The Zeldovich Universe:
Genesis and Growth of the Cosmic Web
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Finding and characterising WHIM structures using the luminosity density method

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Abstract. We have developed a new method to approach the missing baryons problem. We assume that the missing baryons reside in a form of Warm Hot Intergalactic Medium, i.e. the WHIM. Our method consists of (a) detecting the coherent large scale structure in the spatial distribution of galaxies that traces the Cosmic Web and that in hydrodynamical simulations is associated to the WHIM, (b) mapping its luminosity into a galaxy luminosity density field, (c) using numerical simulations to relate the luminosity density to the density of the WHIM, (d) applying this relation to real data to trace the WHIM using the observed galaxy luminosities in the Sloan Digital Sky Survey and 2dF redshift surveys. In our application we find evidence for the WHIM along the line of sight to the Sculptor Wall, at redshifts consistent with the recently reported X-ray absorption line detections. Our indirect WHIM detection technique complements the standard method based on the detection of characteristic X-ray absorption lines, showing that the galaxy luminosity density is a reliable signpost for the WHIM. For this reason, our method could be applied to current galaxy surveys to optimise the observational strategies for detecting and studying the WHIM and its properties. Our estimates of the WHIM hydrogen column density N_H in Sculptor agree with those obtained via the X-ray analysis. Due to the additional N_H estimate, our method has potential for improving the constrains of the physical parameters of the WHIM as derived with X-ray absorption, and thus for improving the understanding of the missing baryons problem.

Keywords. cosmology: large-scale structure of universe, galaxies: intergalactic medium

1. Introduction

At low redshifts (z<2) all observations of the visible matter sum up only to ~70% of the expected cosmological mass density of baryons (e.g. Shull *et al.*, 2012). Large scale structure formation simulations suggest that these missing baryons reside in the form of Warm-Hot Intergalactic Matter (WHIM) in the filamentary cosmic web structure connecting the clusters of galaxies and superclusters (e.g. Cen & Ostriker, 1999, 2006). At the predicted temperatures of 10^{5-7} K and densities $10^{-6} - 10^{-4}$ cm^{-3} the X-ray emission from single WHIM structures is too faint to be detected with current instrumentation.

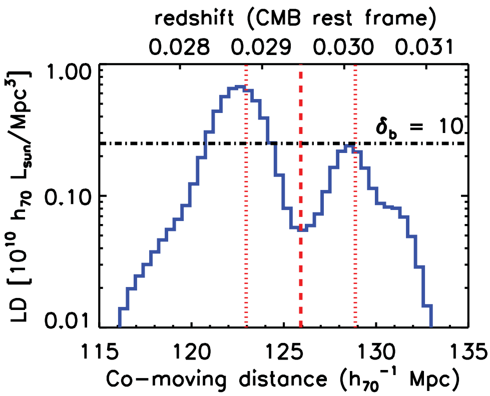

Figure 1. Luminosity density (LD) profile along the Sculptor Wall galaxy structure at z$\sim$0.03 as obtained from the 2dF data is shown with a (blue) solid line. The best-fit value and the 1σ uncertainties of the redshift of the X-ray absorber (Fang *et al.*, 2010) are shown in (red) dashed and dotted lines. Note that the redshifts and distances are reported in CMB rest frame. The luminosity density value corresponding to baryon overdensity δ_b = 10, as estimated with Eq. 2.1, is denoted with horisontal dash-dot line.

However, the column densities of the highly ionised WHIM metals along large–scale filamentary structures can reach a level of 10^{15-16} cm^{-2}, imprinting detectable absorption features on the soft X-ray spectra of background sources (e.g. Nicastro *et al.*, 2010).

While the X-ray absorption measurements are crucial in the analysis of WHIM, they are sparse. To improve this, we focus on *known foreground large scale structures* traced by galaxies, like the cosmic filaments, that most likely contain WHIM. We have applied the Bisous model (Stoica *et al.*, 2005) to trace and extract the filamentary network in the galaxy redshift surveys SDSS DR8 (Tempel *et al.*, 2014) and 2dF. Thus we have an extensive data base of potential WHIM structure locations, sizes and redshifts.

We report distances and lengths in co-moving coordinates (unless stated otherwise), using $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and H = 70 km s^{-1} Mpc^{-1}.

2. The method

2.1. *Luminosity density fields*

We have examined the above galaxy structures using the luminosity density (LD) method, pioneered by our group (e.g. Liivamägi *et al.*, 2012). With this method we quantify the 3-dimensional galaxy distribution using the optical (R - band) light in galaxies. We assume that every galaxy is a visible member of a density enhancement (group or cluster). We place the galaxies at the mean distance of the group or the cluster, to correct for the effect of the dynamical velocities (finger-of-god). We correct the galaxy luminosities for the observational magnitude limited samples by a weighting factor that accounts for the group galaxies outside the visibility window. The galaxy luminosity distribution is then smoothed with a B3-spline kernel function. The smoothing length determines the characteristic scale of the objects under study. We have adopted 1.4 Mpc as the smoothing scale, in order to match the filament widths. We then sample the LD distribution at the points of a uniform grid, encompassing the survey volume, with a sampling scale of 1.4 Mpc, thus creating the LD field. For a given galaxy structure, we use the LD field to evaluate the LD profile (see Fig. 1).

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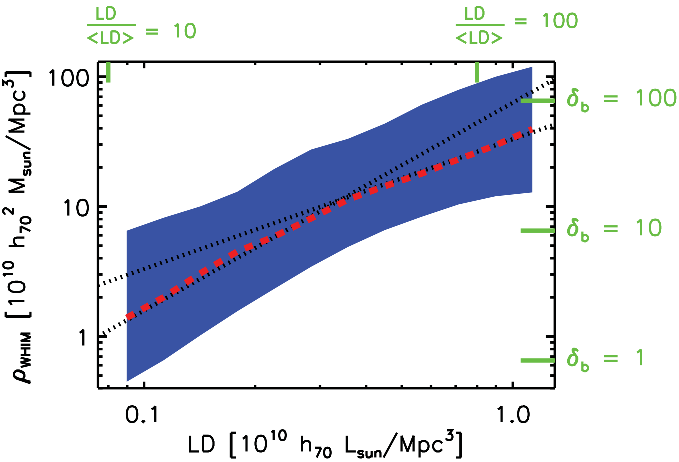

Figure 2. The luminosity density (LD) - WHIM density (ρ_{WHIM}) relation, and the 1σ uncertainties derived from the cosmological hydrodynamical simulations (Cui *et al.*, 2012) are indicated with (red) dashed line and the (blue) shaded region, respectively. The black dotted lines indicate the power-law approximations to the relation (Eq. 2.1). The (green) symbols indicate different levels of overdensity of baryons and luminosity.

2.2. *Large Scale Structure simulations*

If the galaxies follow the underlying dark matter (DM) potential, similarly as the WHIM, then the luminosity density field in filaments can be used to trace the missing baryons. To test the validity of this assumption we have applied our filament–finding and LD field algorithms to a distribution of mock galaxies, DM and the WHIM (i.e. gas at temperatures 10^{5-7} K) at z = 0 in the hydrodynamical simulations (Cui *et al.*, 2012). These simulations make use of smoothed particle hydrodynamics in GADGET-3 code to produce dark matter and diffuse baryonic components within a box with a size of 570 Mpc. The simulations involve radiative cooling, star formation and feedback from supernova remnants. The galaxies are created by populating the DM haloes using a halo occupation distribution constrained with the SDSS data (Zehavi *et al.*, 2011). The simulated data are adequate to follow the different density components with a resolution of ∼1 Mpc.

Indeed the LD and WHIM density (ρ_{WHIM}) in the above simulations correlate rather well (Pearson correlation coefficient = 0.85). We used this correlation to derive a quantitative relation between these, i.e. the LD - $\rho_{\rm WHIM}$ relation, within the filaments identified by the mock galaxies (see Eq. 2.1 and Fig. 2).

$$\rho_{WHIM} \approx 63 \times LD^{1.6}, when\ LD < 0.35$$
$$\rho_{WHIM} \approx 33 \times LD^{1.0}, when\ LD > 0.35, \tag{2.1}$$

where LD and ρ_{WHIM} are expressed in units $10^{10}\ h_{70}\ L_\odot\ Mpc^{-3}$ and $10^{10}\ h_{70}^2\ M_\odot\ Mpc^{-3}$.

We use this relation to convert the observational (SDSS and 2dF) LD values into ρ_{WHIM} estimates. We then integrate the ρ_{WHIM} profile of a given filament to obtain the WHIM hydrogen column density $N_{\rm H}$. The observed LD profile values typically correspond to baryon overdensities of ∼ 10 (see Fig. 1), consistent with those predicted by simulations for the WHIM filaments (e.g. Cen & Ostriker 1999, 2006).

Table 1. Redshifts and WHIM hydrogen column densities $N_{\rm H}$ in Sculptor

system	X-ray[1] redshift[3]	LD[2] redshift[3]	X-ray[1] log $N_{\rm H}$	LD[2] log $N_{\rm H}$
Sculptor Wall (SW)	0.030–0.032	0.028–0.033	21.0[20.1–22.3]	20.0[19.6–20.6]
Pisces-Cetus (PC)	0.060–0.063	0.060–0.063	20.1[19.9–20.3]	19.8[19.4–20.3]
Farther Sculptor Wall (FSW)	0.125–0.127	0.128–0.129	20.8[20.0–21.2]	19.9[19.6–20.5]

Notes:
[1] Redshift centroid (Chandra) and WHIM $N_{\rm H}$ estimates based on X-ray absorption measurements (SW: Fang *et al.*, 2010; PC and FSW: Zappacosta *et al.*, 2010). The log $N_{\rm H}$ values for SW are derived from the reported $N_{O\,VII}$, assuming O abundance 0.1 Solar, O/H ratio from Grevesse & Sauval, 1988, and T = 10^6 K.
[2] Our luminosity density - based estimates for the redshift range corresponding to the extent of the given system intersected by the H2356-309 sightline, and WHIM $N_{\rm H}$ of the given system.
[3] In the observational frame.

3. Results

In order to test the feasibility of our WHIM $N_{\rm H}$ estimation method, we extracted the LD profile along the line-of-sight to the blazar H2356-309 behind the Sculptor Wall, where X-ray measurements of WHIM absorption have been obtained (Fang *et al.*, 2010; Buote *et al.*, 2009, Zappacosta *et al.*, 2010). We found ∼10 Mpc long luminosity density structures at redshifts consistent with those measured with X-rays (see Fig. 1). Our LD-WHIM density relation yields WHIM $N_{\rm H}$ values consistent with those measured in X-rays (see Table 1), proving the reliability of our column density estimation method.

4. Discussion

Our plan is to apply our method to current galaxy surveys (and e.g. to Euclid results in near future) to optimise the observational strategies for detecting and studying the WHIM and its properties. In particular, we will cross-correlate the significant WHIM structures found from e.g. SDSS and 2dF with bright background blazars. We aim at obtaining XMM-Newton/RGS and Chandra/LETGS data of such blazars in a high flux state, which are located in the line-of-sight to WHIM structures with the highest WHIM column density estimates. This will be useful also for next generation X-ray telescopes like ATHENA. We will also extend this work to include far-ultraviolet WHIM measurements with e.g. FUSE and HTS of the low temperature WHIM.

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