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Metal-line System Survey: Characterizing the Low-redshift IGM

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Abstract The low-redshift IGM probes the last ten billion years of metal enrichment from galactic feedback processes. We present preliminary results from a survey of intergalactic metal-line absorption systems in archival *HST* STIS, GHRS, and *FUSE* spectra of ≈ 50 $z \lesssim 2$ UV-bright objects. We summarize the detailed analysis of one sightline (PKS1302–102, $z_{QSO} = 0.2784$) with which we set the methodology for the larger survey. We use simple CLOUDY models to constrain the ionizing mechanism(s) and metallicities for the metal-line systems. For about 15 sightlines, including PKS1302–102, we have a complementary galaxy survey, and we look for correlations between galaxies and absorption systems in order to understand the large-scale distribution of the metal-enriched IGM.

Keywords galaxies: quasars: absorption lines — quasars: individual (PKS1302–102)

1 Introduction

Observations of metal-line absorbers in quasar spectra help characterize the intergalactic medium (IGM): chemical composition; ionization mechanisms; and chemical evolution and galactic feedback processes. At low redshift $z < 2$, O VI $\lambda\lambda 1031, 1037$, Si IV $\lambda, \lambda 1393, 1402$, and C IV $\lambda\lambda 1548, 1550$ are the most studied tracers of the IGM. The O VI doublet is currently favored to trace the so-called warm-hot intergalactic medium (WHIM), predicted to be a reservoir of baryons at $z \approx 0$ (Fang & Bryan 2001). The mass densities of Si IV and C IV in the IGM are roughly constant for $2 \lesssim z \lesssim 5$ (Songaila 2005). The question remains whether this trend continues for $z < 2$, which covers the last ten-billion years and spans the peak in the star formation rate. Evolution or lack thereof in the mass densities of Si IV and C IV relates to feedback processes in galaxies.

The galactic environments of intergalactic absorbers also shed light on feedback processes. With surveys of quasar absorption lines and galaxies in the area, correlations between column density and nearest-neighbor galaxies, metallicity and galaxy type, *et cetera* can be sought.

Here we discuss the first results of a larger project to identify metal-line systems in sightlines to ~ 50 low-redshift, UV-bright objects (primarily quasars) with some combination of archival *Hubble Space Telescope* (*HST*) Space Telescope Imaging Spectrograph (STIS) and Goddard High-Resolution Spectrograph (GHRS) and *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) spectra. We begin by summarizing the results from a detailed study of one sightline before discussing the larger project.

2 PKS1302–102

We performed a detailed analysis of the sightline to PKS1302–102 ($z_{QSO} = 0.2784$; for full details, see Cooksey et al. 2007). PKS1302–102 was observed for 22 ks with the STIS (Program 8306; PI: M. Lemoine) and 149 ks with the *FUSE* (Program P108; PI: K. Sembach). This study sets the methodology for the larger

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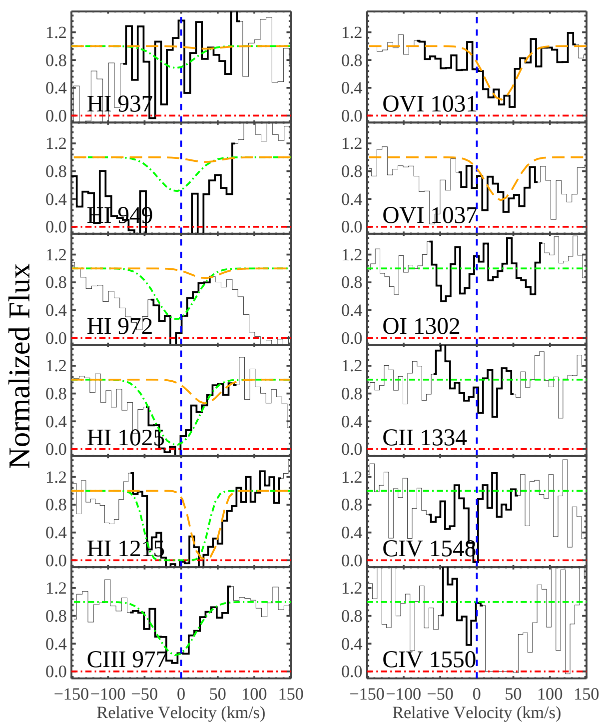

Fig. 1.— Velocity plot for $z_{abs} = 0.04226$. This system is a multi-phase medium, as seen from the line profiles (thin solid lines) and velocity offset between Lyα/C III and the O VI doublet. The absorption lines are displayed with respect to the centroid of Lyα (blue vertical dashed line). The dark outlined portions of the spectra are used to measure the equivalent widths and column densities; H I 949, 972, 1025, and the O VI doublet are blended. From COG analysis, $\log \mathrm{N_{HI}} = 15.1$ and $b = 22\,\mathrm{km\,s^{-1}}$; based on these values, the H I Voigt profiles are over-laid, centered at $z_{abs} = 0.04224$ (green dashed-dot line). Also shown is the assumed Voigt profile for the weaker component of Lyα at $z_{abs} = 0.04238$ with $\log \mathrm{N_{HI}} \approx 14$ and $b \approx 15\,\mathrm{km\,s^{-1}}$ (orange long-dashed line). C III ($\log \mathrm{N(C^{++})} = 13.7$) is associated with the stronger component of Lyα and the O VI doublet ($\log \mathrm{N(O^{+5})} = 14.5$) with the weaker. The remaining lines are not detected at 3σ, and the (green) dashed-dot line is the flux at unity. In each panel, the (red) dashed-dot line is the flux at zero.

survey of ~ 50 UV-bright objects with archival spectra. We summarize the study below.

The STIS spectra were reduced by the standard CalSTIS pipeline, and the *FUSE* spectra were reduced with a slightly modified version of the recommended CalFUSE pipeline. Then, the spectra from each instrument were coadded in IDL.

We developed a program to automatically find potential absorption lines. From this list, we disentangled Galactic from intergalactic lines. We further sorted the latter category into systems (*e.g.*, H I Lyman lines and metal-lines like the O VI doublet). We identified 95% of the features in STIS that could be Lyα and $> 80\%$ of the features in *FUSE*. The PKS1302–102 sightline has 23 Lyα absorbers, 14 of which have $\log \mathrm{N_{HI}} > 14$, and eight of which have at least one metal line. The metal-line systems are summarized in Table 1.

Hot, highly ionized gas would have broad Lyα absorption that would not be readily detectable in the moderate S/N spectra of PKS1302–102. Such gas likely represents the WHIM and might be associated with O VI absorption. In order to be unbiased towards doublets without detected Lyα absorption, we performed a "blind search" whereby we search the automatically-detected features for lines with the correct characteristic separation. In the PKS1302–102 spectra, there are no such doublets.

The H I column density and Doppler parameter were measured with the curve-of-growth (COG) analysis where more than one H I Lyman line was available. The apparent optical depth method (AODM) from Savage & Sembach (1991) was used for Lyα-only and metal-line column densities. Ionization mechanisms and metallicities derived from relative abundances of detected species and simple CLOUDY (as last described in Ferland et al. 1998) photoionization or collisional-ionization equilibrium models. The metal-line systems are predominately photoionized, and none are assuredly collisionally ionized (see Table 1). The systems are also predominately low metallicity $-3 \lesssim [\mathrm{M/H}] \lesssim -1$.

Two systems at $z_{abs} = 0.04226$ and 0.09487 are multi-phase absorbers, as evidenced most strongly by the multi-component structure of their line profiles (see Figures 1 and 2, respectively). Both systems have multi-component Lyα profiles and, at least, C III and O VI absorption. In the $z_{abs} = 0.04226$ system, there is likely two photoionized phases, with the stronger and weaker H I components associated with the C III and O VI absorption, respectively. On the other hand, the O VI absorption in the $z_{abs} = 0.09487$ system is possibly collisionally ionized since it is very broad; any associated broad Lyα absorption is masked by the partial Lyman limit system Lyα feature, which has narrow, multi-component C III and Si III associated with it. In both systems, a single-phase, collisionally-ionized model is excluded since C IV is not detected.

Supplementing the archival data is a magnitude-limited survey of galaxies in the field around PKS1302–102. It is complete to 95% and 70% with 5′ and 10′, respectively, for objects brighter than $R \approx 19.5\,$mag. Seven of the eight metal-line systems have at least one galaxies with velocity separation $|\delta v_{\rm gal}| < 500\,{\rm km\,s^{-1}}$ and with impact parameters $\rho < 500\,h_{75}^{-1}\,$kpc (see Figure 3). The eighth system is at $z_{abs} = 0.00442$ where the survey only covers $\approx 25\,h_{75}^{-1}\,$kpc, but the PKS1302–102 sightline is known to go through the Virgo cluster at that redshift. The metal absorbers arise in a diverse set of galactic environments, with no obvious trends between nearest-neighbor luminosity or type with respect to the H I column density. There is a trend that the impact parameter of the closest galaxy in the survey increases with decreasing $\log {\rm N_{HI}}$. The metal-line systems at $z_{abs} \approx 0.094, 0.192$, and 0.225 have at least one other strong $\log {\rm N_{HI}} \geq 14$ absorber with $|\delta v_{\rm gal}| < 500\,h_{75}^{-1}\,$kpc as well as several galaxies.

In conclusion, the majority of the metal-line systems in the PKS1302–102 sightline are photoionized media, and none are conclusively single-phase, collisionally-ionized absorbers. They are predominately low metallicity. We detect O VI absorption in multi-phase media for two systems. From the complementary galaxy survey, we see the intergalactic absorbers arise in a variety of galactic environments.

3 Future Work

In the future, we plan to analyze the archival STIS, GHRS, and *FUSE* spectra of ~ 50 UV-bright objects in the same manner as the PKS1302–102 data was analyzed. We will be concerned primarily with the C IV and Si IV doublets in order to focus on the question of chemical evolution discussed in the introduction. We are first focusing on objects with galaxy survey complements so that with a larger statistical sample, we may search for trends in galactic environments of intergalactic absorbers, especially metal-line systems.

As requested by the organizing committee for the first NUVA conference "Space Astronomy: the UV window to the Universe," we contribute our suggestions for future UV missions. We would like a high-S/N (≈ 10), high-resolution (10 to $20\,{\rm km\,s^{-1}}$), uniform survey of low-redshift ($z < 2$) quasars with coverage of C III to C IV. High S/N so that we may detect weak lines and probe the low- density IGM; high resolution to see multiple components and observe substructure within individual clouds; and uniform in the sense that all the observations come from the same instrument, as opposed

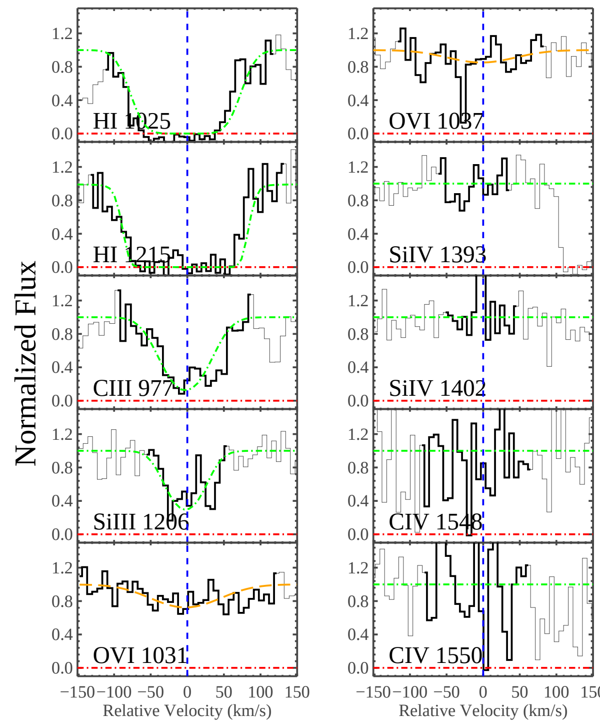

Fig. 2.— Velocity plot for $z_{abs} = 0.09487$ (see Figure 1 description). This system is a multi-phase medium where Lyα, C III, and Si III have multiple components and the O VI doublet is broad. From the H I COG, $\log {\rm N_{HI}} = 16.9$ and $b = 31\,{\rm km\,s^{-1}}$, as shown with the Voigt profile centered at $z_{abs} = 0.09486$. The H I Doppler parameter is assumed in the Voigt profiles for C III ($\log {\rm N(C^{++})} = 13.9$) and Si III ($\log {\rm N(Si^{++})} = 13.1$). The broad, well-aligned O VI doublet ($\log {\rm N(O^{+5})} = 14$) is assumed to have $b \approx 60\,{\rm km\,s^{-1}}$. The remaining lines are not detected at 3σ.

to the current situation where full wavelength coverage requires use of STIS, GHRS, and *FUSE*. The background quasars should well sample the redshift space to allow for study of the evolution of the IGM. The *HST* Cosmic Origins Spectrograph is capable of fulfilling most of these requirements, and with its increased sensitivity compared to STIS, it can observe an order of magnitude more background quasars. The Galaxy Evolution Explorer survey potentially contains the target list. In the more distant future, the World Space Observatory-UV, as a dedicated UV instruments with much of the same capabilities as COS, will be yet another chance for a large high-S/N, high-resolution, uniform survey of low-redshift quasars.

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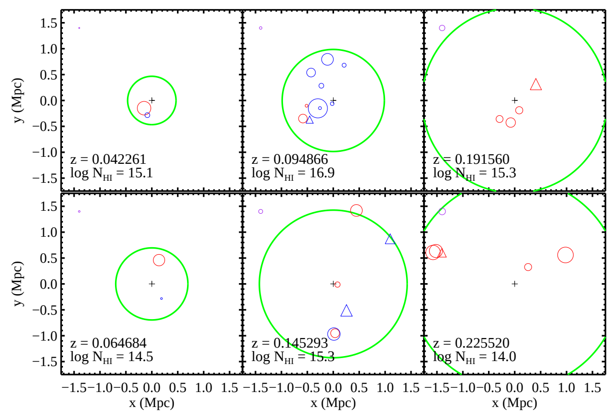

Fig. 3.— Galaxies with $|\delta v_{gal}| \leq 1000\,km\,s^{-1}$ from metal-line systems. Circles indicate $|\delta v_{gal}| \leq 500\,km\,s^{-1}$ and triangles $500\,km\,s^{-1} < |\delta v_{gal}| \leq 1000\,km\,s^{-1}$. Blue indicates $\delta v_{gal} < 0\,km\,s^{-1}$ and red $\delta v_{gal} > 0\,km\,s^{-1}$. The (green) solid circle indicates $10'$ where the survey is 70% complete to a limiting $R = 19.5$ mag. The symbol sizes are proportional to the apparent brightness, where the (purple) symbol in the upper left-hand corner of each pane shows the magnitude limit.

Table 1 PKS1302–102 Metal Absorbers Summary

z_{abs}	$\log N_{HI}$	b_{HI}	$\log N(C^{++})$	$\log N(O^{+5})$	Ion.	$[M/H]_{phot}$	δv ($km\,s^{-1}$)	ρ (h_{75}^{-1} kpc)
0.00442	15.8	17	> 13.5	< 14.0	Photo	[-1.9, -1.6]	⋯	⋯
0.04226	15.07	22	13.7	14.5	Multi	[-0.9, -0.7]	87	212
0.06468	14.47	26	< 13.1	13.8	???	[-1.2, -0.5]	0	338
0.09400	15.05	28	> 13.3	< 13.8	Photo	[-0.9, -0.6]	−115	65
0.09487	16.87	31	> 13.9	14.0	Multi	[-2.1, -1.4]	−352	65
0.14529	15.37	57	13.2	< 14.1	Singl	[-1.8, -0.5]	2	82
0.19156	15.27	24	13.1	< 14.0	Photo	[-1.9, -0.7]	37	209
0.22552	14.01	30?	< 13.5	14.3	Coll?	[-0.2,+0.4]	12	416

Note. — The measured redshifts, column densities, and Doppler parameters are given for each metal-line system. The likely ionization mechanisms (Ion.) are based on kinematic arguments and CLOUDY modeling. $[M/H]_{phot}$ is the range of possible metallicities from the single-phase CLOUDY photoionization models, The velocity separation δv and impact parameter ρ of the closest galaxy in the survey are also given.

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