Probing Galaxies through Quasar Absorption Lines
Proceedings IAU Colloquium No. 199, 2005
P. R. Williams, C. Shu, and B. Ménard, eds.

doi:10.1017/S174392130500311X

Hunting for the missing baryons in the warm-hot intergalactic medium

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Abstract. We discuss the physical properties and the baryonic content of the Warm-Hot Intergalactic Medium (WHIM) at low redshifts. Cosmological simulations predict that the WHIM contains a large fraction of the baryons at $z = 0$ in the form of highly-ionised gas at temperatures between 10^5 and 10^7 K. Using high-resolution ultraviolet spectra obtained with the *Space Telescope Imaging Spectrograph* (STIS) and the *Far Ultraviolet Spectroscopic Explorer* (FUSE) we have studied the WHIM at low redshifts by searching for intervening O VI and thermally broadened Lyman α (BLA) absorption toward a number of quasars and active galactic nuclei (AGNs). Our measurements imply cosmological mass densities of $\Omega_b(\text{O VI}) \geqslant 0.0022\ h_{75}^{-1}$ and $\Omega_b(\text{BLA}) \geqslant 0.0035\, h_{75}^{-1}$. Our results suggest that the WHIM at low z contains more baryonic mass than stars and gas in galaxies.

1. Introduction

Weakly and highly ionised intergalactic gas most likely makes up for most of the baryonic matter in the local Universe. While the diffuse photoionised intergalactic medium (IGM) that gives rise to the Lyman α forest is expected to account for ~ 30 percent of the baryons today (Penton, Stocke & Shull 2004), the highly-ionised *Warm-Hot Intergalactic Medium* (WHIM) at temperatures $T \sim 10^5 - 10^7$ K possibly contributes at a comparable level to the cosmological mass density of the baryons at $z = 0$ (e.g. Davé *et al.* 2001). Gas and stars in and around galaxies and galaxy clusters make up the rest (Fukugita 2003). The total cosmological mass density of the baryons, Ω_b, has been restricted to a value of $\Omega_b \approx 0.04$, e.g. by measuring the deuterium-to-hydrogen ratio in high-redshift absorption line systems (e.g. Burles & Tytler 1998) and by analysing the small-scale anisotropy of the cosmic-microwave background (Spergel *et al.* 2003). However, the contribution from the WHIM to Ω_b has been estimated mainly from numerical simulations of structure formation in the Universe rather than from observational results (e.g. Cen & Ostriker 1999; Davé *et al.* 2001). So far, only a few percent of the baryonic matter residing in the WHIM at $z = 0$ has actually been detected. To test the cosmological simulations and to learn about the distribution of the baryons in the local Universe it is of crucial importance to look for possibilities to pinpoint the baryon budget in the WHIM by direct observations.

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2. O VI absorbers

Five-times ionised oxygen (O VI) currently is the most important high ion to trace the WHIM at temperatures of $T \sim 3 \times 10^5$ K in the FUV regime. Oxygen is a relatively abundant element and the two available O VI transitions (located at 1031.9 and 1037.6 Å) have large oscillator strengths. A number of detections of intervening WHIM O VI absorbers at $z < 0.5$ has been reported in the literature (see Sembach *et al.* 2004 and references therein), based on observations with HST/STIS and FUSE. These measurements imply a number density of O VI absorbers per unit redshift of $dN_{\mathrm{OVI}}/dz \approx 13$ for equivalent widths $W_\lambda \geqslant 50$ mÅ, as derived from the analysis of six lines of sight (Sembach *et al.* 2004). Assuming that 20 percent or less of the oxygen is present in the form of O VI ($f_{\mathrm{O\,VI}} \leqslant 0.2$) and further assuming a mean oxygen abundance of 0.1 Solar, the measured number density corresponds to a cosmological mass density of $\Omega_b(\mathrm{O\,VI}) \geqslant 0.0022\ h_{75}^{-1}$. For the interpretation of this value it has to be noted that O VI absorption mainly traces gas with temperatures around 3×10^5 K, but not the million-degree gas phase which probably contains the majority of the baryons in the WHIM.

3. Broad Lyman α absorbers

Next to high-ion absorption from oxygen and other metals, recent observations with STIS (Richter *et al.* 2004; Sembach *et al.* 2004) suggest that WHIM filaments can be detected in Ly α absorption of *neutral* hydrogen. Although the vast majority of the hydrogen in the WHIM is ionised, a tiny fraction ($< 10^{-5}$, typically) of neutral hydrogen should be present if the gas is in collisional ionisation equilibrium (CIE; see Sutherland & Dopita 1993). Depending on the total gas column density of a WHIM absorber and its temperature, weak H I Ly α absorption at column densities $12.5 \leqslant \log N(\mathrm{H\,I}) \leqslant 14.0$ may arise from WHIM filaments and could be used to trace the overlaying ionised hydrogen component. The Ly α absorption from WHIM filaments is expected to be very broad due to thermal line broadening, resulting in large Doppler parameters of $b > 40$ km s^{-1}. For pure thermal broadening, the b value of the Ly α line is related to the temperature of the gas via $\log T \approx \log(60\,b^2)$. In CIE, the ionised gas fraction ($f_{\mathrm{H}} = \mathrm{H}_{\mathrm{total}}/\mathrm{H\,I}$) can be approximated via $\log f_{\mathrm{H}}(T) \approx -13.9 + 5.4 \log T - 0.33\,(\log T)^2$ (Richter *et al.* 2004). Under the assumption that thermal broadening dominates the widths of the WHIM Ly α absorbers, one then can derive the total hydrogen mass of an individual absorber from its b value and H I column density. However, intergalactic Ly α absorbers with b values > 40 km s^{-1} are generally difficult to detect, as they are broad and shallow. High resolution, high S/N FUV spectra of QSOs with smooth background continua are required to successfully search for broad Ly α absorption in the low-redshift WHIM. STIS (functional until 2004) was the only instrument available that delivered such data, but due to the instrumental limitations of space-based observatories, the number of QSO spectra eligible for searching for WHIM broad Ly α absorbers is very limited. The cosmological mass density of the broad Ly α absorbers (BLAs) at low z, $\Omega_b(\mathrm{BLA})$, can be derived from the observed number statistics of broad Ly α absorbers in high-resolution STIS data. We can write:

$$\Omega_b(\mathrm{BLA}) = \frac{\mu\, m_{\mathrm{H}}\, H_0}{\rho_{\mathrm{c}}\, c} \sum_{ij} f_{\mathrm{H},ij}\, N(\mathrm{H\,I})_{ij} \Big/ \sum_j \Delta X_j, \tag{3.1}$$

with $\mu = 1.3$, $m_{\mathrm{H}} = 1.673 \times 10^{-27}$ kg, $H_0 = 75$ km s^{-1} Mpc^{-1}, and $\rho_{\mathrm{c}} = 3{H_0}^2/8\pi G$. The index i denotes an individual broad Ly α system along a line of sight j. Each measured absorption system i is characterised by its neutral hydrogen column density $N(\mathrm{H\,I})_{ij}$ and ionisation fraction $f_{\mathrm{H},ij}$. Each line of sight j has a characteristic co-moving absorption

https://doi.org/10.1017/S174392130500311X Published online by Cambridge University Press

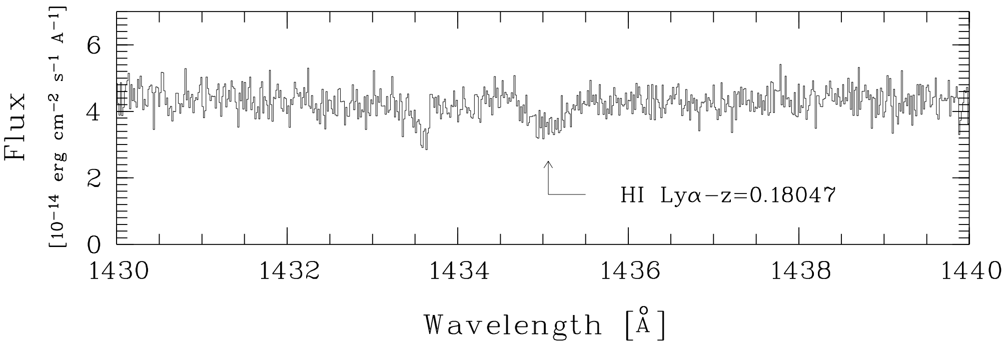

Figure 1. The well-detected broad Ly α absorber at $z = 0.18047$ in the STIS spectrum of H 1821+643 is shown. This system has an H I column density of log N(H I)= 13.21 and a b value of ~ 56 km s^{-1}.

path length, ΔX_j, available for detecting broad Ly α absorption (see e.g. Sembach *et al.* 2004).

We recently have measured the number density of broad Ly α absorbers at low z in the directions of the quasars PG 1259+593, PG 1116+215, H 1821+643, and PG 0953+415, using high-resolution STIS data (Richter *et al.* 2004; Sembach *et al.* 2004; Richter *et al.* 2005, in preparation) and have detected 26 candidate systems along a total redshift path of $\Delta z = 0.939$. Fig. 1 shows an example of a BLA at $z = 0.18047$ in the STIS spectrum of H 1821+643. The detected broad Ly α candidate systems have H I column densities of $12.7 \leqslant \log N \leqslant 14.0$ and b values ranging from 40 to 200 km s^{-1}. Our measurements imply a number of broad Ly α systems per unit redshift of $dN_{\rm BLA}/dz \geqslant 26$ for $z < 0.4$ and a lower limit for the cosmological mass density of Ω_b(BLA)$\approx 0.0035\, h_{75}^{-1}$, which is higher than the limit obtained for the O VI absorbers. A large fraction of the baryons in the low-redshift Universe may exist in those absorbers because the implied temperatures and ionisation corrections are very large. However, absorbers with $b > 100$ km s^{-1} are difficult to study because of their weakness and large width. Non-thermal line broadening mechanisms that may contribute to the observed large b values most likely contribute to the observed broad spectral features. Such non-thermal processes include broadening by the Hubble flow, peculiar gas motions, and macroscopic turbulence. Future observational and theoretical investigations of Ω_b(BLA) will need to address the influence of these processes for the determination of T from the measured line widths. This will be crucial to more precisely pinpoint the baryon budget of the the broad Ly α absorbers at low z.

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