CHANDRA OBSERVATIONS OF TWO HIGH-REDSHIFT QUASARS

TAOTAO FANG, HERMAN L. MARSHALL, GREG L. BRYAN,¹ AND CLAUDE R. CANIZARES

Department of Physics and Center for Space Research, Massachusetts Institute of Technology, NE80-6081, 77 Massachusetts Avenue, Cambridge, MA 02139; fangt@space.mit.edu, hermann@space.mit.edu, gryan@alcrux.mit.edu, crc@space.mit.edu

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ABSTRACT

We report the first high-resolution X-ray spectra of two high-redshift quasars, S5 0836 + 710 and PKS 2149 − 306, obtained with the Chandra High-Energy Transmission Grating Spectrometer (HETGS). The primary goal of this observation is to use the high spectral resolving power of the HETGS to detect X-ray absorption produced by a hot intergalactic medium (IGM). The continuum of both quasars can be fitted by absorbed power laws. The power-law photon index (Γ') of S5 0836 + 710 is consistent with that found in previous observations with ROSAT and ASCA, while the power law of PKS 2149 − 306 is harder than found in a previous observation by ROSAT. Excess continuum absorption above the Galactic value is found in S5 0836 + 710, as evidenced in ASCA and ROSAT observations. No significant emission or absorption feature is detected in either source at the ±3 σ level. Based on the detection limits we constrain the properties of possible emitters and absorbers. The upper limit of the equivalent width of Fe-K emission lines could be as low as ~10 eV. Absorbers with a column density higher than 8 × 10^16 cm^-2 for O viii or 5 × 10^16 cm^-2 for Si xiv would have been detected. We propose a method to constrain the cosmological parameters (namely, Ω_m and Ω_L) via the X-ray forest theory, but current data do not give significant constraints. However, we estimate that observing about seven bright quasars should give at least one O viii and more O vii absorption lines at 95% possibility. We also find that combined with the constraints from the distortion of the cosmic microwave background spectrum, the X-ray Gunn-Peterson test can marginally constrain a uniform, enriched IGM.

Subject headings: cosmology: observations — intergalactic medium — quasars: absorption lines — quasars: individual (S5 0836 + 710, PKS 2149 − 306) — X-rays: galaxies

1. INTRODUCTION

Cosmological numerical simulations suggest that a large fraction of the baryonic matter should reside in intergalactic space in the form of a hot/warm intergalactic medium (IGM) (see, e.g., Fukugita, Hogan, & Peebles 1998; Cen & Ostriker 1999; Davé et al. 2001). This hot/warm IGM contains at least 30%–40% of the baryons predicted by the standard theory of big bang nucleosynthesis (BBN) at temperatures between 10^3 and 10^7 K. Observationally little is known about this IGM. Recent observations of O vi absorption lines (see, e.g., Tripp, Savage, & Jenkins 2000; Tripp & Savage 2000; Oegerle et al. 2000) indicate that these O vi absorbers could be a significant "baryon reservoir" at low redshift.

Detecting the X-ray absorption features in the X-ray spectrum of a distant quasar was first proposed by Shapiro & Bahcall (1980). Using the X-ray Gunn-Peterson test, they suggested that an intervening uniform, hot IGM would introduce an "absorption trough" into the X-ray continuum spectrum of a distant quasar. Absence of such an absorption trough would put constraints on the temperature, density, and ionization states of the diffuse IGM. Aldcroft et al. (1994) extended this idea by including photoionization from the X-ray background radiation. Using numerical simulations, Hellsten, Gnedin, & Miralda-Escudé (1998) explored the idea that a clumpy, highly ionized IGM concentrated in the gravitational potential caused by dark matter might introduce resonant absorption lines into the X-ray spectrum of a background quasar, and they denoted these lines the "X-ray Forest," in analogy to the Lyα forest in the optical/UV bands. Similar ideas were discussed by Perna & Loeb (1998) and Fang & Canizares (2000, hereafter FC).

A rough estimate shows that even for the largest-mass concentrated objects, such as clusters of galaxies, the maximum column densities of the absorption ions (such as O vii and Si xiv) are between 10^16 and 10^17 cm^-2 and the maximum equivalent width (EW) is far below 10 eV (see, e.g., Sarazin 1988; David 2000). All previous observations have been limited by the spectral resolving power. For instance, ROSAT and ASCA could not detect any spectral feature with an EW smaller than 10 eV. However, the launch of the Chandra X-ray Observatory and XMM-Newton makes it possible to study the X-ray spectrum of a distant quasar with high-resolution spectroscopy. The High-Energy Transmission Grating Spectrometer (HETGS; see Markert et al. 1994; Canizares et al. 2000) on board Chandra provides excellent spectral resolution with ΔE ~ 1 eV around 1 keV. Given such an energy resolution, it is possible to study the resonant absorption lines or edges produced by the hot IGM in the X-ray spectrum of a distant quasar (Canizares & Fang 1998).

In this paper we present observations of two high-redshift quasars: S5 0836 + 710 (z = 2.17) and PKS 2149 − 306 (z = 2.34). At redshift higher than 2, these two sources are the brightest (S5 0836 + 710) and the second brightest (PKS 2149 − 306) known quasars in X-ray band. Given such a high redshift, the light from the source traverses approximately 80% of the universe, which greatly increases the possibility of being attenuated by the intervening systems.

¹ Hubble Fellow.

² See http://chandra.harvard.edu.

³ See the data archive under http://heasarc.gsfc.nasa.gov.
Our primary goal is to find if the predicted "X-ray forest" is detectable with the Chandra HETGS and, if not, what are the limits of possible absorbers.

This paper is organized as follows. We describe the observations in § 2 and the data reduction and analysis in § 3. In § 4 we discuss the constraints on the IGM, and § 5 is a summary. Throughout the paper, unless specifically mentioned, we use a Hubble constant of \( H_0 = 70 h_{70} \) km s\(^{-1}\) Mpc\(^{-1}\).

2. CHANDRA OBSERVATION

S5 0836 + 710 and PKS 2149 – 306 were observed with the High-Energy Transmission Grating Spectrometer on board Chandra. Detailed target information is listed in Table 1. The observation of PKS 2149 – 306 was broken into two parts, with approximately 18 hr between them. The HETGS produces a zero-order image at the aim point of the focal plane detector, the ACIS-S array, with higher-order spectra dispersed to either side (for ACIS-S, see Garmire et al. 2001, in preparation). The moderate energy resolution of the ACIS-S is used to separate the overlapping orders of the dispersed spectrum. The HETGS consists of two different grating assemblies, the High-Energy Grating (HEG) and the Medium-Energy Grating (MEG), and provides nearly constant spectral resolution (\( \Delta\lambda = 0.012 \) Å for HEG and \( \Delta\lambda = 0.023 \) Å for MEG) through the entire bandpass (0.8–10 keV for HEG and 0.4–8 keV for MEG).

The ACIS-S array consists of six chips (S0–S5); however, because of a temporary malfunction of a portion of the onboard readout electronics (the FEP problem; see Chandra Proposers' Observatory Guide, or POG at the Chandra X-ray Center [CXC] site\(^4\)), only five chips could be used (S1–S5). Because of the radiation-induced charge transfer inefficiency (CTI), the energy resolution of the four front-illuminated chips has become a function of the chips' row number, with a better resolution near the readout nodes. Therefore, we moved the nominal aim point closer to the readout nodes by about 3.3 mm for S5 0836 + 710 and 2.4 mm for PKS 2149 – 306 to get better ACIS energy resolution. The resulting ACIS resolution is adequate to allow unambiguous separation of the spectral orders.

Data were analyzed with the standard pipeline for the Chandra HETGS provided by the CXC (same site as Chandra POG). We use a combination of Chandra Interactive Analysis of Observations (CIAO, version 1.1) and custom routines in interactive data language. The standard screening criteria were applied to the data. We selected photon events with ASCA grades 0, 2, 3, 4, and 6 and excluded those with energies above 10 keV. We also removed hot columns and bad pixels in each CCD chip. Figure 1 displays the zeroth-order images of both targets in a 50' × 50' region. We have smoothed the images in Figure 1 with a Gaussian (\( \sigma = 1.2' \)) for visual clarity. Both unsmoothed zeroth-order images are consistent with point sources and can be well fitted by a single Gaussian with \( \sigma \approx 0.38' \) for S5 0836 + 710 and \( \sigma \approx 0.35' \) for PKS 2149 – 306. The light curves derived from the zeroth orders of both sources were constant to within statistics.

\(^4\) See http://asc.harvard.edu.

![Figure 1](image_url)
S5 0836+710 was reported as having a one-side, superluminal radio jet (Krichbaum et al. 1990; Lobanov et al. 1998) at a position angle of $-146^\circ$. The jet has a length of at least 1.5, which is at the spatial resolving limit of the ACIS-S. The head of the jet is located between 1$'$ and 2$'$ from center, with an opening angle of $\sim 2^\circ$. We examine this region in the zeroth-order image and find that the 3 $\sigma$ upper limit of the flux from this region is $\leq 0.04\%$ of the total flux from the source. Comparing this measurement with those of 0.4% and 6% for the jets of 3C 273 (Marshall et al. 2001) and PKS 0637−752 (Schwartz et al. 2000), respectively, we conclude that no X-ray jet was found during this observation. The observation of PKS 2149−306 was separated into two parts, and the zeroth-order images show that the aim points of the two observations were shifted by approximately 2 pixels. We analyzed the two observations separately and summed them at level 2 of the CXC pipeline to get a combined spectrum.

3. DATA ANALYSIS

3.1. Continuum Fitting

To fit both MEG and HEG spectra, we ignored the 1−2 keV portion of the MEG spectrum, because of unmodeled and the best-fit parameters are from Table 2. The spectral model is an absorbed power law, and the spectral model is an absorbed power law, and the best-fit parameters are from Table 2.

![HEG spectra](image)

Fig. 2.—HEG spectra of S5 0836+710 (top) and PKS 2149−306 (bottom). The solid line and dashed line in each panel are the observed and fitted spectra, respectively. The spectral model is an absorbed power law, and the best-fit parameters are from Table 2.

**TABLE 2**

| Object          | $N_H$ (10$^{20}$ cm$^{-2}$) | $\Gamma$ (0.5−8 keV) | $A_{pl}$ | $\chi^2_{red}$/dof | $f_{2−10}$ | log $L^c$ (ergs s$^{-1}$) |
|-----------------|-----------------------------|----------------------|---------|-------------------|-----------|----------------------|
| S5 0836+710     | 7.0 $\pm$ 1.2               | 1.388 $\pm$ 0.012   | 3.96 $^{+0.04}_{-0.07}$ | 1.072/605 | 26.42     | 47.43h$^{-2}$        |
| PKS 2149−306    | 1.9                         | 1.255 $\pm$ 0.020   | 0.910 $^{+0.015}_{-0.011}$ | 0.965/605 | 7.58      | 46.94h$^{-2}$        |

* Normalization at 1 keV (observer’s frame) in units of 10$^{-3}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$.
* Absorbed flux between 2 and 10 keV (observer’s frame) in units of 10$^{-12}$ ergs cm$^{-2}$ s$^{-1}$.
* Intrinsic luminosity between 2 and 10 keV (quasar frame); $q_0 = 0.5$.
* All errors are quoted at 90% confidence level.
RLQs. Previous observations by *Einstein*, *ROSAT*, and *ASCA* showed that the two types of quasars have significantly different X-ray properties, where typically RLQs have flatter power-law indices ($\Gamma \sim 1.6$) than RQQs ($\Gamma \sim 1.9$; see, e.g., Reeves & Turner 2000). Our observations are consistent with this finding, although the spectra we observed are significantly harder than the average.

### 3.2. Line Analysis

We are interested in any possible line features in the quasar spectra. To identify line features, we need a good measurement of the continuum. We use the above-described absorbed power-law models for HEG spectra. For MEG spectra, we use the same models and fit the residuals with a five-order polynomial to account for the remaining uncertainty in the calibration. This fitted continuum serves as a reference point for measuring line features.

Since the MEG spectrum spans from 2 to 26 Å, the five-order polynomial will affect spectral features larger than 5 Å but will preserve narrow line features. The MEG spectra for both sources are shown in Figure 3. The bottom panel of each plot gives $\chi$, and the two dotted lines within the $\chi$ plot correspond to the $\pm 3 \sigma$ level, where $\sigma$ is the square root of the observed counts in each bin.

If the model fits the observation well, the counts in each bin should follow the Poisson statistic, with a mean count from the fitted spectrum. To verify this, we calculate the Poisson probability $P_x(\geq k)$ for each bin, where $x$ is the expected mean number and $k$ is the observed value. $P_x(\geq k)$ should uniformly distribute between 0 and 1, given that the model fits the observed spectrum. In Figure 4 we show the cumulative distributions of $P_x(\geq k)$ for both quasars. We also show the cumulative distribution of the uniform distribution as the dotted line. We run a Kolmogorov-Smirnov (K-S) test to test the null hypothesis that $P_x(\geq k)$ is uniformly distributed for both objects. The K-S test shows that the null hypothesis is accepted at a significance level of 0.59 for S5 0836 + 710 and 0.32 for PKS 2149 — 306.

A line feature should at least have a signal-to-noise ratio at or above the $\pm 3 \sigma$ level to be identified. Figure 3 shows that most of the bins are well distributed within the $\pm 3 \sigma$ level. The two exceptions occur at around 22.6 Å for S5 0836 + 710, where $\chi = 3.52$, and at around 17.76 Å for PKS 2149 — 306, where $\chi = 3.51$. Assuming a Poisson distribution for each bin, we ran 1000 Monte Carlo simulations for both spectra and find that the probability for observing one bin with $\chi \geq 3.52$ in one observation of S5 0836 + 710 is 63.5% and for observing one bin with $\chi \geq 3.51$ in one observation of PKS 2149 — 306 is 48.9%. So we conclude that no line feature is identified.

#### 3.2.1. Emission Lines

Iron emission lines have been detected in several high-redshift quasars with *ASCA* (see Reeves & Turner 2000 and references therein). However, no previous observation discovered any emission lines in these two sources, with the exception of Yaqoob et al. (1999, hereafter Y99) for PKS 2149 — 306, which we will discuss below. In *ASCA* observations the upper limit on the equivalent width of an Fe-K$\alpha$ emission line ($\sim 6.4$ keV) is 110 eV for S5 0836 + 710 and 85 eV for PKS 2149 — 306, respectively (Cappi et al. 1997; line

![Figure 3](image)

**Fig. 3.** — MEG spectra of S5 0836 + 710 (top two panels) and PKS 2149 — 306 (bottom two panels) in wavelength space. The bin size is 0.04 Å for S5 0836 + 710 and 0.06 Å for PKS 2149 — 306. The observed spectra are first fitted with an absorbed power law (same parameters as in HEG spectra); the residual is then fitted with a five-order polynomial. The bottom plot in each panel shows the $\chi$, and the two dotted lines indicate the $\pm 3 \sigma$ level.

![Figure 4](image)

**Fig. 4.** — Cumulative distribution of the Poisson probabilities for S5 0836 + 710 (solid line), PKS 2149 — 306 (dashed line), and the uniform distribution (dotted line). The K-S test shows that the null hypothesis that they are the same distribution is accepted at a significance level of 0.59 for S5 0836 + 710 and 0.32 for PKS 2149 — 306.
The instrumental line response function is taken into account to emphasize that the low value of the equivalent width of the iron emission lines. We should use ASCA power than 6.9 keV, for both MEG and HEG spectra for two assumed upper-limit equivalent width (EW) at two energies, 6.4 and 6.9 keV, respectively, to produce an instrumental line response function that is their 90% confidence lower bound. A recent observation by BeppoSAX (Elvis et al. 2000) also addressed the existence of such a feature.

3.2.2. Absorption Lines

X-ray-resonant absorption lines are produced by highly ionized heavy elements. The detection of any absorption line depends on three factors: (1) the spectral intensity of the background quasar; (2) the physical properties of the intervening absorbers, specifically, the ion column density and velocity dispersion (both turbulent and thermal broadening); and (3) the instrumental properties, such as the resolving power and effective area. Given that factors 1 and 3 are already known, we can constrain the properties of the absorbers. For demonstration we select the spectrum of S5 0836+710 and calculate the expected signal-to-noise ratio (S/N) for Si XIV and O VIII (see Fig. 5), given the column density of Si XIV and O VIII at different redshifts and velocity dispersions (b, in units of kilometers per second). Two values of the b-parameter, 200 and 500 km s\(^{-1}\), are adopted to bracket the typical velocity dispersions of hot gas associated with groups and clusters of galaxies. Because the strongest resonance lines of Si XIV and O VIII, the Ly\(\alpha\) transitions, are located at 2.01 keV and 0.654 keV (rest frame), respectively, we calculate the S/N of Si XIV based on HEG (HEG has a better energy resolution there) and the S/N of O VIII based on MEG (HEG has no effective area below 0.8 keV). The maximum redshift of O VIII is 0.3, because MEG has negligible effective area below 0.5 keV. The horizontal line in Figure 5 is the 3 σ detection level. The column density of O VIII or Si XIV must be at least \(8 \times 10^{16}\) cm\(^{-2}\) or \(5 \times 10^{16}\) cm\(^{-2}\), respectively, to produce an absorption line at or above the 3 σ level.

4. X-RAY CONSTRAINTS ON THE INTERGALACTIC MEDIUM

4.1. X-Ray Forest

The detection of the X-ray–resonant absorption lines is closely related to the overall baryon density (\(\Omega_b\)) and matter density (\(\Omega_0\)) in the universe. For a given level of metal enrichment, higher baryon density in general implies larger amounts of highly ionized metals and a higher possibility of detecting the X-ray absorption lines created by these metals in the spectrum of a distant quasar. On the other hand, as we predict in Fang, Bryan, & Canizares (2001, in preparation), most of the high column density ions (specifically, at column density higher than \(10^{15}\) cm\(^{-2}\)) are located in the collapsed, virialized objects, such as groups or clusters of galaxies, in the form of hot intracluster or intra-

| Object          | HEG   | MEG   |
|-----------------|-------|-------|
|                  | \(\sigma = 0\) | \(\sigma = 0.1\) | \(\sigma = 0\) | \(\sigma = 0.1\) |
|                 | (keV) | (keV) | (keV) | (keV) |
| S5 0836+710     | 6.4   | 9     | 72    | 8     | 49   |
|                 | 6.9   | 14    | 100   | 15    | 84   |
| PKS 2149–306    | 6.9   | 10    | 83    | 8     | 53   |
|                 | 6.9   | 12    | 94    | 12    | 69   |
|                 | 17.0  | 67    | 188   | 97    | 215  |

* The equivalent width is measured in the rest frame of quasar (eV).

* Line energy, in quasar frame. The Fe-K emission lines are located between 6.4 and 6.9 keV; the 17.0 keV line is the redshifted Fe-K line reported by Y99.

* Intrinsic line width.

measured in the observer’s frame, with line width \(\sigma = 0\) for an unresolved line.

The Fe-K emission lines are located between 6.4 and 6.9 keV, ranging from neutral iron to helium or hydrogen-like iron. For both sources these lines are expected at energies around 2 keV in the observer’s frame, where the Chandra HETGS has a large collecting area and high resolving power. No significant line feature was detected in the spectrum of either source at a 3 σ level. In Table 3 we list the upper-limit equivalent width (EW) at two energies, 6.4 and 6.9 keV, for both MEG and HEG spectra for two assumed intrinsic line widths, \(\sigma = 0\) and \(\sigma = 0.1\) keV, respectively. The instrumental line response function is taken into account. Since the Chandra HETGS has better resolving power than ASCA, we can put a much tighter constraint on the equivalent width of the iron emission lines. We should emphasize that the low value of \(\sigma = 0\) is adopted to calculate the theoretically low limit of detectable EW, and, because we have no constraint on the upper limit of the intrinsic line width, the EW limit could be worse by a factor of 2 if \(\sigma = 0.5\) keV.

Y99 reported that they found a significant emission feature around 5 keV in the ASCA spectrum of PKS 2149–306. They proposed that this line was blueshifted Fe-K emission with a bulk-motion velocity around 0.73c (head-on) and a rest-frame EW of 300 ± 200 eV (assuming an intrinsic line width of 0.01 keV, errors are 90% confidence). We do not detect any emission feature around 5 keV at the 3 σ level in either HEG or MEG spectra, and we set an upper limit of the EW as low as 67 eV (Table 3). If we adopt the value of \(\sigma = 0.01\) keV as used by Y99, the rest-frame EW limit is 75 eV, still much smaller than 100 eV, which is their 90% confidence lower bound. A recent observation by BeppoSAX (Elvis et al. 2000) also addressed the existence of such a feature.

![Figure 5](image-url)
Because the XFDF is determined by cosmological parameters, such as $\Omega_0$ and $\Omega_\Lambda$ (see Figs. 2–4 of FC), by comparing the expected absorption line number ($n$) with observations, we may set the constraints on these cosmological parameters.

Based on the Chandra observations, we set the upper limit of different ion column densities (see § 3.2.2), which gives $N_0$ in equation (1). The minimum detectable column density is $N_0 = 8 \times 10^{16}$ cm$^{-2}$ for O VIII and $N_0 = 5 \times 10^{16}$ cm$^{-2}$ for Si XIV. We find that, even in the extreme case where $\Omega_0 = 1$ and $Z_0 = 1$, the expected absorption line number is only $n = 0.65$ for O VIII absorption lines and even less for Si XIV. Here $Z_0$ is the metal abundance relative to the solar value, where $Z_0 = 1$ indicates solar abundance, and we integrate equation (1) to $z = 0.3$ for O VIII and to $z = 2.17$ for Si XIV.

This method illustrates the possibility of constraining the cosmological parameters by observing more X-ray–bright quasars with longer exposure time. For example, if a quasar is brighter than $S_5 0836+710$ by a factor of 2, by increasing the exposure time to 100 ks, the minimum detectable column density for O VIII can be as low as $N_0 = 3 \times 10^{16}$ cm$^{-2}$. For a low-density cold dark matter (LCDM) model with $\Omega_0 = 0.3$ and $\Omega_\Lambda = 0.7$, the expected number of O VIII absorption lines is 0.42, given a reasonable cluster gas fraction ($\sim 0.2$) and metallicity ($\sim 0.5$ $Z_\odot$ for oxygen). The Poisson statistic shows that the probability of observing at least one line is 95% if the expectation is three. This means that, by observing about seven sources twice as bright as S5 0836+710, we should have a 95% chance of detecting at least one O VIII absorption line with an exposure time of 100 ks. Previous observations show that at low and moderate redshifts, there are several tens of quasars having a flux higher than $5 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ between 2 and 10 keV, or $2 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ between 0.1 and 2.4 keV (see, e.g., Brinkmann, Yuan, & Siebert 1997; Yuan et al. 1998; Reeves & Turner 2000). By increasing the number of observations of bright quasars at low and moderate redshifts, there is a significant chance of detecting oxygen absorption lines.

Similar constraints can be made with current and future missions, such as XMM and Constellation-X. For example, XMM and Constellation-X are able to detect O VIII at a column density as low as $7.9 \times 10^{15}$ cm$^{-2}$ and $10^{15}$ cm$^{-2}$, respectively (see FC). Given such a low column density, we will detect as many as eight (with XMM) or ten (with Constellation-X) O VIII absorption lines for a moderately luminous quasar at redshift of $z \sim 1$. Eventually this method may help us to understand the distribution of the baryonic matter in the highly overdense regions.

4.2. X-Ray Gunn-Peterson Test

Recently, large-scale cosmological hydrodynamic simulations have shown that a large amount of the hot/warm IGM ($\sim 70\%$–$80\%$) lies in the regions at overdensity $5 < \delta < 200$ and temperature $10^5 K < T < 10^7 K$ (see, e.g., Cen & Ostriker 1999; Davé et al. 2001). Here $\delta = \rho/\langle \rho \rangle - 1$ and $\langle \rho \rangle$ is the mean matter density. These regions are typically the extended filamentary structures connecting regions of high mass concentration. The X-ray Gunn-Peterson test may be applied to examine the possible “absorption trough” in the X-ray continuum spectrum of a distant quasar produced by these diffuse structures. Shapiro & Bahcall (1980) and Aldcroft et al. (1994) discussed the absorption produced by a uniformly distributed IGM.

To simplify, we assume that the IGM is uniformly distributed and constrain its properties, following Shapiro & Bahcall (1980) and Aldcroft et al. (1994).

In the case of the X-ray spectrum of a background quasar located at redshift $z_0$, the frequency of a photon emitted at $v_0$ will be $v = v_0(1+z)^{-1}$ when the photon reaches the Earth. The optical depth at frequency $v$ (observer frame) is

$$\text{\tau}(v) = \int_0^{v_0} n(z) \sigma_v(v) \frac{dl}{dz} dz$$

(2)

where $n(z)$ is the comoving number density of absorbing ion $X^i$ at a redshift of $z$ and $\sigma_v$ is the ion absorption cross section at frequency $v' = v(1+z)$. The path length is $dl$.

There are three dominant absorption processes contributing to the optical depth in equation (2): resonant absorption due to the atomic transitions, continuum absorption (edge) due to the bound-free transitions, and electron scattering. Electron scattering is independent of energy in the X-ray band, and the only effect is uniformly lowering the X-ray continuum without altering the spectral shape. We ignore this effect because the absorption produced by this process will not be detectable without knowledge of the intrinsic quasar spectrum.

To simplify, we assume that the IGM is uniformly distributed hot gas in collisional equilibrium at temperature

\[^{5}\text{As we will discuss in § 4.2, numerical simulations show that the X-ray absorption material may also arise from filaments connecting the virialized structures; however, the resonant absorption lines produced by the low column density ions (less than $10^{16}$ cm$^{-2}$) from these filaments are generally too weak to be detectable with Chandra and even Constellation-X.}

\[^{6}\text{Here $\Omega_\Lambda \equiv \Lambda/H_0^2$, where $\Lambda$ is the cosmological constant.}\]
$T \geq 10^6 \text{ K}$. In such an environment, hydrogen- and helium-like O, Ne, Mg, Si, and Fe xvi–xxvi are the most abundant ions (for ionization fractions in collisional equilibrium, see Mazzotta et al. 1998). For the continuum absorption we include all the K edges (i.e., 18 K edges) and L edges for all ions with L shell electrons (i.e., 13 L edges). We obtain the threshold energies and cross sections from Verner & Yakovlev (1995). For resonant absorption, we select those transitions with oscillator strength greater than 0.1. This results in a total of 65 lines. The energy level and oscillator strength for each resonance line are from Verner, Verner, &quivos {\texttt{&}} (1994). Here $A$ is a normalization constant and $f(N_{\text{H}})$ is the gas absorption, where $N_{\text{H}}$ is the hydrogen column density. The exponential term is the absorption of the IGM at a baryon fraction $\Omega_b$ and temperature $T$. We first fit the observed spectrum with $\Omega_b = 0$. Then for each $\Omega_b$ and $T$ we fit the observed spectrum with equation (3) by varying $A$, $N_{\text{H}}$, and $\Gamma$. We then calculate the statistic

$$\Delta \chi^2(\Omega_b, T) = \chi^2(\Omega_b, T) - \chi^2(\Omega_b = 0) .$$

The $\Delta \chi^2$ should follow the $\chi^2$ distribution with 2 degrees of freedom. In this way we can set confidence levels on $\Omega_b$ and $T$.

We select the MEG spectrum of S5 0836 + 710 because the MEG covers the entire range from oxygen to iron. Figure 6a displays the 3 $\sigma$ contour of $\Delta \chi^2(\Omega_b, T)$ for a flat LCDM model ($\Omega_b = 0.3$, $\Omega_{\lambda} = 0.7$). The thick lines indicate an abundance ($Z_{\odot} = 0.5$) and the thin lines are for a low-abundance IGM ($Z_{\odot} = 0.1$). For comparison we also show the constraint from the distortion of the cosmic microwave background (CMB) spectrum (which constrains the Compton $y$-parameter; dotted line) as measured by the COBE satellite (Mather et al. 1994; Fixsen et al. 1996). The regions to the left of the solid and dotted lines are allowed regions.

We also display the total baryon density deduced from standard big bang nucleosynthesis (BBN) and the CMB. BBN implies $\Omega_b h^2 = 0.0388 \pm 0.0037$ (95% confidence level, hereafter cl) (see, e.g., Burles, Nollett, & Turner 2001). The recent measurements of CMB anisotropy by Boomerang and MAXIMA gave $\Omega_b h^2 = 0.065^{+0.015}_{-0.016}$ (95% cl; Jaffe et al. 2001). We note that while the $\Omega_b$ measured in this way reflects the small-angle (subdegree) anisotropies, the constraint based on the Compton $y$-parameter reflects the CMB anisotropies at larger scales. We display both BBN and CMB results in Figure 6a, and the shadowed area shows the 95% cl region.

From this figure we can find that, while for a low-abundance IGM the X-ray Gunn-Peterson test is not able to put strong constraints on the properties of the IGM, for a uniformly enriched IGM with $Z_{\odot} = 0.5$ marginal constraints can be made by combining the Gunn-Peterson test and the Compton $y$-parameter from the CMB anisotropies. For example, for the CMB-predicted baryon density, the temperatures of the IGM are constrained in the range $10^6 \leq T \leq 10^7 \text{ K}$. Temperatures above this range are ruled out by the CMB spectrum, and at a temperature below this range the IGM will produce strong distortion in the quasar spectrum. In Figure 6b we illustrate such a distortion in the MEG spectrum of S5 0836 + 710, based on an LCDM model. The dotted line represents the absorbed spectrum by an IGM with $Z_{\odot} = 0.5$ at $T = 10^6 \text{ K}$ and $\Omega_b h^2 = 0.08$. Given such an IGM, the model severely deviates from the observed spectrum.

Based on the ROSAT PSPC observations of three high-redshift quasars, Aldcroft et al. (1994) concluded that the X-ray opacity of a hot diffuse IGM is too small to constrain the IGM. For instance, they found that their X-ray Gunn-Peterson test did not constrain the IGM temperature above $10^4 \text{ K}$ with $\Omega_b = 0.06$ and solar abundances (Fig. 11 in their paper). Our analysis indicates that the constraint can be improved significantly, even with half-solar abundances, because of the high-energy resolving power of Chandra.
HETGS. Our results are similar to their predictions with *Chandra* Low-Energy Transmission Grating Spectrometer, based on a simulated observation of 3C 273. However, because of the limitation of the small effective area, we are not able to constrain the IGM with low metallicity based on current data. In future, Constellation-X will increase the effective area by 2 mag over Chandra HETGS and may eventually reveal the properties of the IGM.

5. SUMMARY

In this paper we report the *Chandra* observations of two high-redshift, radio-loud quasars, S5 0836 + 710 and PKS 2149 – 306.

1. The photon index (Γ) for S5 0836 + 710 is 1.39, consistent with previous observations with ROSAT and ASCA. Compared with previous observations, PKS 2149 – 306 has a rather soft spectrum, with Γ = 1.255. Both photon indices are consistent with the fact that RLQs have flatter spectra than RQQs. We also find excess continuum absorption (above the Galactic value) in S5 0836 + 710. The flux of S5 0836 + 710 is higher than in previous ASCA observations, marking this source as one of the most luminous objects at high redshift.

2. No significant absorption or emission feature is found in either source at or above the ±3 σ level. We put constraints on the possible emitters or absorbers. For example, Fe-K emission lines were found in several RLQs (Reeves & Turner 2000), although not as frequently as in RQQs. We put tight upper limits on EW, as low as ~10 eV in both sources. We do not find the emission feature reported by Y99 in the spectrum of PKS 2149 – 306 around 5 keV.

3. We also examine the possible intervening systems and give upper limits on the absorbers’ ion column density.

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