X-RAY OBSERVATIONS OF THE WARM-HOT INTERGALACTIC MEDIUM

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Abstract We present Chandra observations that provide the most direct evidence to date for the pervasive, moderate density, shock-heated intergalactic medium predicted by leading cosmological scenarios. We also comment briefly on future observations with Constellation-X.

1. Introduction

Much of our knowledge of the intergalactic medium (IGM) comes from the rest-frame UV line absorption that it imprints on the spectra of background quasars: the Lyα forest of neutral hydrogen and associated metal lines such as C iv and O vi. The Lyα forest thins out at low redshift, and cosmological simulations predict that the continuing process of structure formation heats a substantial fraction of intergalactic gas to temperatures where it produces little hydrogen Lyα absorption, and where the dominant ionization stages of heavier elements have absorption transitions at X-ray wavelengths rather than UV. One of the few prospects for detecting this low density, shock-heated gas is via the “X-ray forest” of absorption lines it should produce in quasar spectra (Hellsten, Gnedin, & Miralda-Escudé(1998)). Here we discuss X-ray forest searches, with focus on absorption towards H1821+643 (z = 0.297) using a high resolution (λ/Δλ ≈ 500) spectrum obtained with the Chandra X-ray Observatory.

The baryon density implied by big bang nucleosynthesis and the estimated primordial deuterium abundance, Ω_{BBN} ≈ 0.04h_{70}^2 (Burles & Tytler (1998); here h_{70} ≡ H_0/70 km s^{-1} Mpc^{-1}), exceeds the density of baryons in known stars and X-ray emitting gas by roughly an order of magnitude (Fukugita, Hogan, & Peebles 1998). The lower density regime of the “warm-hot intergalactic medium” (WHIM, Cen & Ostriker, 1999) could constitute a major fraction of the “missing” low
redshift baryons. Hydrodynamic cosmological simulations predict that 30-50% of the baryons reside in this phase at $z = 0$ (Davé et al. 2001). HST and FUSE detections of O\textsc{vi} ($\lambda\lambda 1032, 1038\text{Å}$) absorption lines towards H1821+643 (Tripp, Savage, & Jenkins 2000, hereafter TSJ) offer a tantalizing hint of this baryon reservoir. Adopting conservative assumptions of $[\text{O/II}]= -1$ and an O\textsc{vi} ionization fraction $f(\text{O\textsc{vi}})=0.2$ (which is close to the maximum in photo- or collisional ionization), TSJ conclude that the gas associated with these weak O\textsc{vi} absorbers accounts for $\Omega_b \approx 0.004h^{-1}_{70}$ of the cosmic baryon budget, comparable in total mass to all other known low redshift components combined. For most reasonable assumptions about the physical conditions of this absorbing gas, the dominant ionization state should be O\textsc{vii} or O\textsc{viii}, and $f(\text{O\textsc{vi}})$ lower than 0.2, implying a substantially higher baryon fraction.

2. \textit{Chandra observations of H1821+643}

We chose H1821+643 for our X-ray forest search for two reasons: (1) it is one of the brightest X-ray quasars at moderate redshift, and (2) it has been studied carefully for intervening O\textsc{vi} absorption (TSJ; Oegerle \textit{et al.} 2000). The latter is important because even long observations with \textit{Chandra} gratings were expected yield a low S/N spectrum, and searching at redshifts with known O\textsc{vi} absorption allows one to adopt a lower effective threshold for significant detection, greatly increasing the odds of success. Furthermore, detections of or upper limits on X-ray absorption provide new constraints on the physical conditions of the six known O\textsc{vi} absorbers ($z_1=0.26659$, $z_2=0.24531$, $z_3=0.22637$, $z_4=0.22497$, $z_5=0.21326$, $z_6=0.12137$).

We observed H1821+643 with \textit{Chandra} LETG for 480 ksec; the 21–28 \text{Å} spectrum is shown in figure 1. The \textit{Chandra} spectrum was fitted with a smooth continuum plus a Gaussian absorption line at the O\textsc{vi}$\lambda 21.602\text{Å}$ wavelength for each of the O\textsc{vi} redshifts $z_1$ to $z_6$ (see Mathur \textit{et al.} 2002 for details of observations and analysis). This fit yielded 2–3$\sigma$ detections at $z_2$ and $z_6$. Applying the same procedure at the expected wavelengths of the O\textsc{viii} $\lambda 18.969\text{Å}$ line yielded a significant detection only at $z_6$.

The existence of features with $>2\sigma$ significance at several wavelengths predicted \textit{a priori} on the basis of O\textsc{vi} absorption suggests that we have indeed detected X-ray forest lines from highly ionized oxygen in these systems. However, we cannot rule out the possibility that the coincidence between observed features and known absorption redshifts is, in fact, just a coincidence. We calculate the probability of a coincidence, in the absence of a true physical correlation, to be about 5%. Since this probability is not extremely small, we will be cautious in interpret-
Figure 1 The $21 - 28 \text{Å}$ region of the observed spectrum. The red line running through the spectrum delineates the continuum + absorption line model fit to the data. The O\textsc{vii} lines are marked in green and O\textsc{viii} lines in red. The solid tickmarks indicate lines at the known O\textsc{vi} redshifts, with thick lines indicating “detected” systems, whose significance is $\gtrsim 2\sigma$. The dashed tickmarks indicate the candidate “new” systems, which are features of comparable strength within $1000 \text{ km s}^{-1}$ of known O\textsc{vi} redshifts. The broad O\textsc{i} absorption line at $\sim 23.5 \text{ Å}$ is from the Galaxy and the O-K edge at $\sim 23 \text{ Å}$ is from the instrument as well as the Galaxy. The blue bar in the upper right corner of the figure represents a typical error-bar.

3. Implications

We convert the observed line equivalent widths to corresponding column densities for each ion species assuming optically thin gas. The z2 system has an inferred O\textsc{vii} column density of $3.9 \pm 1.7 \times 10^{15} \text{ cm}^{-2}$, while the z6 system has $N(\text{O vii}) = 2.8 \pm 1.5 \times 10^{15} \text{ cm}^{-2}$ and $N(\text{O viii}) = 6.7 \pm 3.5 \times 10^{15} \text{ cm}^{-2}$. Upper limits for undetected systems are typically $\sim 1.9 \times 10^{15} \text{ cm}^{-2}$ for O\textsc{vii} and $\sim 3 \times 10^{15} \text{ cm}^{-2}$ for O\textsc{viii}. Using these, we estimate $f(\text{O vii})/f(\text{O vi})$ and $f(\text{O viii})/f(\text{O vi})$ for the six observed systems and compare them to theoretical predictions (Chan et al. 2002). Figure 2 shows tracks in $f(\text{O viii})/f(\text{O vi})$ vs. $f(\text{O vii})/f(\text{O vi})$ plane.
for the intergalactic medium for a range of temperatures and densities. The dot-dashed line is for pure collisional ionization while the other contours include photoionization by the UV and the soft X-ray background, and correspond to overdensities $\delta_b(1 + z)^3 = 1, 10, 10^2, \text{and } 10^3$. The right panel shows lines of constant temperature. Comparing the two panels shows that $f(\text{O VII})/f(\text{O VI})$ is primarily a diagnostic of gas temperature, while $f(\text{O VIII})/f(\text{O VI})$ constrains the gas density for a given value of $f(\text{O VII})/f(\text{O VI})$. This behavior reflects the competing roles of photoionization and collisional ionization, with the latter being more important for higher temperatures, higher densities, and lower ionization states. The filled points with 1$\sigma$ error crosses mark the two detected O VI systems at $z_2$ and $z_6$. For the remaining four systems, we plot arrows showing the 1$\sigma$ upper limits on $f(\text{O VII})/f(\text{O VI})$ and $f(\text{O VIII})/f(\text{O VI})$.

![Figure 2 Constraints on the physical state of the known O VI absorbers. Left: Curves show the tracks in the $f(\text{O VIII})/f(\text{O VI})$ vs. $f(\text{O VII})/f(\text{O VI})$ plane, based on photo- and collisional-ionization calculations. Numbers along these curves indicate log $T$ in degrees Kelvin. Points with 1$\sigma$ error bars show the detected systems at $z_2$ (square) and $z_6$ (circle). Blue arrows indicate 1$\sigma$ upper limits for the remaining four systems, at $z_4$, $z_1$, $z_5$, and $z_3$ (bottom to top). Right: Same, but with tracks of constant temperature.](image)

At the $\sim 1\sigma$ level, our measurements and limits have a number of interesting implications. First, there are variations in the ion ratios...
from system to system. Second, the upper limits on the undetected systems restrict their locations in the temperature-density plane. For example, the z4 system must have \( T \lesssim 10^{5.5} \text{K} \), and if it is close to this temperature, it must have \( \delta_b \gtrsim 5 \). Third, the overdensities implied by the best-fit line parameters of the detected systems at z2 and z6 are significantly below the values \( \delta_b \sim 100 \) corresponding to virialized systems. In physical terms, the co-existence of detectable amounts of O\textsc{vi}, O\textsc{vii}, and O\textsc{viii} requires that photoionization play a central role in determining the abundance ratios, which is possible only if the density is fairly low.

4. The baryon budget

The major uncertainty in determining the contribution of O\textsc{vi} systems to the cosmic baryon budget is \( f(\text{O\textsc{vi}}) \), and this quantity is what we can estimate using the X-ray observations. We treat all of our 2\( \sigma \) detections as real, but where we have only 1\( \sigma \) measurements or upper limits, we conservatively assume the lowest O\textsc{vii} and O\textsc{viii} column densities consistent with the physical expectation that \( f(\text{O\textsc{vi}}) \leq 0.2 \). This calculation yields \( \langle [f(\text{O\textsc{vi}})]^{-1} \rangle = 32 \pm 9 \), substantially higher than the conservative value of 5.0 that TSJ assumed. Combined with the TSJ result, this ratio implies \( \Omega_b(\text{O\textsc{vi}}) = 0.028 \pm 0.008 \, h^{-1} \) for \( [\text{O}/\text{H}] = -1 \), which substantially exceeds the contribution of any other known low redshift baryon component, representing an appreciable fraction of the baryons predicted by BBN.

5. A note of caution

The implications discussed above are only as compelling as the detections themselves. Constraints on the physical conditions of the IGM at the 2\( \sigma \) level are rather weak. The conclusion that \( T < 10^6 \text{K} \), with a tighter upper limit for stronger absorbers, holds robustly, but stronger physical constraints on the O\textsc{vi} systems at the 2\( \sigma \) level require higher S/N than our present observations afford. However, we can still derive an upper limit on \( \langle [f(\text{O\textsc{vi}})]^{-1} \rangle \), even if the 2\( \sigma \) lines are not real detections. The result is \( \langle [f(\text{O\textsc{vi}})]^{-1} \rangle < 60 \) at 1\( \sigma \) and \( \langle [f(\text{O\textsc{vi}})]^{-1} \rangle < 79 \) at 2\( \sigma \). In combination with the TSJ numbers, even the 1\( \sigma \) upper limit is consistent with \( \Omega_b(\text{O\textsc{vi}}) \approx \Omega_{\text{BBN}} \). If we had obtained null results for all of the O\textsc{vi} systems, then the upper limit on \( \Omega_b(\text{O\textsc{vi}}) \) would have come out well below \( \Omega_{\text{BBN}} \).
6. Discussion and future observations

Our results show that definitive measurements of X-ray forest absorption are extraordinarily difficult. Fang et al. (these proceedings) claim a $4.5\sigma$ detection of an intervening O\textsc{viii} system towards PKS 2155-304. However, XMM-Newton observations (Rasmussen et al., these proceedings) rule out any detection at the reported significance. Thus, even with the great technological advance of Chandra and XMM-Newton, we do not have fully convincing evidence yet of any X-ray forest absorption beyond the local group. Mapping the warm-hot IGM appears to be Constellation-X science. A 500 ksec observation with Constellation-X grating will result in an equivalent width limit of 2.8 mA ($5\sigma$). If the grating resolution is further improved to R=3000, then X-ray lines as weak as 1.4mA will be detected. The higher resolution is important because there may not be tall trees in the X-ray forest.

The tantalizing but still ambiguous hints of X-ray forest absorption in current observations are frustrating to live with for half a decade or more before the launch of Constellation-X. In the mean time there are a couple of options for progress. We can wait for a blazar to flare up; a good S/N spectrum may then be possible in a reasonable time. However, the number of X-ray forest systems with column densities large enough to be observable with Chandra gratings is expected to be only about one per unit redshift. This makes success unlikely. The best way forward may be a deep (1Ms) observation of H1821+643. H1821+643 remains the best target for such an investigation because of its X-ray brightness and well studied O\textsc{vi} absorption, and because the Chandra spectrum presented here provides 500 ksec of existing data and clear objectives for a future observation.

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