CHANDRA DETECTION OF X-RAY ABSORPTION FROM LOCAL WARM/HOT GAS

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Abstract Recently, with the Chandra X-ray Telescope we have detected several local X-ray absorption lines along lines-of-sight towards distant quasars. These absorption lines are produced by warm/hot gas located in local intergalactic space and/or in our Galaxy. I will present our observations and discuss the origin of the X-ray absorption and its implications in probing the warm/hot component of local baryons.

1. Introduction

The cosmic baryon budget at low and high redshift indicates that a large fraction of baryons in the local universe have so far escaped detection (e.g., Fukugita, Hogan, & Peebles 1998). While there is clear evidence that a significant fraction of these “missing baryons” (between 20-40% of total baryons) lie in photoionized, low-redshift Ly\textalpha clouds (Penton, Shull, & Stocke 2000), the remainder could be located in intergalactic space with temperatures of $10^5 - 10^7$ K (warm-hot intergalactic medium, or WHIM). Resonant absorption from highly-ionized ions located in the WHIM gas has been predicted based on both analytic studies of structure formation and evolution (Shapiro & Bahcall 1981; Perna & Loeb 1998; Fang & Canizares 2000) and cosmic hydrodynamic simulations (Hellsten, Gnedin, & Miralda-Escudé 1998; Cen & Ostriker 1999a; D'ave et al. 2001; Fang, Bryan, & Canizares 2002). Recent discovery of O VI absorption lines by the Hubble Space Telescope (HST) and the Far Ultraviolet Spectroscopic Explorer (FUSE) (see, e.g., Tripp & Savage 2000) indicates that there may be a significant reservoir of baryons in O VI absorbers. While Li-like O VI probes about $\sim 30 - 40\%$ of the WHIM gas (Cen et al. 2001; Fang & Bryan 2001), the
remaining ~ 60 – 70% is hotter and can only be probed by ions with higher ionization potentials, such as H- and He-like Oxygen, through X-ray observation.

Recently, with Chandra Low Energy Transmission Grating Spectrometer (LETGS) we detected resonance absorption lines from H- and He-like Oxygen in the X-ray spectra of background quasars, namely PKS 2155-304 and 3C 273. The detected lines can be categorized into (1) those at \( z \approx 0 \) and (2) one redshifted intervening system. In this paper, we will discuss these detections and their implications for the physical properties of the hot gases that give rise to these absorption features.

| \( \lambda_{\text{obs}} \) (Å) | PKS 2155-304 | 3C 273 |
|-------------------------------|--------------|--------|
| \( c z \) (km s\(^{-1}\)) | \( 20.02^{+0.015}_{-0.015} \) | \( 21.60^{+0.01}_{-0.01} \) |
| Line Width\(^a\) | \( < 0.039 \) | \( < 0.027 \) | \( < 0.020 \) |
| Line Flux\(^b\) | \( 4.8^{+2.5}_{-1.9} \) | \( 5.5^{+3.0}_{-1.7} \) | \( 4.2^{+1.8}_{-0.9} \) |
| EW (mÅ) | \( 14.0^{+7.3}_{-5.6} \) | \( 15.6^{+8.6}_{-4.9} \) | \( 28.4^{+12.5}_{-6.2} \) |
| SNR | 4.5 | 4.6 | 6.4 |

\( \text{a. 90\% upper limit of the line width } \sigma, \text{ in units of Å.} \)
\( \text{b. Absorbed line flux in units of } 10^{-5} \text{ photons cm}^{-2}\text{s}^{-1}. \)

2. Data Reduction

PKS 2155-304 and 3C 273 are bright extragalactic X-ray sources used as Chandra calibration targets. They were observed with the Chandra LETG-ACIS (the observations ids for PKS 2155 are 1703, 2335, 3168; and the ids for 3C 273 are 1198, 2464, 2471). For detailed data analysis, we refer to Fang et al. 2002. We found all continua are well described by a single power law absorbed by Galactic neutral hydrogen.

After a blind search for any statistically significant absorption features, several absorption features with S/N > 4 were detected in the spectra of both quasars in the 2–42 Å region of the LETGS spectral bandpass (Figure 1). These features were subsequently fit in ISIS (Houck & Denicola 2000).

3. Discussion

3.1 PKS 2155-304

The absorption feature at \( \sim 21.6 \) Å was reported by Nicastro et al. (2002) in the LETGS-HRC archival data. We concentrate on the
absorption feature which appears at 20.02 Å (619 eV). Considering cosmic abundances and oscillator strengths for different ions, O VIII Lyα is the only strong candidate line between 18 and 20 Å, the measured wavelength de-redshifted to the source. It is plausible that the 20 Å absorption is due to O VIII Lyα in a known intervening system at $cz \approx 16,734$ km s$^{-1}$. With HST, Shull et al. (1998) discovered a cluster of low metallicity H I Lyα clouds along the line-of-sight (LOS) towards PKS 2155-304, most of which have redshifts between $cz = 16,100$ km s$^{-1}$ and 18,500 km s$^{-1}$. Using 21 cm images from the Very Large Array (VLA), they detected a small group of four H I galaxies offset by $\sim 400 - 800$ h$^{-1}$ kpc from the LOS, and suggested that the H I Lyα clouds could arise from gas associated with the group (We use $H_0 = 70h_{70}$ km s$^{-1}$Mpc$^{-1}$ throughout the paper).

Taking the absorption line to be O VIII Lyα, we estimate the column density is $N$(O VIII) $\sim 9.5 \times 10^{15}$ cm$^{-2}$ if the line is unsaturated. We can constrain the density of the absorbing gas, assuming it is associated with the intervening galaxy group. Since the line is unresolved, a lower limit of $n_b > (1.0 \times 10^{-5}$ cm$^{-3}$) $Z_{0.1}^{-1}f_{0.5}^{-1}l_{8}^{-1}$ can be obtained. Here $Z_{0.1}$ is the metallicity in units of 0.1 solar abundance, $f_{0.5}$ is the ionization fraction in units of 0.5, and $l_8$ is the path length in units of $8h_{70}^{-1}$Mpc. A more reasonable estimate of the path length comes from the mean projected separation of $\sim 1$ Mpc for the galaxies in the group, which gives $n_b \approx 7.5 \times 10^{-5}$ cm$^{-3}$ $Z_{0.1}^{-1}f_{0.5}^{-1}$. This implies a range of baryon overdensity ($\delta_b \sim 50 - 350$) over the cosmic mean $\langle n_b \rangle = 2.14 \times 10^{-7}$ cm$^{-3}$. Interestingly, Shull et al. (1998) estimate an overdensity for the galaxy group of $\delta_{gal} \sim 100$. 

Figure 1: The Chandra LETG-ACIS spectra of (a) PKS 2155 and (b) 3C273. The dashed lines are the fitted spectra. The average 1σ error bar plotted on the right-bottom of each panel is based on statistics only.
In the case of pure collisional ionization, temperature is the only parameter of importance over a wide range of density so long as the gas is optically thin. The O VIII ionization fraction peaks at 0.5, and exceeds 0.1 for temperatures $T \sim 2 - 5 \times 10^6$ K. Using CLOUDY (Ferland et al. 1998) we find that photoionization by the cosmic UV/X-ray background is not important for $n_b > 10^{-5}$ cm$^{-3}$. CLOUDY calculations of the column density ratios between other ions and O VIII also show that $T \sim > 10^6$ K.

Assuming conservative upper limits of $Z \lesssim 0.5 Z_\odot$ and an O VIII ionization fraction of $f \lesssim 0.5$, and a path length of $\Delta z \lesssim 0.116$, we estimate $\Omega_b(\text{O VIII}) \gtrsim 0.005 h^{-1}$. This is about 10% of the total baryon fraction, or about 30-40% of the WHIM gas, if the WHIM gas contains about 30-40% of total baryonic matter. This baryon fraction is consistent with the prediction from Perna & Loeb (1998) based on a simple analytic model.

### 3.2 3C 273

Based on the detected line equivalent width ($W_\lambda$) and non-detection of local O VII He$\beta$ line at 18.6288Å, we estimate the column density $N(\text{O VII}) = 1.8^{+0.7}_{-0.2} \times 10^{16}$ cm$^{-2}$ if the line is unsaturated$^1$. The O VII indicates the existence of the gas with high temperatures $\sim 10^6$ K. The extremely high temperatures imply that O VII is unlikely to be produced in the nearby interstellar medium (ISM), although we cannot rule out the possibility of an origin from supernova remnants. It is more plausible that the He-like Oxygen is produced in distant, hot halo gas, or even in the Local Group (LG).

#### 3.2.1 Local Group Origin?

We can constrain the density of the absorbing gas, assuming it is associated with the Local Group. The path length can be set equal to the distance to the boundary of the Local Group, where the gas begins to participate in the Hubble flow. Assuming a simple geometry for the Local Group, the path length is $\sim 1$ Mpc (see the following text). Adopting the 90% lower limit of the O VII column density, this gives $n_b > (2.2 \times 10^{-5}$ cm$^{-3}) Z_{0.2}^{-1} f_1^{-1} l_1^{-1}$, where $Z_{0.2}$ is the metallicity in units of 0.2 solar abundance, $f_1$ is the ionization fraction, and $l_1$ is the path length in units of 1 Mpc.

Assuming spherical symmetry and isothermality, a model characterizing the distribution of the Local Group gas is given by the standard

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$^1$Rasmussen et al.(2002) also reported the detection of a similar feature with XMM-Newton in this conference.
β-model. We adopt a simplified geometry model of the LG, where the LG barycenter is located along the line connecting M31 and the Milky Way, at about 450 kpc away from our Galaxy (Rasmussen & Pedersen 2001). At about \( r \sim 1200 \) kpc the gravitational contraction of the Local Group starts to dominate the Hubble flow, and this was defined as the boundary of the Local Group (Courteau & van den Bergh 1999). Based on this simple model we estimate the column density of O\(^{\text{VII}}\) by integrating the O\(^{\text{VII}}\) number density \( n_{\text{O}^{\text{VII}}} \) along this path length. We find a tight upper limit of Local Group temperature \( T \leq 1.2 \times 10^6 \) K; at temperatures higher than \( 1.2 \times 10^6 \) K, the O\(^{\text{VII}}\) ionization fraction drops quickly and O\(^{\text{VIII}}\) starts to dominate. We also find that the temperature of the Local Group should be higher than \( 2.3 \times 10^5 \) K. To satisfy the observed O\(^{\text{VII}}\) column density we find that the gas distribution should have a rather flat core with \( r_c \geq 100 \) kpc.

3.2.2 Hot Halo Gas?

Strong O\(^{\text{VI}}\) absorption (\( \log N(\text{O\,VI}) = 14.73 \pm 0.04 \)) along the sight line towards 3C 273 was detected with FUSE between -100 and +100 km s\(^{-1}\) (Sembach et al. 2001). This absorption probably occurs in the interstellar medium of the Milky Way disk and halo. Absorption features of lower ionization species are also present at these velocities. O\(^{\text{VI}}\) absorption is also detected between +100 and +240 km s\(^{-1}\) in the form of a broad, shallow absorption wing extending redward of the primary Galactic absorption feature with \( \log N(\text{O\,VI}) = 13.71 \). The O\(^{\text{VI}}\) absorption wing has been attributed to hot gas flowing out of the Galactic disk as part of a "Galactic chimney" or "fountain" in the Loop IV and North Polar Spur regions of the sky. Alternatively, the wing might be remnant tidal debris from interactions of the Milky Way and smaller Local Group galaxies (Sembach et al. 2001). It is possible to associate the Chandra-detected O\(^{\text{VII}}\) absorption with these highly ionized metals detected by FUSE. Here we discuss several scenarios:

(1). The O\(^{\text{VII}}\) is related to the primary O\(^{\text{VI}}\) feature: In this case, \( \log N(\text{O\,VI}) = 14.73, \) and \( \log[N(\text{O\,VII})/N(\text{O\,VI})] \sim 1.5, \) assuming \( N(\text{O\,VII}) = 1.8 \times 10^{16} \) cm\(^{-2}\). This is within about a factor of 2 of the O\(^{\text{VII}}\)/O\(^{\text{VI}}\) ratio observed for the PKS 2155-304 absorber and is consistent with the idea that the gas is radiatively cooling from a high temperature (Heckman et al. 2002). This possibility is appealing since the centroids of the O\(^{\text{VI}}\) and O\(^{\text{VII}}\) absorption features are similar (\( \sim 6 \pm 10 \) km s\(^{-1}\) versus \( -26 \pm 140 \) km s\(^{-1}\)), and the width of the resolved O\(^{\text{VI}}\) line (FWHM \( \sim 100 \) km s\(^{-1}\)) is consistent with a broad O\(^{\text{VII}}\) feature. However, this possibility also has drawbacks that the predicted O\(^{\text{VIII}}\) column density is too high and the amount of C\(^{\text{IV}}\) predicted is too low.
(2). The O VII is related to the O VI wing: In this case, the O VII is associated only with the O VI absorption "wing". This seems like a reasonable possibility. Then log[^N(O VII)/N(O VI)] ∼ 2.5. In collisional ionization equilibrium, this would imply a temperature of > 10^6 K (Sutherland & Dopita 1993). The non-detection of O VIII Lyα absorption requires the temperatures lower than ∼ 10^6.3 K.

(3). The O VII is related to none of the O VI: In this case, the temperature should be high enough to prevent the production of O VI ions. We can reach the similar conclusions to those in situation (2).

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