Searching for Baryons with Chandra

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Abstract. At low redshifts, measurements of the total baryon content in stars, atomic and molecular hydrogen, and cluster gas fall a factor of two to four below the baryon density derived from observed light-element ratios and nucleosynthesis arguments. A possible hiding place for a significant fraction of the missing baryons is in the warm/hot gas at temperatures $T = 10^5 - 10^7 K$. We present predictions of the contribution to the soft X-ray background from warm/hot gas emission calculated using new hydrodynamical simulations and discuss the possibility of detecting the spectral signature of this gas using the Chandra X-ray Observatory.

1. Introduction

Lyman $\alpha$ measurements of the total baryon density (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 (Burles & Tytler 1998), 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).

Recent simulations suggest that at low redshift a large fraction of the baryons in the universe could be in the form of warm/hot gas in filaments (Cen et al. 1995; Cen & Ostriker 1999; Davé et al. 2000, and references therein). This diffuse gas is also known as the warm/hot intergalactic medium (WHIM). It is located outside of clusters of galaxies and is heated to temperatures, $T = 10^5 - 10^7 K$, intermediate between those of the hot cluster gas and the warm gas in voids. The comparatively low density and temperature of the WHIM make it a challenge to detect and as yet, attempts to observe it emission have yielded marginal or negative results (Briel & Henry 1995; Wang, Connolly & Brunner 1997; Kull & Böhringer 1999; Scharf et al. 2000).

As part of on-going work to characterize the X-ray background from the WHIM, we have calculated the integrated $0.2 - 10. \text{ keV}$ spectrum from this gas (Phillips, Ostriker, & Cen 2000). We compare predicted flux levels with existing limits from observations. We have also generated model spectra to estimate the possibility of detecting the signature of this gas using the high spatial resolution, energy resolution, and soft X-ray detection capabilities of the ACIS-S chips on the Chandra X-ray Observatory (Phillips 2000).
2. The Integrated X-ray Background Spectrum from the WHIM

The integrated X-ray background spectrum from the large box was calculated by Cen & Ostriker (1999) by adding the contribution from Orion-like stars, AGN and Bremsstrahlung emission from gas in their cosmological hydrodynamical simulation of a large $L = 100 h^{-1}$ Mpc box. 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 $H_0 = 70$. However, the contribution from emission lines to the integrated spectrum was not included.

In order to determine the integrated X-ray spectrum from the WHIM alone, we assume the gas is in thermal and ionization equilibrium. We then 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 spectra from the WHIM in the large box at output redshifts $z \leq 3$. These average spectra are used to obtain the integrated WHIM X-ray background contribution. The AGN spectrum is estimated by normalizing the integrated AGN spectral template obtained from a smaller box so that at high energies ($> 30$ keV) the X-ray background is almost completely resolved into AGN (Mushotzky et al. 2000). A more detailed description of these calculations is given in Phillips, Ostriker, & Cen (2000). Since the contribution from stars falls off rapidly at energies greater than 0.2 keV, we can recover the total Cen & Ostriker (1999) integrated spectrum by adding the AGN contribution to the WHIM Bremsstrahlung spectrum. The sum of the contribution from the WHIM and the AGN spectrum is used as the total simulated XRB spectrum in the discussion below.

The integrated spectrum from the WHIM is shown in Figure 1 and is used in the following section to obtain flux predictions to compare with observational limits. The upper panel depicts our WHIM results along with the total X-ray background spectra from the large box simulation and from the Lockman Hole ROSAT PSPC data in Miyaji et al. (1998). The latter is consistent with a Bayesian fit to the observed X-ray background at 1 keV by Barcons, Mateos, & Ceballos (2000). The predicted fraction due to the WHIM is shown in the lower panel as a function of the mid-range, Miyaji et al. (1998) observed background (dots) and as a function of the total integrated X-ray background from simulations (solid line).

3. The X-ray Background Breakdown

Table 1 shows the current percentage contributions from AGN and other sources to the X-ray background for extremum values of the X-ray background (Hasinger et al. 1998, Mushotzky et al. 2000; Giacconi et al. 2000). The low value for the X-ray background of $3.7 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$ is taken from Gendreau et al. (1995), the mid-range values from spectral fits to ROSAT PSPC data in Miyaji et al. (1998) and the upper limit of $4.4 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$ from Chen, Fabian & Gendreau (1997). In all cases, the errors shown are estimates obtained from adding errors stated in the above papers in quadrature. The residual fraction of the background is given in the last row and varies from 9% to 23%. In the 1 – 2 KeV band, at most $10^{-12}$ erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$ remains to
Figure 1. Integrated XRB from AGN, stars and gas (solid line) and from the WHIM alone (dotted line). The Miyaji et al. (1998) Lockman Hole ROSAT PSPC XRB (circle) and Barcons et al. (2000) Bayesian fit to XRB observations (square) are also shown. The fractional contribution of the WHIM to the simulated total (line) and Miyaji et al. (1998) observed background (symbols) is plotted in the lower panel.
be resolved (Mushotzky et al. 2000). It is unlikely that this will all be resolved into AGN however, 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. Integrating the WHIM spectrum we obtained in the previous section over the energy band $1 - 2$ keV, we obtain a value of $0.22 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$ which represents 9% of the simulated background and is consistent with the limits placed on the contribution by observations.

### Table 1. Sources in 1 to 2 keV X-ray Background

| Reference       | S$^{1,2}$   | Resolved $^{1,3}$ | Remainder $^1$ | % $^4$ |
|-----------------|-------------|-------------------|----------------|-------|
| Gendreau et al. | 3.7 ± 0.53  | 3.38 ± 0.014      | 0.32 ± 0.54    | 9.    |
| Miyaji et al.   | 4.2 ± 0.33  | 3.38 ± 0.014      | 0.82 ± 0.34    | 20.   |
| Chen et al.     | 4.4         | 3.38 ± 0.014      | 1.12           | 23.   |

1 in $10^{-12}$ erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$
2 total surface brightness in 1 - 2 keV band
3 Hasinger et al. (1998) and Mushotzky et al. (2000)
4 of XRB not resolved
5 error information not available

4. Detecting WHIM with Chandra’s ACIS-S

We have simulated spectra obtained from adding all the WHIM emission in a $8' \times 8'$ field of view. A distribution of typical resulting fluxes is shown in Figure 2. The dotted line corresponds to the flux limit for extended sources in deep Chandra exposures above which the count rate in the ACIS-S chips should allow us to use the intermediate energy resolution of the instrument to study the broad band spectral signature of the WHIM (Phillips et al. 1999). We plan to use the high spatial resolution of Chandra to look at the background between the sources detected in the deep ACIS-S observation of the Hawaii Deep Survey field SSA31 field (Mushotzky et al. 2000). We expect the residual background emission to have spectral properties similar to those of the WHIM (Phillips et al. 2000b). The spectra and their implications will be described in greater detail in Phillips (2000).

5. Conclusion

We have shown that the integrated X-ray background spectrum from the WHIM we obtain from a large $100h^{-1}$ Mpc hydrodynamical simulation is consistent with current observational limits placed on the contribution from diffuse gas to the X-ray background. Our preliminary simulations of the spectrum one could obtain in a $8' \times 8'$ field of view indicate that it may be possible to use ACIS-S chips on the Chandra X-ray Observatory to look between the sources and detect the spectral signature of the WHIM. We are now working on a more detailed modeling of
Figure 2. Distribution of expected flux from the WHIM in 8′ × 8′ FOV.
the integrated X-ray background from the WHIM in a \(8' \times 8'\) field of view. For a more detailed description and discussion of the integrated background spectrum simulation outlined in this poster, please see Phillips, Ostriker, & Cen (2000).

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