fig. 3 assumes an optimistic IGM column density expected toward the most distant clusters in the Aquarius filament. Such absorption can be detected already with the CCD instruments ACIS-S onboard Chandra and EPIC onboard XMM, scheduled for launch in the near future. These detectors will have the required sensitivity at the energies below $\sim 0.4$ keV to straddle the expected absorption feature. Because this measurement does not require high spectral resolution of grating spectrometers that have limited efficiency, it can take advantage of the full effective area of the telescopes, making the required exposures practical. Detailed simulations show that for each of the several X-ray clusters on the far end of the filament, a 3σ or better detection of the IGM absorption with the above parameters can be obtained in a $\sim 6 \times 10^7$ s observation with XMM or in a 2–3 times longer but still practical exposure with Chandra. If the IGM is clumpy so that oxygen is in the lower ionization states that have higher absorption depth, its detection would require shorter exposures. Of course, if the unknown IGM density or its metallicity turn out to be much lower than the above upper-limit estimates, longer exposures will be required. For a differential test described in §2, a significant number of clusters members of the filament needs to be studied. As Fig. 2 shows, there is a number of appropriate objects, and also an area with more potential candidates with unknown redshifts. Thus the test proposed above appears to be feasible with Chandra and XMM, if the density and metallicity of low-redshift IGM are close to the above optimistic assumptions.

3.3. Clusters as background candles

Previous work emphasized quasars as background candles for the search of IGM absorption. By studying distant, randomly selected quasars with future large-area telescopes, one

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$^1$ftp://legacy.gsfc.nasa.gov/software/plasma_codes/xstar
$^2$http://constellation.gsfc.nasa.gov
$^3$http://asc.harvard.edu
$^4$http://heasarc.gsfc.nasa.gov/docs/xmm
may eventually be able to determine the average properties of IGM. At present, since IGM has not even been detected yet, one can improve the chances of finding its traces by using galaxy clusters as background sources. Clusters form at the intersection of matter filaments (e.g., Colberg et al. 1997) which greatly increases the probability of a favorable line of sight through a dense region of the universe. Because clusters are extended, any absorption detected in their spectrum would have to arise in the truly diffuse medium as opposed to a possible intervening gas-rich galaxy or a Lyα cloud in front of a quasar. Although clusters may exhibit intrinsic absorption in their central cooling flow regions (e.g., Allen & Fabian 1994), these regions can easily be masked out from the spectral analysis with an imaging instrument. However, because the angular extent of clusters precludes the use of grating spectrometers such as those onboard Chandra and XMM, they would require a calorimeter, such as the future Constellation X or smaller-scale missions, to detect weak absorption lines arising in the IGM with lower column densities than that expected in the unique Aquarius filament.

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