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IS THERE STILL ROOM FOR WARM/HOT GAS? SIMULATING THE X-RAY BACKGROUND SPECTRUM

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ABSTRACT

At low redshifts, a census of the baryons in all known reservoirs falls a factor of two to four below the total baryon density predicted from Big Bang nucleosynthesis arguments and observed light element ratios. Recent cosmological hydrodynamic simulations suggest that a significant fraction of these missing baryons could be in the form of warm/hot gas in the filaments and halos within which most field galaxies are embedded. With the release of source count results from Chandra and recent detections of this gas in O VI quasar absorption lines, it becomes interesting to examine the predictions and limits placed on this component of the X-ray background (XRB). We have used new hydrodynamical simulations to predict the total X-ray spectrum from the gas in the 100 eV to 10 keV range. We find that, when uncertainties in the normalization of the observed XRB and the value of Ω_b are taken into account, our results are consistent with current observational limits placed on the contribution of emission from gas to the XRB. In the $0.5-2$ keV range, we expect the contribution from this component to be 0.63×10^{-12} erg s^{-1}cm^{-2}deg^{-2} or between 6% and 18% of the extragalactic surface brightness. The peak fraction occurs in the $0.5-1$ keV range where the predicted line emission mirrors a spectral bump seen in the latest ASCA/ROSAT XRB data.

Subject headings: diffuse radiation — large-scale structure of universe — X-rays: diffuse background

1. INTRODUCTION

Measurements of the total baryon density from the optical depth of the Lyman α forest (Rauch et al. 1998) at high redshift ($z \approx 2-3$) are in remarkable agreement with those derived from observed light-element ratios and nucleosynthesis arguments (BBN, Burles & Tytler), which yield a value of $\Omega_{b,D/H} = 0.039 \pm 0.002$, assuming $h \equiv H_0/100 = 0.7$. However, in the local universe, the combined observed contributions of stars, atomic and molecular hydrogen, and cluster gas fall a factor of two to four below this number (Fukugita, Hogan, & Peebles 1998). This is known as the missing baryon problem.

Cosmological hydrodynamical simulations suggest that, at low redshift, a significant fraction, up to 40%, of all the baryons, could be in the warm/hot gas in filaments (e.g., Cen et al. 1995; Cen & Ostriker 1999; Davé et al. 2000; Croft et al. 2000). This diffuse gas, which is also known as the Warm/Hot Intergalactic Medium (WHIM), is located in filamentary structures between clusters of galaxies and in which groups of galaxies are embedded. It is shock-heated to temperatures $T = 10^5 - 10^7$K, between that of the hot cluster gas and the warm gas in voids. The comparatively low density and temperature of this gas make it a challenge to detect and as yet, attempts to observe it in emission have yielded marginal (Wang, Connolly & Brunner 1997; Boughn 1998; Kull & Böhringer 1999; Scharf et al. 2000) or negative results, with an upper bound of 1.1×10^{-12} erg s^{-1}cm^{-2}deg^{-2} in the 0.5 to 2 keV band for intercluster gas (Briel & Henry 1995). However, warm gas has been detected as O VI absorption features in quasar spectra (Tripp & Savage 2000; Tripp, Savage, & Jenkins 2000, and references therein) which seem to coincide in redshift with galaxy overdensities. The WHIM may have been indirectly detected in the observed X-ray background (XRB) autocorrelation (Soltan & Freyberg 2000) and cross-correlation with the galaxy density distribution (Refregier, Helfand, & McMahon 1997; Soltan et al. 1997). In addition, rocket experiments show some evidence of O VII /O VIII emission from this gas (D. McCammon et al., in preparation).

Most of the soft XRB has now been resolved into AGN and other sources, leading to an upper bound on the fraction of the extragalactic soft $1-2$ keV X-ray component due to the WHIM of 25% (Hasinger et al. 1998; Mushotzky et al. 2000; Giacconi et al. 2000). This is a small fraction of the XRB but could represent a large fraction of the baryons of moderate overdensity (Davé et al. 2000). Markevitch (1999), Phillips, Ostriker & Cen (2000) and Pierre, Bryan & Gastaud (2000) have already described possible methods to detect this gas using Chandra and XMM. In addition, the X-ray properties of this gas have been predicted from large scale simulations using both smoothed particle hydrodynamics (SPH) and Eulerian hydrodynamical methods (Croft et al. 2000; L. A. Phillips, in preparation).

We note that the hot gas component of the XRB is well established. Hot gas associated with rich clusters of galaxies is estimated to produce $\sim 10\%$ of the $1-2$ keV background (Hardy et al. 1998) and represents a fraction of approximately 8% of the computed total baryonic complement of the cosmic mass density (Fukugita et al 1998). These diffuse baryons are associated with the $\sim 5\%$ of all galaxies (Bahcall 2000) which are found in rich clusters. Most galaxies are in fact in lower density, lower velocity dispersion regions (such as poor clusters, groups, filaments and the field) and would be expected to be associated with lower density, lower temperature gas. It is the purpose of this paper to ascertain if the expected emission from this gas is consistent with our knowledge of the relatively soft XRB.

We present the total 100 eV to 10 keV X-ray spectrum from the WHIM calculated from new cosmological hydrodynamical simulations. The simulation is described in Section 2 and discussed in the context of the current limits placed on the different components of the XRB, including point sources, cluster gas and the more diffuse WHIM in Section 3. We summarize our results and briefly discuss the implied prospects of detecting the WHIM with ongoing and future X-ray missions in the Conclusions (Section 4).

2. THE INTEGRATED SPECTRUM

In the following calculations, we use the dark matter, galaxy, and gas temperature, density and metallicity information at redshifts zero, 0.5, 1 and 3 from the cosmological hydrodynamical simulation of a $L = 100h^{-1}$Mpc box, with 512^3 fluid elements and 256^3 dark matter particles, described in detail in Cen & Ostriker (1999). The simulation follows the metallicity history of the gas in each cell, enabling us to examine the contribution of metal lines to the XRB spectrum. The helium mass fraction is set to that of primordial gas, Y = 0.24. The chosen cosmology is the "concordance model" (Wang et al. 2000), a flat low-density ($\Omega_0 = 0.37$) universe with a Cosmological Constant ($\Omega_\Lambda = 0.63$), $\Omega_b = 0.035$ and $H_0 = 70$. The AGN integrated spectrum from a new, higher resolution cosmological hydrodynamical simulation of a smaller $L = 25h^{-1}$Mpc box with 768^3 fluid elements (R. Cen & J. P. Ostriker, in preparation) is also used in estimating the large box AGN XRB spectrum.

We assume that the gas is in thermal and ionization equilibrium, and use the Raymond-Smith (1977) code for optically thin plasmas, as modified by Cen et al. (1995), to obtain the average Bremsstrahlung and emission line spectrum from the large box for each of the four output redshifts. We then integrate the $z = 0, 0.5, 1$, and 3 spectra, assuming no evolution, over the redshift ranges bounded by redshifts $z_{bound} = 0, 0.25, 0.75, 2$ and 3, to obtain the total integrated spectrum from the WHIM.

We remove the contribution from gas within $1.5h^{-1}$ Mpc of the center of low redshift ($z \leq 0.2$) clusters in the simulation which were associated with (dark matter + baryonic) masses $M \geq 5.5 \times 10^{14}h^{-1}M_\odot$ (or richness ≥ 2, Bahcall & Cen 1993) by Nagamine, Cen, & Ostriker (2000). Cluster gas emission regions are usually treated as "sources" and removed from the total observed background when attempting to estimate the residual "hot gas background". The component we are addressing in this paper is of course not uniformly distributed. It is also clumped, albeit with a far lower clumping factor than the hot gas in clusters (see Davé et al. 2000 for a detailed discussion). We nevertheless remove the cluster gas from our computation to make this analysis comparable with those usually undertaken in studies of the X-ray sky.

A composite AGN spectrum was obtained from the small box by integrating an AGN template spectrum (Edelson & Malkan 1986) over all redshifts, adopting an AGN emission efficiency in keeping with those observed and proportional to the star formation rate averaged over the whole box (Cen et al. 1998). We use this to estimate the contribution to the XRB spectrum from AGN in the large box. We normalize the integrated AGN spectrum so that at high energies (> 30 keV) the XRB from the large box is completely resolved into AGN (Mushotzky et al. 2000). Cen & Ostriker (1999) integrated the XRB spectrum from AGN, Orion-like stars, and Bremsstrahlung emission from gas over all redshifts for the large box. We can recover the $0.1 - 10$ keV portion of this spectrum to within a few percent by adding the WHIM Bremsstrahlung spectrum obtained above to the estimated contribution from the AGN. This sum will therefore be used as the total simulated XRB spectrum in the discussion below.

The total integrated X-ray spectrum from the WHIM (dotted line) is shown in the upper panel of Figure 1 along with the total XRB spectrum from the large box simulation (solid line). The latest XRB spectra (T. Miyaji et al. 2000, private communication) obtained from the ASCA LSS region for the $0.6 - 10$ keV range (filled circles) and from ROSAT PSPC measurements at lower energies (filled triangles) are also shown. The simulation results scale as Ω_b^2 and our uncertainty concerning this basic parameter must be added to the other uncertainties. The errors due to the finite number of simulation output redshifts and that introduced by only integrating out to a redshift of $z = 3$ are both negligible when compared with this uncertainty. Average published values of $\Omega_b h^2$ range from the low BBN value of 0.019 (Burles & Tytler 1998) to a high estimate of 0.035 from BOOMERANG data (Lange et al. 2000). Ultimately, the uncertainty with regard to simulated surface brightness is not less than a factor of three. The predicted fraction due to the WHIM is shown in the lower panel as a function of the observed ASCA and ROSAT backgrounds (symbols) and as a function of the total integrated XRB from our simulations (dotted line).

3. THE COMPONENTS OF THE X-RAY BACKGROUND

Deep X-ray images (Hasinger et al. 1998; Mushotzky et al. 2000; Giacconi et al. 2000) have shown that at least 75% of the soft XRB is accounted for by sources (including X-ray emission from hot gas in clusters). The percentage of the background remaining after currently known contributions from AGN and other resolved sources have been subtracted is shown in the lower panel of Figure 1, for extremum values of the XRB. A sizeable 25 ± 6% of the latest measurement of the $1 - 2$ keV XRB from the ASCA LSS field, $4.5 \pm 0.33 \times 10^{-12}$ erg s^{-1}cm^{-2}deg^{-2} (T. Miyaji et al. 2000, private communication), remains unresolved. Previous combined ROSAT and ASCA measurements of the XRB have yielded similar or lower average surface brightnesses, as is evidenced by the Barcons, Mateos & Caballos (2000) Bayesian fit to XRB measurements at 1 keV of $6.63^{+0.4}_{-0.6} \times 10^{-26}$ erg s^{-1}cm^{-2}sr^{-1}Hz^{-1} (with 90% confidence errors), which appears as the square in the upper panel of Figure 1. For the low value for the XRB of $3.7 \pm 0.53 \times 10^{-12}$ erg s^{-1}cm^{-2}deg^{-2} (Gendreau et al. 1995) the remainder becomes 9 ± 13%, consistent with zero. Taking their upper limit from Chen, Fabian & Gendreau (1997), Mushotzky et al. (2000) conclude that at most 10^{-12} erg s^{-1}cm^{-2}deg^{-2} of the soft XRB remains unresolved. This value is consistent our prediction of 0.22×10^{-12} erg s^{-1}cm^{-2}deg^{-2} from the WHIM (or 9% of the computed total) in the same energy band. When possible, we have estimated the error bars from information given in the above papers and by assuming that the error for the Hasinger et al. (1998) counts is comparable to that of Mushotzky et al. (2000). This has most probably led to an underestimate of the errors involved in the other quantities described.

In the $0.5-2$ keV band the predicted contribution of emission from gas to the total background is $\sim 13\%$. At first glance, this value is quite a bit lower than the 35% from the intergalactic medium obtained by Croft et al. (2000). However this discrepancy can be explained by the inclusion in the Cen & Ostriker (1999) code of substantial feedback and our excluding the contribution from nearby clusters. We obtain an AGN contribution of 86%. The remaining 1% of the emission comes from hot gas in nearby rich clusters and agrees remarkably well with the observed 1.4% associated with ($z \leq 0.2$) Abell (1958) clusters (Soltan et al. 1996). As expected, in the $2-10$ keV band, the WHIM contribution falls to 5% of the computed background. Metal line emission produces 49% (11%) of the $0.5-2$ keV ($2-10$ keV) WHIM contribution. The peak fraction occurs in the $0.5-1$ keV range where a spectral bump coincides with that seen in the ASCA and ROSAT data. The factor of two difference between the normalization of our total computed background and that of the observed background may be due to our low assumed value of Ω_b or to an underestimate of the observed AGN formation rates which we used to compute the AGN spectrum. If we assume that the latter is indeed the case, we can compare the contribution from gas predicted by our simulations with the observed background. In the $1-2$ keV range, this results in a 6% contribution from the WHIM (up to 18% using the upper limit value of Ω_b).

If one accepts the latest value of the XRB as correct, then a portion of the soft XRB has yet to be explained. It is unlikely that all of the remainder will be resolved into AGN, since fainter AGN have harder spectra and the high spatial resolution (0.5 arcsec) of Chandra ensures that most of the sources have now been resolved. We know that most of the XRB is due to sources but there must also be a contribution from the gas whose presence has been established in clusters, groups and galaxies. In addition, the amount attributable to gas emission can only increase as flux and surface brightness observational limits are improved and the WHIM at the outskirts of groups and clusters is detected. It is therefore likely that the remaining portion of the XRB is due to a combination of gas and some (point) sources.

The current detections of and limits on the WHIM emission in the $0.5-2$ keV band can be compared with the integrated surface brightness of 0.63×10^{-12} erg $\mathrm{s^{-1} cm^{-2} deg^{-2}}$ which we obtain from the simulated XRB gas spectrum. (This value is comparable to that quoted in Croft et al. (2000), if one takes into account a factor of 1.8 difference in Ω_b^2). Briel & Henry (1995) used ROSAT All-Sky Survey data to search for filaments between 40 Abell (1958) cluster pairs separated by less than $25h^{-1}$ Mpc. They placed a 2σ upper limit on the filament X-ray surface brightness of 1.1×10^{-12} erg $\mathrm{s^{-1} cm^{-2} deg^{-2}}$ in the $0.5-2$ keV band, using a plasma temperature of 0.5 keV, typical of those seen for the intercluster medium in the hydrodynamical simulations quoted above.

In a deep ROSAT PSPC observation around the galaxy cluster A2125, at $z = 0.25$, Wang, Connolly & Brunner (1997) find evidence of low surface brightness X-ray emission from 0.85 keV gas with an extent of $\sim 1.7h^{-1}$ Mpc (11 arcmin). It appears correlated with an overdensity of galaxies and is probably part of a $\sim 6h^{-1}$ Mpc (35 arcmin) superstructure which they liken to filamentary structures seen in simulations. Kull & Böhringer (1999) found evidence of X-ray emission extending over $\sim 9h^{-1}$ Mpc, connecting three clusters in combined ROSAT PSPC and ROSAT All-Sky Survey observations of the core of the Shapley Supercluster. Both of these detections yield surface brightnesses that are a factor of 4 to 10 higher than the upper limit established by Briel & Henry (1995) and may be evidence of gas stripped during cluster interactions rather than true filament gas. However, the gas temperature and physical extent of the emission are consistent with the filamentary structures seen in our simulations. In their analysis of a deep ROSAT PSPC field, Scharf et al. (2000) find a half degree filamentary structure with a $0.5-2$ keV surface brightness of 0.58×10^{-12} erg $\mathrm{s^{-1} cm^{-2} deg^{-2}}$. This filament is also present in the form of an I Band galaxy overdensity. The X-ray surface brightness of this 5σ significance detection is well within the residual limits outlined above and is consistent with the computed average surface brightness.

4. CONCLUSIONS

Our prediction for the fractional X-ray contribution to the total XRB spectrum is consistent with the latest limits from AGN and other resolved sources in deep pointings from ROSAT (Hasinger et al. 1998) and Chandra (Mushotzky et al. 2000; Giacconi et al. 2000). The average integrated surface brightness from the gas of 0.63×10^{-12} erg $\mathrm{s^{-1} cm^{-2} deg^{-2}}$ in the 0.5 - 2 keV band falls below the upper limits set by Briel & Henry (1995) and therefore, as of yet, the presence of gas between pairs of clusters cannot be ruled out. We are just reaching the flux limits necessary for the detection of this gas. The expected average flux levels lead us to predict that the WHIM could be observable with current missions such as Chandra and XMM. This possibility is explored in greater detail for XMM in Pierre et al. (2000) and for Chandra in Phillips et al. (2000). In the next decade, an effort should be made to quantify this WHIM component in clusters, groups, galaxies, filaments and/or sheets since a significant fraction of the baryons in the universe could be in this medium.

One of the major challenges in detecting the intermediate temperature gas in filaments will be to confirm the extragalactic origin of emission whose broad band spectral signature matches that predicted for the WHIM. The cross-correlation of the observed XRB and projected galaxy density distribution proves to be an ideal tool for this (L. A. Phillips, in preparation). The cross-correlation (CCF) flattens into a signature plateau at at scales of a few to ten arcmin (Refregier et al. 1997; Soltan et al. 1997). Soltan & Freyberg (2000) also see this feature in XRB autocorrelation calculations. The plateau in the CCF can be reproduced by the correlation of the X-ray emission from the WHIM in filaments with the simulated projected galaxy distribution (Phillips et al. 1999; Croft et al. 2000; L. A. Phillips, in preparation). If the gas is not detected at the predicted fluxes, the metallicity history of the WHIM in the simulations should be closely re-examined since a large fraction of the soft X-ray emission from this gas arises from metal line emission. Indeed, the peak fractional contribution from the WHIM occurs in the $0.5 - 1$ keV range where we predict a bump due to line emission coincident with a similar bump seen in the observed ASCA and ROSAT XRB spectrum.

The presence of the WHIM in groups of galaxies has already been established (Mulchaey et al. 1996). Groups that reside in galaxy filaments tend to have higher diffuse X-ray fluxes, indicating a higher density of gas (Mahdavi et al. 2000). Warm gas has also been detected in the halos of galaxies and in galaxy filaments (both in O VI absorption and in X-ray emission, see references above). Therefore the question is not whether there is a WHIM, but rather how much of it there is and where it is located. And once the answer to this question is known, we can move towards a better understanding of the physical state of most of the baryons in the universe.

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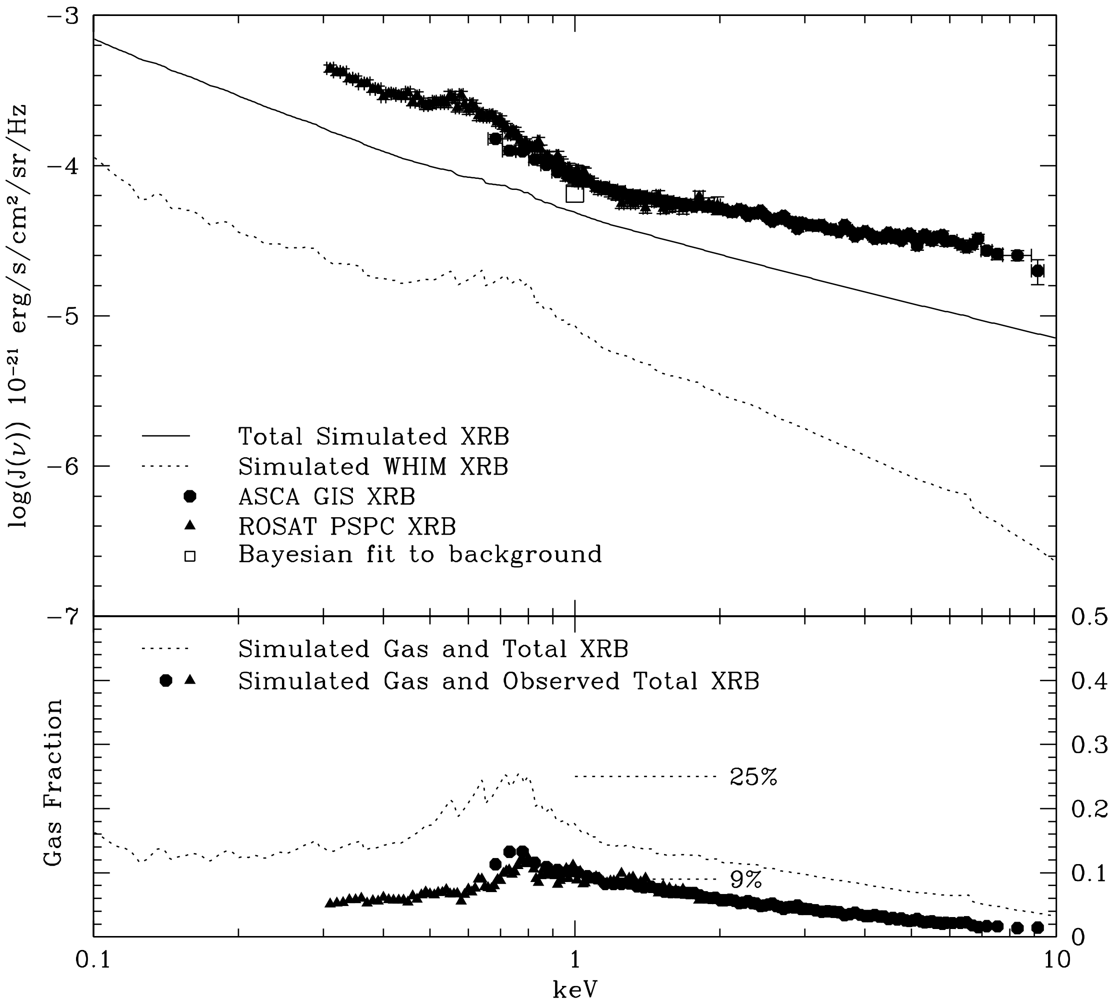

Fig. 1.— Integrated XRB from AGN, stars and gas (solid line) and from the WHIM alone (dotted line). The latest Miyaji et al. (2000, private communication) observations of the XRB spectrum from the ASCA LSS region and ROSAT PSPC fields (circles and triangles, respectively) are also shown along with the Barcons et al. (2000) Bayesian fit to observations of the X-ray background (square, vertical scale illustrates size of error-bars). The fractional contribution of the WHIM to the simulated total (line) and Miyaji et al. (2000) observed backgrounds (symbols) is plotted in the lower panel.