FAR ULTRAVIOLET SPECTROSCOPIC EXPLORER OBSERVATIONS OF THE GALACTIC AND INTERGALACTIC MEDIUM TOWARD H1821+643

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ABSTRACT

We have obtained moderate-resolution spectra of the bright QSO H1821+643 (z = 0.297) in the wavelength interval 990–1185 Å with the Far Ultraviolet Spectroscopic Explorer (FUSE). Strong, complex O vi λ1032 and Fe II λ1145 absorption arising in gas above several spiral arms and the outer warp of our Galaxy is detected. We have identified absorption by a high negative-velocity (−215 km s⁻¹) component of O vi, which corresponds to the limiting velocity of vLSR ≈ −190 ± 20 km s⁻¹ for Milky Way gas along this line of sight, assuming corotation of disk and halo gas and a flat rotation curve for the outer Galaxy. We report the detection of four absorbers in the intergalactic medium, through detections of Lyβ at z = 0.02438 and 0.1213, Lyδ, Lyε, Lyγ in a system at z = 0.2249. C iii λ977 at z = 0.1705, and O vi λ1032 at z = 0.12137. The FUSE data show that the Lyman absorbers at z = 0.225 are composed of two components separated by ~70 km s⁻¹. Finally, we have observed associated absorption from O iii λ832, O iv λ787, and possibly S v λ786 at the redshift of the QSO (z ~ 0.297). Ne viii λ770, 780 is not detected in this associated system. When combined with the previous detection of associated O vi λ1032, we conclude that this system is a multiphase absorber, and we discuss the origin of the absorption in this context.

Subject headings: Galaxy: halo — intergalactic medium — ISM: general — quasars: absorption lines

1. INTRODUCTION

In this Letter, we present intermediate-resolution (~20 km s⁻¹) spectra of the quasar H1821+643 (V = 14.2, z = 0.297), which is visually the brightest known object in the sky at z > 0.2. H1821+643 is an X-ray–selected, radio-quiet quasar (Pravdo & Marshall 1984) and resides in a cD galaxy at the center of a rich cluster of galaxies (Schneider et al. 1992). The optical properties of the QSO have been reported by Hutchings & Neff (1991) and Kolman et al. (1993). The latter authors find evidence for a strong optical/UV bump and a soft X-ray excess. The cluster of galaxies hosting the QSO is one of the most luminous X-ray clusters known (Hall, Ellingson, & Green 1997). Spectroscopic studies of H1821+643 have been carried out in the UV at low resolution (Bahcall et al. 1992; Kolman et al. 1993; Tripp, Lu, & Savage 1998) and intermediate resolution (Savage, Sembach, & Lu 1995; Savage, Tripp, & Lu 1998; Penton, Stocke, & Shull 2000) in order to study the Galactic and intergalactic medium along the line of sight.

2. OBSERVATIONS

H1821+643 was observed by the Far Ultraviolet Spectroscopic Explorer (FUSE) on 1999 October 10 and 13 for a total integration time of 48.8 ks. Moos et al. (2000) provide an overview of the FUSE instrument and its performance. Data in the wavelength interval 990–1185 Å covered by both LiF channels were obtained. Processing steps included orbital Doppler compensation, background subtraction, and flux and wavelength calibration. No flat-fielding of the data was performed. The dispersion solution was derived from prelaunch calibration spectra and adjusted based on comparison of FUSE absorption-line velocities to velocities of appropriate absorption lines in the Space Telescope Imaging Spectrograph (STIS)/Hubble Space Telescope (HST) echelle spectrum of H1821+643 obtained by Tripp, Savage, & Jenkins (2000). In general, the velocities are accurate to ~5 km s⁻¹. The measured spectral resolution was ~20–25 km s⁻¹ depending on wavelength. The detector background and scattered light in the instrument are extremely low, leading to accurate knowledge of the residual intensities in absorption lines. Equivalent widths and column densities of selected absorption lines were measured using the techniques described by Sembach & Savage (1992) and are reported in Table 1. Spectra shown in Figures 1–3 have been smoothed by 5 pixels (0.03 Å).

3. GALACTIC ABSORPTION

The H1821+643 sight line (l, b) = (94°, 27°) passes over three spiral arms seen in H i emission in a survey above the Galactic plane by Kerpner (1970): the intermediate arm (vLSR ≈ −75 km s⁻¹), the Perseus arm (vLSR ≈ −75 km s⁻¹), and the outer arm (vLSR ≈ −93, −120 km s⁻¹). For the observations reported here, vLSR = vhel + 16 km s⁻¹. The sight line is also in a direction in which the warp of the outer Galaxy extends to large Galactic latitudes. The interstellar spectrum of H1821+643 is dominated by lines of H2 and Fe II in the FUSE bandpass. Also present are Ar I, C ii, Si ii, P ii, and O vi. Strong O i and N i lines were also detected in spectra obtained while the satellite was in the Earth’s shadow, where the terrestrial dayglow emission lines in these species are absent. The 1030–1040 Å region of the spectrum displaying O vi λ1032, 1038, C ii λ1036, and several H2 lines is shown in Figure 1.
The Fe II lines are strong and have negative-velocity wings extending out to as much as $\sim -170$ km s$^{-1}$ for Fe II $\lambda 1145$. These negative-velocity components are formed above the outer arm and are also seen in Mg II and Si II lines in Goddard High Resolution Spectrometer (GHRS) data (Savage et al. 1995). The H$_2$ lines are local and are not seen at large negative velocities.

It is interesting to compare the strengths of the Ar I $\lambda 1048, 1066$ lines to those in the N I multiplet at 1134 Å. In a fully neutral medium, these lines should have similar equivalent widths since they have nearly equal values of $P = 0.0154$ km s$^{-1}$ and a cloud excitation temperature of $T_{ex} \sim 5000$ K. Based on this model, the Ar I lines are noticeably weaker than the strongly saturated N I lines in the spectra of H1821+643. Sofia & Jenkins (1998) have pointed out that in diffuse clouds Ar I is unlikely to be depleted onto dust grains. Nevertheless, they argue that in regions that are partially ionized by EUV radiation, Ar I may appear to be deficient relative to H I (or N I) because it has a substantially larger ionization cross section and thus might be more ionized. Note that Ar I is only clearly detected in the intermediate arm. It is not detected in the Perseus or outer arms, probably because the Ar is more highly ionized at greater distances from the Galactic plane.

The O VI absorption at $\sim -120$ to $-150$ km s$^{-1}$ is associated with the outer arm and distant warp of our Galaxy. If we assume that the halo corotates with the underlying disk, the implied Galactocentric distance of the absorbing gas is $\sim 25$–50 kpc and the distance above the plane is $\sim 10$–20 kpc. Independent evidence for the existence of O VI absorption in the outer halo of our Galaxy is supplied by the absence of O VI absorption at velocities exceeding $-70$ km s$^{-1}$ in the FUSE spectrum of K1-16, which is only $85^\circ$ away from H1821+643 on the sky and is at a distance of 1.6 kpc (J. W. Kruk et al. 2000, in preparation). Consequently, the high negative-velocity O VI absorption seen in H1821+643 must be formed in the Galactic halo beyond K1-16.

A high-negative-velocity ($-215$ km s$^{-1}$) component of O VI $\lambda 1031.93$ is coincident with a low-velocity H$_2$ line from the (6–0) $P(3)$ rotational level at 1031.19 Å. We have modeled the $J = 3$ H$_2$ lines in the spectrum and find a good fit for a total column density of $N$(H$_2$) $\sim 2 \times 10^{15}$ cm$^{-2}$ and a cloud excitation temperature of $T_{ex} \sim 500$ K. Based on this model, the
expected H\textsubscript{2} absorption at 1031.19 Å cannot account for the depth or width of the observed line, indicating significant absorption by O\textsc{vi} \lambda 1032 at −215 km s\textsuperscript{-1}. This confirms the tentative identification of this component in the C \textsc{iv} \lambda 1549 line made with GHRSHST by Savage et al. (1995). This detection is quite interesting, since the line velocity corresponds to the limiting velocity of \( v_{\text{lim}} \sim -190 \pm 20 \text{ km s}^{-1} \) for Milky Way gas assuming corotation and a flat rotation curve for the outer Galaxy. Collisional ionization seems the most likely source of O\textsc{vi} ionization in this component. Photoionization would require a very hard radiation field (\( E > 114 \text{ eV} \)) to ionize O \textsc{v} to O\textsc{vi}, and the large photoionization parameter \( U \) requires a very low value of \( n_{\text{H}} \) and an extremely long path length, \( l = N_{\text{H}}/n_{\text{H}} > 100 \text{ kpc} \), to produce the absorption (see Sembach et al. 2000).

4. INTERVENING ABSORPTION

Tripp et al. (1998) have detected strong (\( W_{\lambda} > 200 \text{ m}\text{Å} \)) Ly\textalpha toward H1821+643 at redshifts of 0.1213, 0.1476, 0.1699, 0.2132, and 0.2249. Savage et al. (1995) also reported intervening Ly\textalpha absorption at \( z = 0.02454 \). We have detected absorption from four of these absorbers in the FUSE spectrum, and the column densities are reported in Table 1. The Lyman series lines detected with FUSE in these systems provide important constraints on N(H \textsc{i}) since the stronger lines in the HST bandpass are saturated. The reader is also referred to Shull et al. (2000) for discussion of intervening Ly\textbeta absorbers. One must be aware of the potential for ejected material from the QSO to masquerade as intervening gas, as shown for C \textsc{iv} absorption-line systems by Richards et al. (1999). We believe that there is good evidence that the absorbers in H1821+643 are truly intervening, based on the proximity of intervening galaxies to the line of sight (Tripp et al. 1998; D. Bowen & T. Tripp 2000, in preparation).

Tripp et al. (1998) report a strong, blended line of Ly\textalpha at \( z = 0.12123, 0.12157 \). In addition to detecting the Ly\textbeta line in this system, we report the detection of a line at 1157.17 Å which we have identified as O \textsc{vi} \lambda 1032 at \( z = 0.12137 \) (see Fig. 2). The line is clearly seen in both the LiF1 and LiF2 spectra. The O \textsc{vi} \lambda 1038 line is blended with the Ly\textalpha line in the \( z = 0.225 \) absorber and could not be measured. This is the sixth intervening O \textsc{vi} absorption system observed toward H1821+643, and it provides further evidence that low-\( z \) O \textsc{vi} systems contain a large fraction of the baryons at the present epoch (Tripp et al. 2000; Tripp & Savage 2000). These observations are in accord with cosmological simulations by Cen & Ostriker (1999) that predict a substantial fraction of present-day baryons are in a shock-heated phase at \( 10^{5}–10^{7} \text{ K} \).

We have identified an observed line at 1143.6 Å as C \textsc{iii} \lambda 977 at \( z = 0.1705 \). This identification was made possible by comparison with the wavelength of a Ly\textdelta absorber recently observed by Tripp et al. (2000) with STIS/HST. The Ly\textbeta line for this absorber is not conclusively detected in the FUSE spectrum, although a weak, rather broad feature is at the predicted wavelength. The Ly\textbeta line in this absorber is redshifted into the strong Galactic N \textsc{i} triplet at 1200 Å.

Intervening absorption at \( z = 0.225 \) has been detected in the Ly\textalpha and Ly\textbeta lines in O \textsc{vi} with HST (Savage et al. 1998). Recently, Tripp et al. (2000) have also clearly detected Si \textsc{iii} in this system, and the component structure establishes that this is a multiphase absorber. However, this absorber is not detected by HST in low ionization lines such as Si \textsc{ii} or the high ionization lines of Si \textsc{iv} and C \textsc{iv}. Savage et al. (1998) showed that the absorption could occur in low-density, extended gas photoionized by the UV background or in hot collisionally ionized gas in an intervening galaxy or galaxy group. Evidence for the presence of a galaxy group at \( z = 0.225 \) has been provided by Schneider et al. (1992) and Tripp et al. (1998).

The Ly\textdelta, Ly\textepsilon, and Ly\textzeta lines at \( z = 0.22491 \) are detected in the FUSE spectrum. Two of these lines are shown in Figure 2. The lines are clearly resolved into two components with velocity separation of \( \sim 70 \text{ km s}^{-1} \). We have not identified any metal lines arising in the \( z = 0.225 \) system in the FUSE spectrum. It would be interesting to obtain FUSE short-wavelength (SIC) spectra covering 900–995 Å, where we have the possibility of detecting the redshifted Ne \textsc{viii} \lambda 770, 780 doublet. Ne \textsc{viii} has a higher ionization potential than O \textsc{vi} (207 vs. 114 eV). If detected, it would indicate the presence of collisionally ionized gas at a temperature of \( T \sim 10^{5.5} \text{ K} \).

5. ASSOCIATED ABSORPTION

We report the detection of several “associated” (\( z_{\text{em}} \approx z_{\text{abs}} \)) absorption lines in the spectrum of H1821+643. We identify the observed line at 1021.45 Å as absorption by the rest-frame
EUV line O IV λ787.7 (see Fig. 3). This line has a FWHM of ≈150 km s^{-1}, which places it in the category of narrow absorption line absorbers (Weymann et al. 1979; Hamann & Ferland 1999). We have also identified O III λ832.93 with an observed line at λ_{abs} ≈ 1080.05 Å. Finally, we have tentatively identified a weak line at λ_{abs} ≈ 1019.85 Å as S V λ786, although this line is much narrower than the O IV λ787 line. These lines cannot be redshifted, higher order Lyman lines because the corresponding Lyα lines are not detected in the longer wavelength UV spectra obtained with GHRS and STIS.

Associated absorption by C III λ977, Si IV λ1394, C IV λλ1548, 1550, and O VI λλ1032, 1038 as well as several members of the Lyman series of hydrogen have been detected in H1821+643 by Savage et al. (1998) and Penton et al. (2000). The FUSE and HST observations combined show a broad range of ionization in the associated absorber(s)—including O III, O IV, and O VI. However, no low-ionization species such as Mg II or Si II have been observed. We see no evidence for Ne vii λλ770, 780 absorption in the FUSE data at z_{abs} = 0.29673.

There are three possible sites of associated absorption in the H1821+643 spectrum: the host galaxy of the QSO, the intracluster medium, or a cluster galaxy or galaxies along the line of sight to the QSO. Absorbing gas that is near the QSO central engine is often called "intrinsic" absorption. In many specific cases, there is strong spectroscopic evidence that associated narrow absorption lines are intrinsic. The evidence includes (1) time-variable line strengths, (2) smooth absorption that is broad compared to the thermal line width, (3) partial covering of the continuum source, and (4) the presence of excited-state absorption (Hamann & Ferland 1999). None of these properties convincingly describes the H1821+643 associated absorber. Time variability of absorption lines has not been reported and cannot be addressed with this data set. The O IV line is broader than its thermal line width, but is narrower than most intrinsic systems, which typically have widths of ≈500 km s^{-1}. The associated Lyα line observed in the HST/STIS spectrum obtained by Tripp et al. (2000) is black at the line center (T. M. Tripp 2000, private communication). This requires full coverage of the continuum source. Finally, excited-state absorption is not observed. All of this evidence points to the associated absorber in H1821+643 being unlike normal "intrinsic" absorbers.

Nevertheless, we still think that a likely origin of the associated absorption lies in the nearby environs of the H1821+643 host galaxy. Halos of cluster galaxies will be ram-pressure stripped by their passage through the intracluster medium. Gas in the intracluster medium is extremely hot (T ~ 10^{7} K) and will have negligible ionic fractions of O III and O IV. If a cooling flow exists in the cluster, then the O VI and less ionized species formed in this cooling gas would exist close to the cD galaxy at the cluster center—the host of H1821+643.

The photoionization models presented by Hamann (1997) indicate that an ionization parameter of U ~ 0.1 (for a wide range of continuum shapes) is needed to simultaneously produce O IV and O VI, but then the fractional ionization of O III will be much too low to explain the absorption we detect. Hence, a multiphase model is required to explain the broad range of ionization present in the H1821+643 absorber. Multiple sites for the formation of the absorption is also consistent with the O IV λ787 line width.

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