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DAMPED LYMAN-ALPHA ABSORPTION IN Q0957+561A, B[1]

DAVID A. TURNSHEK
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260
AND
RALPH C. BOHLIN
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
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ABSTRACT

A series of archival *IUE* low-dispersion spectral observations of the double quasar Q0957+561A, B are analyzed. The components of this gravitationally lensed quasar are separated by ~6″. Damped Lyα absorption at redshift $z_{abs} = 1.3911$ with neutral hydrogen column density $N(\text{H I}) \simeq 7 \times 10^{19}$ cm^{-2} is present in the spectra of both the A and B components. Using an accepted model by Young et al. for the gravitational lens, the damped Lyα absorber is inferred to have a minimum size of $\sim 0.5 h_{50}^{-1}$ kpc.

The standard interpretation is that a damped Lyα absorber represents a galactic or protogalactic H I disk. In the context of this standard model, the absorption-line properties and evidence for Faraday rotation are discussed.

Subject headings: gravitational lensing — quasars: absorption lines — quasars: individual (Q0957+561A, B) — ultraviolet: galaxies

1. INTRODUCTION

Absorption lines in QSO spectra can be used to investigate a variety of phenomena. Gas outflowing from a QSO at high velocity may create Broad Absorption Lines (BALs) or P Cygni–like profiles in the spectrum. Alternatively, the gas in galaxies and the intergalactic medium, which lies between the observer and a QSO, may give rise to narrow absorption-line systems in the spectrum. A small subset of these absorption-line systems characteristically exhibit a damped Lyα line. In this paper we present the discovery and analysis of one such system.

The damped Lyα systems with neutral hydrogen column densities $N(\text{H I}) \gtrsim 10^{20}$ cm^{-2} are easily identified in QSO spectra. The Lyα line is kinematically narrow but is broadened to large equivalent width, since the damping wings of the Lyα Voigt absorption profile become visible. Because of their large H I column densities, the systems are thought to arise in galactic or protogalactic H I disks (see Wolfe et al. 1986; Wolfe 1988; Turnshek et al. 1989; Lanzetta et al. 1991; Lu et al. 1992; Wolfe et al. 1993). Thus, studies of the evolution with redshift of the properties of the damped Lyα systems lead to constraints on theories of galaxy formation and evolution. Studies of individual damped Lyα systems can likewise lead to important constraints.

The main aim of this paper is to report an analysis of archival *IUE* spectra to search for possible damped Lyα absorption toward the gravitationally lensed quasar Q0957+561A, B. This quasar has an emission-line redshift $z_{em} \simeq 1.41$. The existence of such absorption in both image components would provide a rare opportunity to estimate the spatial extent of matter in a damped Lyα absorber.

In § 2 we summarize some previous observational results on Q0957+561A, B which are relevant to the work presented here. We also discuss the analysis of 18 *IUE* low-dispersion images used to form the ultraviolet spectra of components A and B. Analysis of these archival spectra indicate that damped Lyα absorption is present in the previously known $z_{abs} = 1.3911$ system. The neutral hydrogen column density is $N(\text{H I}) \simeq 7 \times 10^{19}$ cm^{-2} with an uncertainty of ~30%. The damped Lyα line is seen in the spectra of both A and B image components. For an accepted model of the lens system, the lower limit on the transverse extent of the absorber is $\sim 0.5 h_{50}^{-1}$ kpc, where h_{50} is the Hubble constant in units of 50 km s^{-1} Mpc^{-1}. In § 3 we discuss the implications of our discovery.

2. OBSERVATIONS AND ANALYSIS

The Q0957+561 gravitational lens system has been the subject of a considerable amount of observational work. In § 2.1 some of the work is reviewed. In § 2.2 we discuss the *IUE* data processing and present final spectra for components A + B, component A, and component B. In § 2.3 we discuss the analysis of the $z_{abs} = 1.3911$ system.

2.1. *Summary of Previous Relevant Observational Work*

The Q0957+561 gravitational lens system, which was the first of its kind to be recognized, was discovered by Walsh, Carswell, & Weymann (1979) and has been the subject of considerable observational scrutiny. At ultraviolet and optical wavelengths the two prominent $V \simeq 17$ mag images (A and B) are separated by ~6″. Subsequent work on the lens system included discovery of the foreground lensing galaxy and associated cluster, models for the lens geometry, implications from observed similarities and differences in emission lines and narrow absorption-line systems, results from radio observations, and results from monitoring brightness variations (see Weymann et al. 1979; Young et al. 1980; Stockton 1980;

[1] Based on observations with the NASA *International Ultraviolet Explorer* Satellite.

Young et al. 1981a, b; Gorenstein et al. 1984; Falco, Gorenstein, & Shapiro 1985; Roberts et al. 1985; Greenfield, Roberts, & Burke 1985; Altner & Heap 1988; Schild 1990; Falco, Gorenstein, & Shapiro 1991; Kochanek 1991; Lehar et al. 1992). Reviews and additional references are given by many of these authors. The accepted configuration is a quasar with $z_{em} \simeq 1.41$, which is multiply imaged by a gravitational lens consisting of a $z \simeq 0.36$ bright cluster galaxy and the associated cluster itself.

Narrow absorption-line systems are found in the spectra of images A and B at $z_{abs} = 1.1249$ and $z_{abs} = 1.3911$ (Weymann et al. 1979; Young et al. 1981b). The optical spectra show that the $z_{abs} = 1.1249$ system contains moderate strength absorption lines due to C IV but no evidence for low-ionization lines. Comparisons of the spectra of images A and B show no significant differences in the strength or velocity structure of the $z_{abs} = 1.1249$ system. The $z_{abs} = 1.3911$ system, which is the subject of this paper, contains moderate to strong low-ionization absorption lines due to Mg I, Mg II, Fe II, and Si II. Relatively weak C IV absorption is also present. The observations of Weymann et al. (1979) and Young et al. (1981b) show that the C IV λλ1548, 1550 absorption lines appear stronger and wider in the spectrum of component B, while the Si II λ1526 and Fe II λ1608 absorption lines have similar equivalent widths in the two spectra but are less deep in the spectrum of component B. In both systems, ultraviolet data would be required to search for other absorption lines of interest (e.g., C II λλ1334, 1335 and Lyα).

To this end, we have analyzed 18 long wavelength, low-dispersion ultraviolet spectra of Q0957+561A, B obtained with the *IUE*. Altner & Heap (1988) have analyzed these spectra mainly for the purpose of studying lens component brightness variations and note that the Lyα emission/absorption profile is *P Cygni* in appearance. While the appearance of the profile is indeed P Cygni–like, use of this terminology might suggest that the quasar belongs to the class of QSOs called Broad Absorption Line (BAL) QSOs (Turnshek 1988), which exhibit *intrinsic* absorption due to material outflowing from the central source toward the observer. However, such an interpretation seems unlikely in the case of Q0957+561 because there is no evidence for high-ionization metal-line BAL profiles (e.g., C IV λλ1548, 1550) at the redshift of the broad Lyα absorption line. These lines are present in the spectra of all known BAL QSOs. Furthermore, Q0957+561 is a radio source, and BAL QSOs are predominantly radio quiet (Stocke et al. 1992). Instead of the BAL scenario, the spectral properties indicate that the broad Lyα absorption line arises in the kinematically narrow *intervening* absorber at $z_{abs} = 1.3911$. This absorber contains sufficient neutral hydrogen gas to cause a damped Lyα absorption line.

2.2. *IUE Observations*

The 18 long wavelength (LW) low-dispersion *IUE* observations of Q0957+561 A, B are listed in Table 1 and are the same as presented by Altner & Heap (1988). The actual image representations of each of the *IUE* spectral observations are in Figure 1 of Altner & Heap (1988), while the entire LW *IUE* spectrum of Q0957+561A, B is shown in Altner & Heap (1988), Kinney et al. (1991), and Lanzetta, Turnshek, & Sandoval (1993). The radiation background on LWP 2417 renders the signal-to-noise ratio so poor that this image is excluded from our study. The optimal extraction technique of Kinney, Bohlin, & Neill (1991) is used to extract the summed A + B spectrum from each image. The weighted co-addition of the 17 A + B spectra uses the uncertainties for the individual spectra that are computed by the optimal extraction algorithm. The result is shown in Figure 1. In order to extract spectra for the A and B components separately, the *IUE* line-by-line file with 110 lines in the image is examined. (LWP 2525 has only 55 lines.) Note that the *IUE* plate scale is ~1".5 pixel^{-1} (Bohlin et al. 1980), where the line spacing is 0.707 pixels in the 110 line files and twice that in the 55 line files. The three or four lines of each image that lie above 0.5 of the brightest line for each component are selected to define the flux for A and B. A gap of

TABLE 1

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Image	Date (year/day)	Exposure (minutes)	Image: A lines	Image: B lines	Exclusions
LWR 6472	1979/358	347	58–60	53–55	...
LWR 6473	1979/359	398	57–59	52–54	...
LWR 8877	1980/267	350	60–62	54–57	A[a]
LWR 8890	1980/269	340		55–58	A[b]
LWR 8896	1980/270	277	59–61	54–57	A[a]
LWR 9445	1980/341	348	58–61	52–55	...
LWR 9458	1980/343	350	58–61	52–55	...
LWR 10724	1981/174	715	51–54	56–59	...
LWP 1404........	1981/335	577	57–60	51–54	...
LWP 1550........	1982/132	330	53–56	60–62	B[a]
LWP 1565........	1982/154	323	49–52	54–57	...
LWP 1579........	1982/163	315	51–54	56–59	,,,
LWP 1603........	1982/182	320	52–55	57–60	...
LWP 1744........	1982/349	390	57–60	53–55[c]	...
LWP 1752........	1982/363	300	56–59	52–54	...
LWP 1888........	1983/154	390	51–54	56–59	...
LWP 2417........	1983/349	240	...	...	A, B[d]
LWP 2525........	1983/363	366	29–30	26–27	...

[a] Continuum $< 5 \times 10^{-16}$ ergs cm^{-2} s^{-1} Å^{-1}.
[b] Component A is very weak in LWR 8890.
[c] Noise glitch in line 52.
[d] Radiation background is too high.

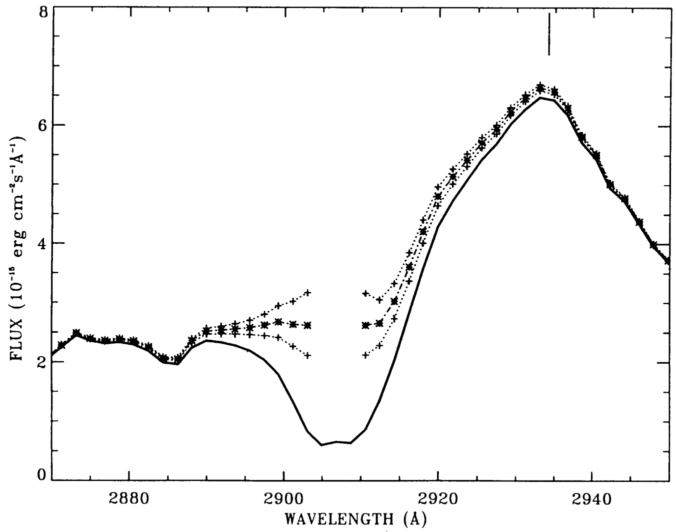

FIG. 1.—Sum of 17 optimally extracted *IUE* spectra of Q0957+561A, B (*heavy solid line*). The symbols connected by *dashed lines* are the data points that have been reconstructed for different values of N(H I). The middle reconstruction is for $N(\text{H I}) = 7 \times 10^{19}$ cm^{-2} and represents the best estimate of the absorbing column of neutral hydrogen. The upper and lower sets of cross symbols are reconstructions that represent the likely limits of uncertainty for the nominal N(H I) multiplied by 1.3 and 0.7, respectively.

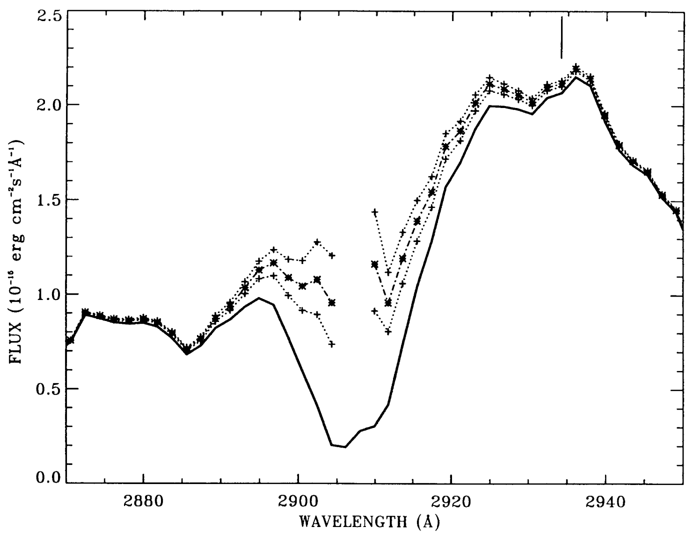

FIG. 3.—Sum of 16 *IUE* spectra for component B only. Otherwise the same as for Fig. 1.

at least one line between each component is required to maintain the purity of the separate spectra (see Table 1). Since the co-addition of the separate components is weighted only by the exposure time, the weakest spectra with continuum fluxes near Lyα of less than 5×10^{-16} ergs cm^{-2} s^{-1} Å^{-1} are excluded to avoid adding excess noise. As summarized in Table 1, 14 images of component A and 16 of component B comprise the final co-additions. The co-additions, which form the separate spectra of component A and B, appear in Figures 2 and 3, respectively. Before co-addition in all three cases (Figs. 1–3), the individual spectra are cross-correlated in the region of Lyα and shifted in wavelength to correct for small *IUE* pointing errors and for the displacement of the separate components from the central axis of the *IUE* entrance slit.

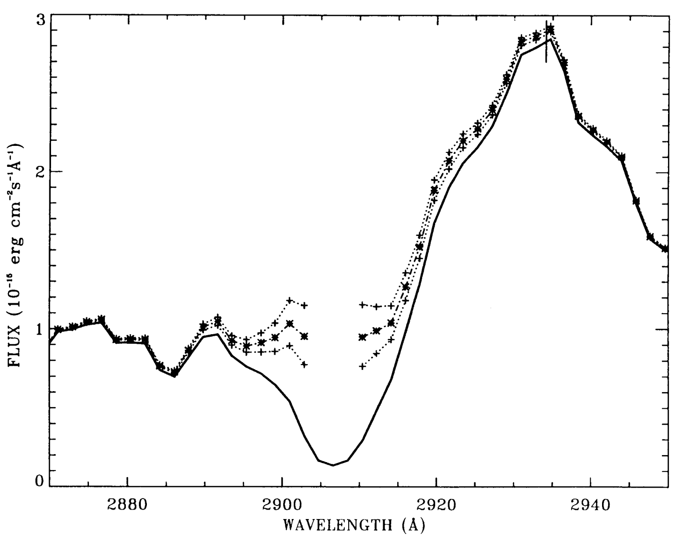

FIG. 2.—Sum of 14 *IUE* spectra for component A only. Otherwise the same as for Fig. 1.

2.3. *Analysis of the $z_{abs} = 1.3911$ System*

Our analysis of the individual *IUE* spectra of Q0957+561A, B does not rule out the possibility that there have been time variations in the $z_{abs} = 1.3911$ damped Lyα profile. However, given the quality of the data, any temporal variations which might be perceived (see Fig. 1 of Altner & Heap 1988) are probably noise. Time variations in the damped Lyα profile of an intervening absorber would not be expected.

To determine the column density of neutral hydrogen, N(H I), that is responsible for the absorption, theoretical Voigt profiles are computed, convolved with the *IUE* line spread function (LSF), and divided into the data to find the most plausible reconstruction of the unabsorbed continuum plus emission. This technique is the standard one used by Bohlin (1975). The central wavelength of the Lyα absorption is consistent with $z_{abs} = 1.3911$ within the *IUE* wavelength uncertainty of 2–3 Å and the expected offsets of the components from the center of the slit. A Gaussian with FWHM = 6.2 Å is used for the *IUE* LSF (Cassatella, Barbero, & Benvenuti 1985). The reconstructions are shown with the original data in Figures 1–3. The reconstructed data points with corrections of more than a factor of 5 are not shown, because noise and small background uncertainties dominate near the line center. The best fit is $N(\text{H I}) = 7 \times 10^{19}$ cm^{-2} $\pm$ 30% for the spectrum of A + B in Figure 1. The noisier separate components are consistent with the same value of N(H I), as illustrated in Figures 2 and 3. However, in the case of the B component, a best fit would be near the upper limit of the uncertainty range.

3. DISCUSSION

We have shown that the $z_{abs} = 1.3911$ system in the spectrum of Q0957+561 exhibits damped Lyα absorption. Any results gleaned from the analysis of this system are of general interest to understanding the nature of damped Lyα absorbers. The damped Lyα absorbers are of particular importance, because they may represent galactic or protogalactic H I disks, which are fundamental to understanding galaxy formation and evolution, while other types of intervening QSO absorption-line systems may be identified with galactic halos and/or clouds in the intergalactic medium. However, many of the surveys for damped Lyα absorption in QSO spectra (Wolfe et al. 1986; Lanzetta et al. 1991) are complete only for systems with $N(\text{H I}) > 2 \times 10^{20}$ cm^{-2}. Thus, the $z_{\text{abs}} = 1.3911$ system in Q0957+561A, B has a somewhat smaller neutral hydrogen column density than those normally studied.

3.1. *Transverse Size of the Damped Lyα Absorber and Mass Determinations*

With the aid of a model for the gravitational lens, our results can be used to infer a minimum size for the transverse extent of the damped Lyα absorber. The first step is to derive the distance between the damped Lyα absorber and the quasar. The velocity separation between the damped absorber and the quasar is only 2270 km s^{-1}. The most straightforward approach is to interpret this velocity separation as being purely due to the expansion of the universe. In principle, corrections should be made to account for systematic shifts in emission lines and peculiar velocities, but these corrections are unknown. For example, the redshift of the quasar itself is based on measurements of the broad emission lines; and studies have shown that the true redshift, as derived from observations of the narrow emission lines, might be as much as $\sim 10^3$ km s^{-1} higher (e.g., Gaskell 1982; Tytler & Fan 1992). However, Junkkarinen (1989) presents contradictory evidence. As for peculiar velocities, a recent search for high-redshift galaxies in the vicinity of a damped Lyα absorber at $z_{\text{abs}} \simeq 3.4$ has resulted in the discovery of a galaxy separated in velocity by $\sim$2600 km s^{-1} from the damped absorber (Turnshek et al. 1992; Macchetto et al. 1993). Since finding such a galaxy in a blind search would be statistically unlikely, empirical evidence for some type of clustering between damped Lyα absorbers and galaxies at these velocity separations exists (see also Wolfe 1993). Therefore, the damped absorber at $z_{\text{abs}} = 1.3911$ and Q0957+561 may reside in a related cluster environment.

The most recent models in the literature for the Q0957+561 lens are those due to Falco et al. (1991) and Kochanek (1991). However, for our purpose, the model of Young et al. (1981b), which assumes that velocity separation is only due to the expansion of the universe, is adequate to address constraints on sizes of clouds that make up the $z_{\text{abs}} = 1.3911$ system. We adopt a cosmological model with $q_0 = 0.5$, but the results are not very sensitive to the choice of q_0. The size constraints are also not sensitive to the complicated image geometries considered by Young et al. (1981a). The model and presence of damped Lyα absorption in the spectra of both components A and B suggests that the $z_{\text{abs}} = 1.3911$ damped Lyα absorber has a transverse extent $d > 0.5h_{50}^{-1}$ kpc. If we assume that the absorber is a thin, disklike H I layer (Wolfe 1988), the lower limit on the neutral hydrogen mass of the absorber is approximately $M(\text{H I}) \simeq \pi(d/2)^2 N(\text{H I}) m_{\text{H}}$ where m_{H} is the mass of hydrogen. Therefore, $M(\text{H I}) > 10^5 h_{50}^{-2}\ M_{\odot}$. If the absorber is spherical in shape, a density $n(\text{H I}) \simeq N(\text{H I})/d$ is required. Thus, $n(\text{H I}) < 5 \times 10^{-2} h_{50}^{-1}$ cm^{-3} is implied for a spherical absorber, and the lower limit on M(H I) is approximately the same. Because of the nature of the constraints, a meaningful limit cannot be placed on n(H I) for the case where the absorber is an arbitrarily thin H I layer. However, if future observations of the C II λ1334 absorption line reveal the presence of a C II λ1335 fine structure line, collisional excitation might be used to infer a lower limit on n(H I) and result in evidence for a thin H I layer. The constraints on d and M(H I) are consistent with dwarf galaxies to larger spirals. They are the first such determinations for a damped Lyα system made with the use of a gravitational lens.

Since 21 cm absorption-line systems give rise to damped Lyα absorption (Briggs 1988), radio observations of 21 cm absorption lines across the extended radio structure in background quasars have also been used to infer minimum transverse sizes for damped Lyα absorbers. Wolfe et al. (1976) report that the damped Lyα absorber in 3C 286 at $z_{\text{abs}} = 0.682$ with $N(\text{H I}) \simeq 9 \times 10^{20}$ cm^{-2} must exceed $0.3h_{50}^{-1}$ kpc. Brown & Mitchell (1983) report that the damped Lyα absorber in 3C 196 at $z_{\text{abs}} = 0.437$ with $N(\text{H I}) \simeq 1.2 \times 10^{21}$ cm^{-2} must exceed $4.1h_{50}^{-1}$ kpc. Following this determination, Foltz, Chaffee, & Wolfe (1988) used results from optical spectroscopy with the earlier radio results to infer that the 3CR 196 damped absorber must exceed $13h_{50}^{-1}$ kpc. Briggs et al. (1989) report that the damped Lyα absorber in PKS 0458−020 at $z_{\text{abs}} = 2.038$ with $N(\text{H I}) \simeq 6 \times 10^{21}$ cm^{-2} must exceed $4h_{50}^{-1}$ to $16h_{50}^{-1}$ kpc. Absorption at 21 cm has not been detected at $z_{\text{abs}} = 1.3911$ in Q0957+561, but this result is not surprising since the absorber has a smaller neutral hydrogen column density, $N(\text{H I}) \simeq 7 \times 10^{19}$ cm^{-2}.

In addition to deriving a constraint on the transverse size of the damped Lyα absorber, there are at least two similarities between the $z_{\text{abs}} = 1.3911$ system in Q0957+561A, B and other damped Lyα systems which should be emphasized. One similarity concerns the properties of the metal-line absorption, and the other is evidence for Faraday rotation.

3.2. *Metal-Line Absorption Properties*

The metal lines in the $z_{\text{abs}} = 1.3911$ system are mostly moderate to strong low-ionization species. High-ionization species are present but weak, which is typically characteristic of the properties of some damped Lyα systems (Turnshek et al. 1989; Lu et al. 1992; Wolfe et al. 1993). The strength or equivalent width of the metal lines is not a measure of the column density of the species in question but is more a function of the velocity extent of the absorption. Typically the velocity extent of the metal lines is several hundred km s^{-1}. When metal lines observed at moderate spectral resolution are studied at high resolution, they are found to break up into numerous components, many of which lie on the flat part of the curve of growth. Absorption observations at 21 cm of damped Lyα absorbers in front of background radio quasars indicate that only one or a few of the metal-line components have neutral hydrogen column densities large enough to cause the Lyα Voigt profile to exhibit damping wings, because the velocity extent of the 21 cm absorption is often less than 20 km s^{-1} and sometimes only a few km s^{-1} (see Briggs 1988). The interpretation of the absorption-line observations is that the metal-line properties are indicative of a more extensive galactic halo-like region, while the damped Lyα absorption line and its corresponding 21 cm absorption line arise in the H I disk. As discussed in § 2.1, in the case of the $z_{\text{abs}} = 1.3911$ system, comparison of the optical spectroscopy of images A and B shows that slight but real differences in velocity extent and equivalent width of the metal lines do exist for the two different sight lines. Thus, the properties of the halo are observed to differ between the two sight lines, while no significant change in the neutral hydrogen column density is observed across the putative H I disk. Note, therefore, that this result is consistent with the standard model which suggests that two different components of the galaxy are probed by the observations, that is, at moderate spectral resolution the damped Lyα absorption would essentially reveal only the properties of the disk, and the metal-line absorption would essentially reveal only the properties of the halo.

3.3. *Faraday Rotation*

Wolfe, Lanzetta, & Oren (1992) have studied the incidence of Faraday rotation in a sample of radio-selected quasars which contain metal-line absorption in their spectra. The aim of their study was to determine the probability of finding significant Faraday rotation in various types of metal-line absorbers. They compared Faraday rotation found in metal-line absorbers (i.e., H I disk systems) to Faraday rotation found in metal-line absorbers which did not exhibit damped Lyα profiles (i.e., halo-only systems). They showed that the probability of finding Faraday rotation was significantly higher in the damped subset, suggesting that magnetic fields are significantly stronger in protogalactic H I disks than in protogalactic halos. They report that the observations are consistent with magnetic field strengths of at least a few μG in the damped absorbers. Wolfe et al. (1992) further discuss the implication of their findings for the origin of galactic magnetic fields, and we refer the reader to their discussion for interpretation of the Faraday rotation data. In addition, Kronberg, Perry, & Zukowski (1992) should be consulted for recent observations and analysis of Faraday rotation that presumably arises in the $z = 0.395$ damped Lyα absorber seen in the spectrum of PKS 1229−021. Welter, Perry, & Kronberg (1984) report that the residual rotation measure (RRM), which excludes the Galactic component from the observed rotation measure, is RRM $= -63 \pm 10$ rad m^{-2} for Q0957+561A and RRM $= -163 \pm 10$ rad m^{-2} for Q0957+561B. The RRM is

$$\mathrm{RRM} = 2.7(10^{-19})(1 + z_{\mathrm{abs}})^{-2} x_e N(\mathrm{H\ I}) B_{\parallel} \ \mathrm{rad\ m^{-2}}$$

where x_e is the average electron fraction of an H I layer with column density N(H I) and $B_{\parallel}$ is the line-of-sight component of the magnetic field (in μG) averaged along the sight line through the damped absorber and weighted according to electron density (Welter et al. 1984; Wolfe et al. 1992). This suggests that $x_e B_{\parallel} = 19$ μG for the H I layer in front of Q0957+561A and $x_e B_{\parallel} = 50$ μG for the H I layer in front of Q0957+561B. Because the damped absorbers are opaque to ionizing radiation, the H I layers must be basically neutral. A good conservative limit on the electron fraction is therefore $x_e < 0.1$, which suggests that $B_{\parallel}$ may be more like several hundred μG in the H I layers. While the *IUE* data indicate that neutral hydrogen column densities along the two sight lines are similar, the RRMs along the two sight lines clearly seem to be different. Greenfield et al. (1985) suggest that the difference in RRM may be due to the lensing galaxy at $z \simeq 0.36$. Note that the value of N(H I) for Q0957+561A given by Wolfe et al. (1992), which was based on preliminary work, is incorrect, and therefore their inferred magnetic field strength is too low.

The $z_{\mathrm{abs}} = 1.3911$ damped Lyα absorber seen in front of the Q0957+561A, B images will be an interesting object for future study. In the context of the standard interpretation of damped Lyα absorbers, *HST* can provide the ultraviolet sensitivity needed to reconsider the results presented here, possibly revealing information about differences across a young H I disk. High-resolution observations with the next generation of large ground-based telescopes may reveal the kinematic structure of the halo and chemical composition of the disk along two different sight lines. The C II $\lambda\lambda$1334, 1335 absorption line, predicted to occur near ~3195 Å, will also be interesting to study as it may provide a way to constrain the density of the absorbing region and provide a test of the standard H I disk model for damped Lyα absorbers.

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