EFFECT OF METALLICITY ON X-RAY EMISSION FROM THE WARM-HOT INTERGALACTIC MEDIUM

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ABSTRACT

Hydrodynamic simulations predict that a significant fraction of the gas in the current universe is in the form of high temperature, highly ionized plasma emitting and absorbing primarily in the soft X-ray and UV bands, dubbed the warm-hot intergalactic medium (WHIM). Its signature should be observable in redshifted emission and absorption lines from highly ionized elements. To determine the expected WHIM emission in the soft X-ray band we used the output of a large scale smoothed particle hydrodynamic simulation to generate images and spectra with angular resolution of $14''$ and energy resolution of 1 eV. The current biggest limit of any hydrodynamic simulation in predicting the X-ray emission comes from metal diffusion. In our investigation, by using four different models for the WHIM metallicity we have found a strong dependence of the emission on the model used, with differences up to almost an order of magnitude. For each model, we have investigated the redshift distribution and angular scale of the emission, confirming that most photons come from redshift $z < 1.2$ and that the emission has a typical angular scale of less than a few arcminutes. We also compared our simulations with the few currently available observations and found that, within the variation of the metallicity models, our predictions are in good agreement with current constraints on the WHIM emission, and at this time the weak experimental constraints on the WHIM emission are not sufficient to exclude any of the models used.

Key words: diffuse radiation – intergalactic medium – large-scale structure of universe – methods: numerical – radiation mechanisms: thermal – X-rays: diffuse background

Online-only material: color figures

1. INTRODUCTION

The problem of the missing baryonic matter in the nearby universe is still open. On one hand, we have the observations of the Lyα forest at redshift $z = 2$, the results from the Wilkinson Microwave Anisotropy Probe experiment, and the prediction of the standard nucleosynthesis model. They all suggest a baryonic density, $\Omega_b$, expressed as fraction of the critical density, being about 0.045 (Rauch et al. 1997; Weinberg et al. 1997; Burles & Tytler 1998; Kirkman et al. 2003; Bennett et al. 2003; Spergel et al. 2007; Komatsu et al. 2009). On the other hand, from the observed mass distribution function of stars, galaxies, and clusters, the measured baryonic fraction of the local universe comes out about two to four times lower (Fukugita et al. 1998). In recent years, large-scale cosmological hydrodynamic simulations (Cen & Ostriker 1999a; Croft et al. 2001; Davé et al. 2001; Yoshikawa et al. 2003; Borgani et al. 2004; Cen & Ostriker 2006) have allowed us to trace the history of baryons from very high redshifts to $z = 0$, and they all predict that almost 50% of the baryonic mass in the nearby universe is in the form of a filamentary structure of gas at a temperature in the range of $10^3$–$10^7$ K, the warm-hot intergalactic medium (WHIM). This gas is highly ionized and can be observed in the soft X-ray band ($0.1$–$1$ keV) and in the far ultraviolet (FUV) band. Soft X-rays probe mostly gas at $T > 10^6$ K, while FUV is a better probe for gas at $T < 10^6$ K. If we assume thermal and ionization equilibrium, thermal emission models that comprise bremsstrahlung and emission lines (Raymond & Smith 1977), in the approximation of thin gas, one obtains a detected $\Omega_{\text{WHIM}}/\Omega_b \sim 0.1$, depending on the assumptions about metallicity, this fraction could be higher (Danforth & Shull 2008). This leaves up to $\sim 50\%$ of low-redshift baryons that still need to be accounted for (Danforth & Shull 2008). They are predicted to be in the form of the warmer WHIM ($10^6 < T < 10^7$ K), visible in the soft X-rays, and have O vii and O viii as primary tracers.

X-ray observations are more difficult than observations in FUV because of instrumental limits. So far there are claims for
only four detections in absorption. Two O vii absorbers along the line of sight of Mrk 421 were identified with Chandra (Nicastro et al. 2005), but not confirmed by XMM-Newton (Rasmussen et al. 2007). An O viii absorber has been detected at \( z \sim 0.55 \) toward PKS 2155−304 (Fang et al. 2002; Fang et al. 2007), while another O vii absorber has been identified in the Sculptor Wall at a redshift range of 0.028–0.032 (Buote et al. 2009).

Detecting the WHIM in emission is even harder, since its contribution is at most 20% of the total DXB and current instruments are not suited to identify its weak signal. However, it is possible to analyze global statistical properties of the WHIM, or to identify filaments of WHIM where they are expected to be very strong. Recent observations found the WHIM signature in the X-ray angular correlation function obtained from XMM-Newton images (Galeazzi et al. 2009). Furthermore, an XMM-Newton pointing in the region between clusters A222 and A 223 found evidence of excess emission attributed to a filament connecting them (Werner et al. 2008).

In this paper, we use the cosmological hydrodynamic simulation by Borgani et al. (2004) to predict the X-ray emission from the WHIM. Compared to our previous work (Ursino & Galeazzi 2006), we exploited the good spatial resolution (on the order of the adopted gravitational softening of 7.5 h\(^{-1}\) kpc, compared to the \( \sim 195\ h^{-1}\) kpc resolution element used by Cen & Ostriker 1999a) of a Lagrangian simulation to create high-resolution maps of the baryon distribution.

We focused our attention on the effect of the metallicity model used on the X-ray emission. Metallicity in the filaments is one of the greatest uncertainties in this type of simulation. Observations of the intergalactic medium (IGM) put some limits on metals in the IGM. At \( z \lesssim 0.5 \) groups and clusters have metallicity \( Z \sim 0.3 Z_\odot \), while Ly\( \alpha \) clouds have \( Z \sim 0.1 Z_\odot \) with a large scatter (0.01 < \( Z/Z_\odot \) < 1). At higher redshifts metallicity becomes lower, possibly by a factor of 10 already at \( z \approx 3 \) (Finoguenov et al. 2003; Prochaska et al. 2004; Simcoe et al. 2006). From the analysis of the low redshift O vi absorbers, colder WHIM structures have \( Z \sim 0.15 Z_\odot \) (Danforth & Shull 2008). Although there is a possible correlation between higher metallicities and higher densities, a simple modeling of IGM metallicity is difficult. At the present time it is even uncertain if there was an early metal enrichment (\( z \approx 4 \)), if metals in the IGM are due to newborn (\( z < 2 \)) galaxies, or if metal enrichment history is described by a mixture of the two models (Aguirre & Schaye 2005). Cosmological simulations with an accurate physical description (galactic winds, star formation, black hole feedback, and so forth) can come to an avail in reproducing the proper metallicity (Cen & Ostriker 1999b; Borgani et al. 2004; Cen & Ostriker 2006; Tornatore et al. 2009; Wiersma et al. 2009). These models predict that the average WHIM metallicity is of the order of 0.1 \( Z_\odot \) but the behavior as a function of density changes widely from simulation to simulation. Due to the lack of tight constraints on metallicity from both observations and simulations, we allowed our code to work with a set of metallicity models in addition to the one coming directly from the Borgani simulation. Thanks to this degree of freedom we were able to investigate the dependence of the soft X-ray emission on the different metallicity models.

The paper is structured as follows. In Section 2, we introduce the hydrodynamic cosmological simulation, in Section 3 we describe the code we used to simulate the X-ray emission in a selected field of view (FOV), in Section 4 we show the simulated images and spectra, and in Section 5 we discuss how the emitted spectra depend on the metallicity models.

### 2. THE HYDRODYNAMIC MODEL

The general properties of the cosmological model are described in detail in Borgani et al. (2004) and references therein. The simulation uses a flat \( \Lambda \) cold dark matter ( \( \Lambda \) CDM) model with cosmological constant \( \Omega_\Lambda = 0.7, \Omega_m = 0.3, \) and a baryon density \( \Omega_b = 0.04, \) the Hubble constant is \( H_0 = 100 \) h km s\(^{-1}\) Mpc\(^{-1}\), with \( h = 0.7, \) and \( \alpha \approx 0.8. \) The Plummer-equivalent gravitational softening was set as \( \epsilon_pl = 7.5\ h^{-1}\) kpc. The code used to perform the simulation is the TREESPH code GADGET-2 (Springel et al. 2001; Springel 2005). The simulation follows the evolution of 480\(^3\) dark matter (DM) particles and as many baryonic gas particles from redshift \( z = 49 \) to \( z = 0 \). The box for the simulation is a cube of side 192 \( h^{-1}\) Mpc, and the DM and gas particles have initial masses \( m_{DM} = 4.62 \times 10^6 M_\odot\) and \( m_{gas} = 6.93 \times 10^8 h^{-1} M_\odot\), respectively.

### Detecting the WHIM in emission

The treatment of radiative cooling assumes an optically thin gas in CIE and uses only the primordial abundances (hydrogen mass fraction \( X = 0.76, \) helium \( Y = 0.24 \)). Metals generated by the simulation itself are not considered for radiative cooling.

Star formation is introduced following a hybrid multiphase model for the interstellar medium (Springel & Hernquist 2003). The interstellar medium, where star formation takes place, is represented as cold clouds (cold gas) embedded in a hot gas. Clouds are not accounted for individually in a given star-forming particle, but rather they are treated all together as a fraction of the total mass of the given star-forming particle. Every gas particle is considered to be composed of two parts, the hot gas, with its own mass and density, and the cold cloud fraction; temperature and density determine the relative abundances of the two components. Whenever star formation takes place, a new star particle is spawned (with just a fraction of the starting gas particle), thus increasing the number of star particles. Stars are created, following a Salpeter initial mass function (Salpeter 1955), and instantly produce metals and release energy as SNe. Metals and energy are carried to the intracluster and IGM by galactic winds. Winds are introduced in the simulation as mass outflows with rate equal to twice the star formation rate and with a wind velocity of 360 km s\(^{-1}\).

The output of the simulation consists of 102 boxes, equally spaced in the logarithm of the expansion factor between \( z = 9 \) and \( z = 0 \). As shown in previous work (e.g., Ursino & Galeazzi 2006) the X-ray emission above redshift 2 is negligible. For our work, we therefore only used the simulation up to redshift 2.

Besides the improvement in spatial resolution compared to our previous work, this simulation suits our needs well due to its large scale, which allows us enough statistics for distant regions. More recent cosmological simulations have box sizes of at most 100 \( h^{-1}\) Mpc (Cen & Ostriker 2006; Oppenheimer & Davé 2008; Tornatore et al. 2009; Wiersma et al. 2009), reducing the simulated sky area by at least a factor of three.

From the analysis of the baryonic matter we decided to group the gas particles in five phases, depending on density...
and temperature. At temperatures below $10^5$ K we defined two phases, a dense (overdensity $\rho/\langle \rho \rangle > 1000$) cold phase associated with matter undergoing star formation, and a cold low density ($\rho/\langle \rho \rangle < 1000$) gas that corresponds to the diffuse gas that resides in the voids of the web structure of the universe, and that has been identified with the Lyα absorbers. For intermediate temperatures ($10^5 < T < 10^7$ K) we have the warm-hot gas. Also in this case we defined two phases, the low density one ($\rho/\langle \rho \rangle < 1000$) that roughly corresponds to the filamentary structure of the WHIM, and the high density ($\rho/\langle \rho \rangle > 1000$) gas associated with groups of galaxies. Finally, at $T > 10^7$ K, we identify clusters of galaxies and the hot intracluster medium (ICM).

Figure 1 shows the phase diagram in the temperature–density space. The choice of the threshold between diffuse and dense WHIM is somewhat arbitrary and different authors have used different thresholds in the range $100 < \rho/\langle \rho \rangle < 1000$. For consistency with a significant fraction of the literature, including our previous work (Ursino & Galeazzi 2006), we adopted the definition of Cen & Ostriker (1999b).

3. THE SIMULATION

To create a simulated light cone up to redshift 2, we adopted a procedure similar to the one described in Roncarelli et al. (2006), where several boxes from the output snapshots of the Borgani simulation were piled one after the other. Since the boxes have a side of $192 \ h^{-1} \ Mpc$, the redshift interval covered by each box is $\Delta z \gtrsim 0.06$ (increasing at higher redshift). The time step between two consecutive snapshots of the Borgani simulation corresponds to $\Delta z \gtrsim 0.02$ at small redshift, increasing at higher redshift, therefore $\Delta z$ corresponds to the time step between three consecutive snapshots. For our simulation, we created one box taking slices of $64 \ h^{-1} \ Mpc$ from three consecutive snapshots as shown in Figure 2. This allows us to better follow the evolution of the gas. Since consecutive boxes represent the same structure evolved in time and they do not change much for small redshift intervals, particular attention was given to avoiding encountering the same structures at different redshifts. We therefore used random rotations around the line-of-sight axis, random permutations of the coordinate axes of each composite box, and random shifts along the three axes. These randomizations give a very large number of degrees of freedom to avoid periodicity. The downside of this procedure is that it introduces discontinuities between two adjacent snapshots. Although these discontinuities are unphysical, their effect on our simulation is minor due to the very small probability of finding a significant WHIM structure right at the edge of the smoothed particle hydrodynamics (SPH) box.

The last step in the simulation is piling up the modified cubes to form a simulated light cone. Figure 3 shows a representation of a simulated light cone, with a selected FOV superposed. The code itself is capable of spanning any distance as long as the angle of the FOV is smaller than the angular size of the last box, but we chose a maximum corresponding to redshift $z = 2$, equivalent to 19 cubes. Emission from greater distances is expected to be a small fraction of the total emission, while at the same time the calculation drastically increases the computing time. The angular size of the furthest box, which determines to largest FOV that can be constructed in a single simulation, is $\sim 21 \times 21$. The typical FOV used is $1 \times 1$.

The FOV starts from the center of the first box, and only particles that are inside such FOV (see Figure 3) are selected. Besides this geometrical filter, we adopted two more filters. Since baryons at $T < 10^5$ K do not emit any significant amount of X-rays, we filtered out all the particles with temperature lower than this limit to speed up the computational process. At $z = 0$, the diffuse warm gas and the star-forming gas cover $\sim 50\%$ of the gas mass (roughly $\sim 50\%$ of the particles) and that this fraction increases to $\sim 75\%$ at $z = 2$. Our filter therefore reduces the computational time by more than a factor of two. One more final filter discriminates between particles of the three remaining warm-hot phases and labels them accordingly.

For temperatures in the range $10^5 < T < 10^7$ K, the two main sources of radiation between 0.1 and 1 keV are thermal bremsstrahlung and emission lines from highly ionized elements (i.e., C v, C vi, O vii, O viii, Ne ix, Mg xi, and Fe xvii), although our investigation is focused on O vii and O viii. In order to properly evaluate emission from the lines, it is necessary to set metal abundances.

As we stated previously, we designed the program with the capability of working with different metallicity models, in addition from the original metallicity predicted by the hydrodynamic code. This choice is aimed at overcoming the lack of precise information about metal formation and metal diffusion in the IGM, and to compare the X-ray emission expected from different metal distributions.

The first metallicity model (from now on defined as “Borgani model”) we adopted is the original model coming from the Borgani simulation. This model underestimates the diffusion of metals in most of the WHIM, assigning metals to only a fraction of the gas particles. The reason for the uneven distribution of metals in the WHIM depends on the treatment of metal diffusion in SPH simulations, as it is well explained in Figure 4 of Wiersma et al. (2009). An SPH star-forming particle enriches the neighboring particles and they are driven away by the energy released by stars in the star particle. The metal-enriched particles mix with metal-free gas particles, but do not enrich them since there is no diffusion from gas particles. Therefore, the metal distribution is not evenly smoothed, but concentrated in the few gas particles that have been directly enriched by star-forming particles. As a result most of the WHIM is poor in metals and its emission is underestimated. This can be avoided if a model of diffusion of metals from one particle to the others is included.
in the simulation, which is not the case of the simulation we used.

In addition to the metallicity extracted from the Borgani model, we used three analytical models based on relations between metallicity and density (see Figure 4).

The first analytical model (defined as “Croft model”) links the metallicity directly to the gas density, using the relation $Z \propto (\rho/\bar{\rho})^{1/2}$. Metallicity is normalized to $Z = 0.005 Z_\odot$ at $\rho = \bar{\rho}$, so that it matches the measured metallicity of the Ly$\alpha$ forest, while an upper limit of $Z = 0.3 Z_\odot$ fits well with data on clusters (Fang et al. 2005). This model is in agreement with the metallicity predicted by Cen & Ostriker (1999a) at $z = 3$ and is about a factor five lower than the IGM metallicity at more recent times. Nevertheless, we adopted this model as a comparison since it has also been used by other authors (Croft et al. 2001; Fang et al. 2005).

The second analytical metallicity model (which we call the “Scatter model”) is based on the distribution function of...
metallicity from Cen & Ostriker (1999b) at redshift $z = 0$. Part of the output of that simulation consists of three boxes of $512^3$ cells with values of temperature, density, and metallicity. Using the three boxes, we generated the probability distribution function of metallicity as a function of density, where metallicity is divided into 110 intervals from $10^{-7}$ to $10^4$ $Z_\odot$ and density is divided into 70 intervals from $10^{-3}$ to $10^4$ $\rho_0$. When this model is selected, the code reads the density of each particle and assigns a random metallicity based on the probability distribution function at the corresponding density. The average distribution of metallicity for this model is represented by the black curve in Figure 4. This model has the highest metallicity among the four models (a factor of two to three for overdensities between 10 and 1000) and, since at first order the intensity of the lines depends linearly on metallicity, we use the emission with the Scatter model as an upper limit for our set of simulations.

The third analytical metallicity model, labeled “Cen model,” is an improved version of the Scatter model, where we also include redshift dependence evaluated from Figure 2 of Cen & Ostriker (1999b). A “random” metallicity is initially evaluated following the same procedure used for the Scatter model, then it is modified according to redshift of the particle. We note that the redshift dependence of the metallicity is optimized for WHIM particles and would overestimate the metallicity of clusters and groups. By definition the average values of the Cen model at $z = 0$ are identical to those of the Scatter model. To show the redshift variation, in Figure 4, we plot the average values of the Cen model at $z = 0.5$ and $z = 1$ in tones of gray. We introduced this model for two main reasons: to evaluate the influence of time evolution on metallicity and to compare the predictions of this model with the results of our previous work (Ursino & Galeazzi 2006), where we used the same fitting function to estimate time evolution of metallicity.

We stress the fact that in the original Borgani simulation the cooling function does not depend on metals but only on primordial abundances and that the models of metallicity that we adopt are introduced a posteriori and do not affect the baryon history. It has been shown that including a self-consistent metal dependence in a simulation increases the cooling rates, resulting in a lower emission (above all for strongly emitting gas) than what is predicted using only primordial abundances, even by an order of magnitude (Bertone et al. 2010).

The following step is to calculate the spectrum of emitted photons, as a function of electron number density $n_e$, temperature $T$, and metallicity $Z$ for every SPH particle. We did not consider peculiar velocities. Velocities of a few hundred km s$^{-1}$ correspond to $\Delta z \sim 0.001$, more than a factor of 30 less compared to the redshift interval between two boxes. These velocities correspond to displacements of the emitters of less than 10 Mpc if we attempt to estimate the distance from the redshifted spectrum of an absorber. We used the XSPEC version of the APEC model$^3$ (Smith et al. 2001) using solar relative abundances to produce the spectra, in the assumption of an optically thin gas in CIE and no photoionization from a background radiation. We assumed CIE since we expect to probe the WHIM mainly in regions at higher temperature and density, where the ionization balance is dominated by collisions. Models show that the WHIM could depart from ionization equilibrium (Yoshida et al. 2005; Cen & Fang 2006) and the abundances of ions in the case of non-equilibrium are generally higher (Gnat & Sternberg 2007), however, the expected differences between the observables in ionization equilibrium and non-equilibrium are small (Yoshikawa & Sasaki 2006). In detail, our procedure goes as follows. We create a grid of spectra as a function of temperature and metallicity, equally spaced on a logarithmic scale both in temperature between $10^7$ K and $10^9$ K, and metallicity $Z$ between $5 \times 10^{-4} Z_\odot$ and $5 Z_\odot$, respectively. We set the energy resolution at 1 eV between 0.05 and 3 keV, and at 50 eV between 3 and 50 keV. We interpolate from the grid, using the temperature and metallicity of a given SPH particle to compute a reference spectrum $\Delta T, Z(\Lambda_0)$, with $\Lambda_0$ the rest-frame energy. Then we calculate the emitted spectrum, corresponding to the number of emitted photons per unit of time, with the formula

$$s_0(\Lambda_0) = x_e n_H^2 V \Delta T, Z(\Lambda_0)$$

where $V$ is the physical volume of the particle (defined as mass of the particle divided by density), $n_H$ is the number density of hydrogen nuclei (given by the SPH simulation), and the density of electrons is given by $n_e = x_e \times n_H$, with $x_e = 1.225$ (assuming near full ionization).

Finally, we compute the observer-frame spectrum $s(E)$, applying the energy redshift $E = E_0(1 + z)$ to $s_0(E_0)$, and the corresponding flux in each energy channel

$$S(E) = \frac{s(E)}{4\pi d_c^2(1 + z)}$$

where $d_c$ is the comoving distance of the particle from the observer and the factor $(1 + z)$ accounts for the redshift dimming of the signal.

This quantity is then distributed in the different map pixels by using the SPH smoothing kernel

$$w(r) \propto \begin{cases} 1 - 6r^2 + 6r^3, & 0 \leq r \leq 0.5 \\ 2(1 - r)^3, & 0.5 \leq r \leq 1 \\ 0, & r \geq 1 \end{cases}$$

$^3$ http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/
where $r \equiv \Delta \theta/\alpha_h$ is the angular distance from the particle position in the map in units of the angle $\alpha_h$ subtended by the particle smoothing length provided by the hydrodynamic code. In this kind of computation, the smoothing procedure is the most time consuming. However, the mathematical properties of the smoothing function can help speed up the computation. First of all, since the function of Equation (3) is the approximation of a two-dimensional Gaussian in the sky plane, the distribution can be separated into the product of its two components along the map axis,

$$w(r) \simeq w(x) \times w(y).$$

Then, since the function is integrable, we can directly define

$$W(x) \equiv \int_{x-1}^{x} w(\tilde{x}) d\tilde{x}$$

and use it for the computation. The normalization of $w(x)$ is chosen to have $W(1) = 1$. Therefore, for a given pixel $(i, j)$ we compute its corresponding flux fraction

$$f_{i,j} = [W(x_1) - W(x_0)] \times [W(y_1) - W(y_0)]$$

where $(x_0, y_0, x_1, y_1)$ identify the pixel limits in the two directions. We highlight also the fact that our definition of $W(x)$ ensures that $\Sigma_{i,j} f_{i,j} = 1$ without the need to renormalize it.

This procedure is done separately for the three gas phases (WHIM, dense WHIM, and hot gas) in order to keep the information about their different contributions.

The final result of the simulations is a three-dimensional array (the two angular coordinates and the energy) for each gas phase (hot, WHIM, and dense WHIM) containing photon counts per second per cm$^2$. We also saved one array for each box used to build the simulated light cone, so that we have information about the spectrum as a function of redshift.

At the end of the process, we included the absorption due to the neutral hydrogen in our galaxy using the model described by Morrison & McCammon (1983), with a typical value at high latitude of $n_H = 1.8 \times 10^{20}$ cm$^{-2}$ (McCammon et al. 2002).

4. RESULTS

The imaging capability of the simulation gives us the opportunity to study the WHIM morphology and emission, or focus on the properties of individual objects. We can also extract energy spectra for every pixel of the image.

As an example of the capabilities of our simulations, Figures 5 and 6 show images in the energy band 380–950 eV, with an FOV of $1^\circ \times 1^\circ$ and 256 $\times$ 256 pixels, with an angular resolution of $14'' \times 14''$. The simulation runs to a distance equivalent to $z = 2$.

The energy band 380–950 eV is adopted throughout the paper, unless otherwise stated, and is the same as the one we used in our previous work (Ursino & Galeazzi 2006). We chose the upper limit to include the emission from NeIX at 921 eV and the strong FeXVII lines in the energy band 0.725–0.827 keV, while with the lower we could exclude the strong C V and C VI lines at 0.308 keV and 0.367 keV, respectively. This makes us sensitive to O VII out to redshifts of $z = 0.5$. It is also advantageous to avoid instrumental effects due to the neutral carbon absorption edge at 0.284 keV, which is present in most instruments.

The angular resolution is a trade-off between the requirements of accuracy and computing resources. In our previous work, we have shown that the detected WHIM emission depends...
on the angular resolution (Ursino & Galeazzi 2006). We have
seen that the characteristic angular size of filaments is of the
order of a few arcminutes and that with a coarse resolution the
probability of detecting individual WHIM filaments becomes
negligible. Similarly, a more detailed analysis on the effect of
the angular resolution has also been reported in Bertone et al.
(2010). The chosen angular resolution is well below the typical
WHIM scale as indicated in both papers, and should allow a
good, unbiased characterization of the angular distribution of
the WHIM emission.

For this exercise we generated images for each of the three
gas phases, for each redshift slice corresponding to a box of
the hydrodynamic simulation, and for the full line of sight, and
we selected a region in the image from which to extract the
relative spectra for different circular FOVs. Looking at the
images of the slice in the redshift interval $0.201-0.273$ (Figure
6), the different nature of the three phases is clear. The WHIM
is collected in large, diffuse regions and is sparse throughout
the whole image in filaments. The dense WHIM is grouped in
much more compact objects and is found in the inner part of the
WHIM regions, where it traces the WHIM filaments. The hot
gas is found in a few large objects, close to the regions where the
WHIM emission is stronger. The general picture confirms the
assumption that was made when we defined the three phases.
The hot gas is associated with big clusters of galaxies while
the dense WHIM corresponds to the groups of galaxies. The
diffuse WHIM, on the other hand, appears mostly as halos that
envelope the groups. As expected, when the contribution at all
redshifts is included, the filamentary structure of the WHIM
is partially hidden in these images (Figure 5). This is due
to the large energy interval used in the generation of these
images. However, when the energy information is taken into
account by focusing, for example, on a narrow energy interval
containing the redshifted O vii line, the spatial information
about the three phases can still be extracted. Figure 7 shows
the image obtained by generating an image of the full line of
sight for the narrow energy band corresponding to the energy
of O vii lines with redshift between 0.201 and 0.273. Notice
that we obtain the same spatial information of Figure 6 for
the WHIM, while the hot and dense sources are more compact
than for the full energy band. In the case of dense sources, this
indicates that we see O vii emission mostly from their core.

With the hot sources, on the other side, although we are
indeed probing the O vii band, we actually see photons emitted
via bremsstrahlung, which dominates (in this band) at high
temperatures.

Figure 8 shows the spectra extracted from the selected FOVs
in Figures 5 and 6, along the full line of sight. We can use
it to set a limit on the angular resolution required to study
the WHIM. The 1′ FOV is centered on a WHIM filament. The
spectrum shows O viii emission lines from the selected filament,
together with lines emitted by baryons at different redshifts.
When we increase the FOV to 3′, we also find the O vii line
from a different region of the filament. At the same time, the
overall flux from the WHIM at all redshifts increases due to
the contribution of other regions, making it more difficult to
identify the signal of the filament being studied. At even larger
FOVs, the lines from the filament are overshadowed by the
total WHIM flux. This indicates that, at redshift $z \sim 0.25$, an
angular resolution of a few arcminutes is necessary in order to
detect a filament. A more systematic investigation of the angular distribution of the WHIM emission is discussed in the next section.

The spectrum on the right side of Figure 8 shows that the emission of the dense WHIM and the hot gas is stronger than the WHIM, and the flux is between 5 and 10 times higher. It is important to note that the cluster contribution to the spectrum in the soft X-rays is mostly due to bremsstrahlung. To separate the WHIM from these two phases we need to identify the emission lines, and this sets the requirement on the energy resolution of any instrument designed to study the WHIM. An energy resolution of a few electron volts is necessary to resolve single lines, in particular if we want to identify the O\textsc{vii} triplet at \(\sim 570\) eV, the main tracer of the WHIM.

5. X-RAY EMISSION AND METALLICITY

We generated four sets of identical simulations, with the metallicity as the only parameter that was changed, using the models described in Section 3. For simplicity, we refer to those models as “Borgani,” “Croft,” “Scatter,” and “Cen.”
To evaluate the contribution of the WHIM to the total diffuse X-ray emission we compared our simulations with results from the X-ray Quantum Calorimeter (XQC) sounding rocket program (McCammon et al. 2002) and the ROSAT All Sky Survey (RASS; Snowden et al. 1994). XQC is the only current mission using high-resolution microcalorimeters for the study of the DXB in the energy range 50–2000 eV, while RASS is the most accurate X-ray survey below 1 keV and is considered the benchmark for any soft DXB study. The most recent XQC results published (McCammon et al. 2002) predict a surface brightness of 29.3 photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in the 0.380–0.950 keV energy band. In Table 1, we report the surface brightness predicted by the four simulations in the same energy band and the predicted flux in the RASS R4 and R5 bands (Snowden et al. 1994) in units of 10$^{-6}$ photons s$^{-1}$ arcmin$^{-2}$ (the default RASS units). The average RASS flux in the R4+R5 bands is $\sim 1.39 \times 10^{-6}$ photons s$^{-1}$ arcmin$^{-2}$. The Borgani model has the lowest brightness, 0.77 $\pm$ 0.04 photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in the 0.380–0.950 keV energy range, and can be used to put a lower limit to the WHIM emission. Note that even if this model has a high average metallicity at low densities (as shown in Figure 4 and Table 1), most of the particles actually have no metals due to the poor diffusion of metals to low-density regions in the hydrodynamic code. Moreover, the few particles with metals have low density and, since emission is proportional to density squared, they give little contribution as well.

The Croft model predicts a relatively low emission as well, 1.84 $\pm$ 0.08 photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This model was designed to work at high redshift ($z \sim 3$), where the gas is still rather poor in metals. Although being somewhat unrealistic, this model is a test of intermediate metallicity.

The Scatter model, on the other hand, was created for gas at $z = 0$, and slightly overestimates the observed metallicities at $0 < z < 0.5$ (Z $\sim 0.3 Z_\odot$ for groups and clusters and Z $\sim 0.1 Z_\odot$ for diffuse gas, as seen in Section 1), but it gives much higher metallicities (possibly up to a factor 10) than what is measured at higher redshift (0.5 $< z < 2$). The average surface brightness is 4.3 $\pm$ 0.2 photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This value is the highest predicted by the set of simulations and we use this as an upper limit to the flux.

Using the Cen metallicity model, the simulation predicts a surface brightness of 4.2 $\pm$ 0.2 photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$. All the values are smaller than what we obtained in our previous work (Ursino & Galeazzi 2006) where, using the hydrodynamic model by Cen & Ostriker, (1999a) we obtained a predicted brightness of 6.9 $\pm$ 0.9 photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$. It must be noted that in the previous work, we analytically extrapolated the values of temperature, density, and metallicity from the data set at $z = 0$ as it was the only data set available. It is therefore possible that the evolution of the gas is rather different than what is used in the current simulations.

Focusing on the O VIII line at 650 eV in Figure 15 of McCammon et al. (2002) we see that, if we consider the local foreground and the AGN component, there is still room for an extragalactic contribution of $\sim 9$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$ ($\sim 0.09$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ if we assume an energy interval $\Delta E = 10$ eV). In the same band, our four metallicity models predict a surface brightness of 9.9E $- 3 \pm 0.6E$ – 3 photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$, 0.02$5 \pm 0.002$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$, 0.05$9 \pm 0.004$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$, and 0.05$8 \pm 0.004$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$, respectively, all within the limits of the XQC sounding rocket data (McCammon et al. 2002).

The two higher metallicity models predict values that are half of the ROSAT data in Figure 1 of Kuntz et al. (2001). The absorbed extragalactic component in the 380–950 eV, in fact, has an almost constant value of $\sim 10$ keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$, corresponding to $\sim 8.8$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

Recently, Hickox & Markevitch (2007) quantified the unresolved X-ray background in the Chandra deep fields as (1.0 $\pm$ 0.2) $\times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ in the 0.65–1 keV band. Although these measurements were performed in a very limited region of the sky (a circle of radius 3/2), this value constitutes an upper limit to the WHIM emission. All of our models fall below this limit, predicting, in the same band (6.5 $\pm$ 0.4) $\times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$, (1.5 $\pm 0.1$) $\times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$, (3.3 $\pm 0.3) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$, and (3.2 $\pm 0.3) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$, respectively.

The results obtained with the Borgani model can also be compared with Roncarelli et al. (2006), who obtained an estimate on the DXB starting from the same cosmological simulation and with a similar method. They obtain $5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ in the same band (as extrapolated by Hickox & Markevitch 2007), thus almost an order of magnitude higher than the (6.5 $\pm 0.4) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ obtained with the Borgani model, although within the observational upper limit. This difference is due to the fact that Roncarelli et al. (2006) adopted an observationally oriented approach by excluding from their maps the extended sources detected by Chandra observations. This means that their estimate includes also the emission from unresolved clusters and groups (corresponding to our hot and dense WHIM phases, respectively) that are instead excluded in our estimate.

Measurements of the autocorrelation function (ACF) for a set of XMM-Newton observations (Galeazzi et al. 2009) point to the fact that the X-ray emission in the 0.4–0.6 keV band from the WHIM is 12 $\pm$ 5% of the total extragalactic diffuse emission. Our models predict 10 $\pm$ 1%, 12 $\pm$ 1%, 17 $\pm$ 1%, and 13 $\pm$ 1%, in agreement with the observational data.

In order to understand the dependence of flux on the metallicity and redshift of the sources, we calculated the average flux of each slice of the simulations and compared those average with the results from our previous work (Ursino & Galeazzi 2006). Figure 9 clearly shows that, while the overall photon budget is comparable between the old and new analysis, the dependence of flux on metallicity model. The four models show the same trend, with a rather slow decrease of photon flux at increasing redshift (compared to the older simulations), but the relative steepness is different. For the Borgani metallicity, photons coming from low redshift are 10 times more

Table 1

| Model   | Z       | SF$^a$ | RASS R4 flux | RASS R5 flux |
|---------|---------|--------|--------------|--------------|
| Borgani | 0.103   | 0.77 $\pm$ 0.04 | 1.2 $\pm$ 0.2 | 1.3 $\pm$ 0.3 |
| Croft   | 0.043   | 1.84 $\pm$ 0.08 | 3.4 $\pm$ 0.6 | 3.1 $\pm$ 1.7 |
| Scatter | 0.158   | 4.3 $\pm$ 0.2  | 8.4 $\pm$ 1.5 | 7.2 $\pm$ 1.7 |
| Cen     | 0.158   | 4.2 $\pm$ 0.2  | 8.2 $\pm$ 1.6 | 7.1 $\pm$ 1.7 |

Notes. The metallicity is calculated at redshift 0.

$^a$ In the energy range 0.380–0.950 keV in units of photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

$^b$ In units of 10$^{-6}$ photons s$^{-1}$ arcmin$^{-2}$.

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than those coming from very high redshift; in the case of Croft metallicity the ratio of photons from near sources over photons from distant sources is around 20, and for the highest metallicity models this ratio is of the order of ∼30. Since in our model’s metallicity depends directly on density, the metal abundance is higher in high-density regions where there is more star formation. At low redshift, when the universe is older, there are more high-density regions compared to the young universe, and therefore there are more high-metallicity regions. This makes the difference between the abundance of metals at low redshift and at high redshift bigger for those models where metallicity is stronger. This effect is due only to the relation between density and metallicity and does not depend on any assumption of star formation history.

We also investigated the potential capability of a WHIM dedicated future mission such as EDGE (Piro et al. 2009) or Xenia (Hartmann et al. 2009). The Wide Field Imager on EDGE (or Xenia—values in brackets) has a proposed FOV with diameter 1.5 (1.5), an angular resolution of 15′ (10′), an effective area of 580 (1000) cm² at 1 keV, and an energy resolution of 70 eV at 1 keV (70 eV at 0.5 keV). The Wide Field Spectrometer (WFS) on EDGE (Xenia) has a proposed FOV of 0.7 × 0.7 (1′ × 1′), an angular resolution of 3.7 (2.5), an effective area of 1163 (1300) cm² at 600 eV, and an energy resolution of 3 (1) eV at 0.5 keV. We simulated an experiment similar to the WFS, with roughly the same effective area (1000 cm²) and angular resolution (3′ × 3′ pixels), values close to the EDGE/Xenia goal and consistent with our previous work. Figure 10 shows the frequency of flux depending on the metallicity model. The frequency using the Borgani model is peaked at a much smaller value than the other models, and seldom finds pixels with more than 6 photons cm⁻² s⁻¹ sr⁻¹. The Scatter and Cen models behave almost identically. They have a broad distribution, centered at around 5 photons cm⁻² s⁻¹ sr⁻¹, and a long tail going over the 20 photons cm⁻² s⁻¹ sr⁻¹. The Croft model is somehow in between, with a peak at approximately 2 photons cm⁻² s⁻¹ sr⁻¹ and a tail going up to 15 photons cm⁻² s⁻¹ sr⁻¹. The capability of the mission to detect and study the WHIM will strongly depend on the correct metal abundance. In the case of our simulated experiment, with an exposure time of 1 Ms, assuming a total galactic foreground plus extragalactic background of ∼29.3 photons cm⁻² s⁻¹ sr⁻¹ in the 380–950 eV band (obtained using the three-component model by McCammon et al. 2002) and an instrumental noise of ∼0.5 photons cm⁻² s⁻¹ sr⁻¹ (in the same energy band), the threshold for WHIM detection is ∼0.6 photons cm⁻² s⁻¹ sr⁻¹. The probability of finding objects above such threshold is ∼50% for the Borgani metallicity and 99% for the Scatter metallicity. The chance of finding objects with surface brightness greater than 20% of the DXB, equivalent to ∼6 photons cm⁻² s⁻¹ sr⁻¹, is 20% for the Scatter and Cen models, and negligible for the Borgani model.

Figure 11 shows images of the WHIM at redshift z = 0.13–0.20. The ring-like shape of the bright objects is just an artifact due to the fact that X-rays coming from particles classified as hot or dense gas, which are present inside these objects, are not included in these images. The figures represent images of the same part of the sky with X-rays simulated using, respectively, the Borgani (top left), Croft (top right) Scatter (bottom left), and Cen (bottom right) models. Notice that the amplitude of surface brightness of the four maps changes by almost an order of magnitude going from the Borgani to the Cen metallicity model. The Croft metallicity is proportional to density, therefore brightness is a direct function of density squared. For the Scatter and Cen models, the ratio between the mean value of metallicity at low and high density is smaller, and therefore the fainter objects are more visible. There is also the Scatter effect that comes into play, changing the brightness between regions with the same density. The Borgani model is strongly affected by the poor metal diffusion that leaves many particles depleted in metals, therefore there is limited contribution from lines, and the emission is characterized almost only by the continuum due to bremsstrahlung.

In Figure 12, we show the energy spectra in the 480–520 eV band extracted from two different regions of Figure 11 where the WHIM is particularly bright. The lines correspond to the O vii...
triplet coming from two emitters at redshift $z \sim 0.15$. Looking at the spectra, we see how the metallicity model influences the intensity of the lines. The Scatter and Cen models have the highest metallicity and they predict the strongest emission line for an O\textsc{vii} emitter. The lines simulated with the two models have almost the same intensity, with a little difference due to the correction to metallicity that the Cen model applies to the Scatter one. Since in this case the redshift is small and the overdensity is relatively high, the correction to metallicity is small. From Figure 4 we see that for the Croft model the metallicity is three to five times lower than for the Scatter model, and the difference with the Cen model at higher redshift is smaller. The same ratio holds between the intensity of the lines in the spectra extracted and emission follows the lead of metallicity quite well. For the Borgani model things are different, as expected. The emitter in the left panel shows no sign of emission lines, even if simulations with the other models show an emitter at that position. Again, this is due to the poor metallicity distribution; this is a region where the particles of the simulation had no contact with metal-rich particles and therefore have no metals at all, and the emission is only in the continuum. The spectrum in the right panel shows the presence of O\textsc{vii} lines also for the Borgani model, showing that this region has gone through metal enrichment, even if not as much as in the case of other metallicity models.

Using maps along the full line of sight we can try to characterize the angular ACF (Kuntz et al. 2001) of the three phases in order to extract the signal of the WHIM. So far experimental work has been done on the DXB (Kuntz et al. 2001; Soltan et al. 2001; Giacconi et al. 2001), giving evidence of a signal at an order of less than 10 arcmin. In our previous work (Ursino & Galeazzi 2006), we used WHIM maps with rather broad angular resolution (1 arcmin) and found a characteristic angle comparable with the experimental values. With the current angular resolution of 14″ we study the angular ACF of the WHIM at even smaller scales, and how it evolves with metallicity. Figure 13 shows the average ACFs for the Borgani, Croft, Scatter, and Cen metallicity models, with error bars representing the cosmic variance for each set of simulated maps. They are in good agreement with each other, giving a characteristic angle of $\sim$10 arcmin and well within the error bars (at this angle) of our previous work. The lower metallicity models hint to a somewhat slightly larger structure scale. The bad match with the older model has more than one reason aside from the very fact that we are dealing with different models. The older maps were smaller ($30′ \times 30′$ instead of $60′ \times 60′$) and the angular resolution was smaller ($1′ \times 1′$, limited by the resolution of the hydrodynamic simulation). The small area gives rise to the much bigger variance and possibly to the fluctuation below 0 at $θ > 5$ arcmin. The worse angular resolution...
Figure 12. Zoom in the 480–520 eV of the simulated emission spectra from the selected dark and bright WHIM regions in the bottom right map of Figure 11. The lines shown correspond to a redshifted O\textsubscript{vii} triplet. The spectra are relative to simulations with the Borgani metallicity model (solid black line), the Croft model (dashed red line), the Scatter model (dotted green line), and the Cen model (dot-dashed blue line).

(A color version of this figure is available in the online journal.)

Figure 13. Average angular autocorrelation function of the WHIM for the Borgani (solid black line), Croft (dashed red line), Cen (dotted green line), and Scatter (dot-dashed blue line) metallicity models compared with our previous work (double dot-dashed purple line). The error bars represent the cosmic variance for each set of maps.

(A color version of this figure is available in the online journal.)

also explains (at least in part) the steeper slope at small angular scales.

6. CONCLUSIONS

In our work, we used the cosmological simulation by Borgani et al. (2004) to predict spectral and spatial properties of the WHIM. Since metallicity is the main source of uncertainties for this prediction, we used four metallicity models, one self-consistent with the Borgani simulation, and three analytical models, two of them based on statistics adopted from Cen & Ostriker (1999a). The first model gives a lower limit to metallicity predictions, while the last two give a higher limit. For each model, we generated a set of 1° × 1° maps up to redshift $z = 2$.

The tools we developed allowed us to characterize the WHIM emission, obtaining the following main results.

1. The predicted X-ray emission from the WHIM depends strongly on the metallicity model: the strongest emission comes from the more metallic model, and it can be up to an order of magnitude stronger than from the low metallicity models. The predicted emission, in particular from high metallicity models, is in good agreement with observational data. It accounts for a fraction between 2.5% and 15% of the total DXB, and between 11% and 66% of the extragalactic emission at the energy of O\textsuperscript{viii} as measured from the XQC experiment (McCammon et al. 2002). It accounts for 8%–49% of the extragalactic component observed with ROSAT (Kuntz et al. 2001) and for 6.5%–33% of that measured with Chandra (Hickox & Markevitch 2007). The WHIM emission spans from 10% to 17% of the total emission, in agreement with the 12% estimated with analysis of the ACF (Galeazzi et al. 2009).

2. The predicted surface brightness decreases with increasing redshift of the emitting gas and most of the photons come from redshift $z < 1.2$.

3. The probability distribution function of emission along a line of sight depends on metallicity. For low metallicity, the distribution is narrow and peaked around its low average value, for high metallicity the distribution is wide and there are higher chances to point at bright objects (20% possibility to find an object brighter than 6 photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for the statistical models).

4. A simple analysis of the maps with the ACF gives a characteristic angular size of less than a few arcmin.

In summary, the prediction from our models is consistent with the constraints from observational data for all the metallicity distributions we assumed. A future mission with high energy resolution and good angular resolution will allow us to discriminate between the signals of the WHIM and of clusters of galaxies and possibly tracing the WHIM structure. Since the expected emission depends strongly on metallicity, measuring the flux from the WHIM will make it possible to estimate the metal abundance of the WHIM.

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