QSO Absorption Line Systems as a Probe of Galaxies Like the Milky Way

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Abstract. Quasar absorption lines provide detailed information on the chemical, kinematic, and ionization conditions in galaxies and their environments, and provide a means for studying the evolution of these conditions back to the epoch of the first quasars. Among the collection of absorbing structures along the lines of sight to quasars there is an evolutionary sequence of galaxies that represent predecessors of the Milky Way and provide a direct view of its history. Absorption spectra of lines of sight through the Milky Way and through nearby galaxies reveal a variety of chemical species, ionization conditions, and kinematic substructures. These absorption profiles are produced by low density gas distributed in rotating disks, high velocity halo clouds, satellite galaxies and their debris, superbubbles, and other sub–galactic gaseous fragments. Guided by knowledge gained by studying nearby galaxies, we are developing interpretations of the variety of observed absorption signatures. Images of $z \sim 1$ galaxies responsible for MgII absorption also allow us to explore the statistical connections between the galaxy properties and their gaseous content. Quasar absorption lines are fast becoming a powerful evolutionary probe of gaseous conditions in the Milky Way.

1. Introduction

Quasar absorption line (QAL) studies have evolved past the stage of simply counting the number of absorption lines due to a particular ion as a function of equivalent width and redshift. No longer do we merely study disjoint classes of objects called MgII, Ly$\alpha$, and CvII absorbers; we are now poised at the dawn of an era in which we can explore the structures, metallicities, ionization conditions,
and kinematics within the individual galaxies that produce the absorption lines. Once the absorption signatures of Milky Way–like galaxies are recognized, QALs can be used to trace the detailed evolution of galactic gas from \( z = 5 \) to \( z = 0 \), the full redshift range over which quasars have been observed.

Historically, QAL systems were divided into various categories based upon how the samples were selected: 1) by Ly\( \alpha \) (classified as damped if the neutral column density \( N_H > 10^{20.3} \) cm\(^{-2}\), Lyman limit if \( 10^{17.2} < N_H < 10^{20.3} \) cm\(^{-2}\), and forest if \( N_H < 10^{17.2} \) cm\(^{-2}\)), 2) by Mg\( \text{II} \), and 3) by C\( \text{IV} \). Evolution in the co–moving number per unit redshift\(^1\) can be measured for each of these “populations” for a given detection threshold in equivalent width (column density in the case of Ly\( \alpha \)). For \( z > 2 \), the number of Ly\( \alpha \) forest systems is observed to rapidly decrease with time with \( \gamma \sim 1.9 \) (Bechtold 1994), and for \( z < 2 \) is observed to slowly decrease with \( \gamma \) consistent with no evolution (Bahcall et al. 1996). In the redshift interval \( 0.4 < z < 2.2 \), the population of Mg\( \text{II} \) absorbers (\( W_0 > 0.3 \) Å) is consistent with no evolution, though the subgroup of stronger absorbers (\( W_0 > 1 \) Å) evolve away with time very strongly (\( \gamma \sim 2.2 \)). The opposite trend, an increasing number with decreasing redshift, is seen for C\( \text{IV} \) systems (\( W_0 > 0.15 \) Å) in the redshift interval \( 1.2 < z < 3.7 \) (Steidel 1990). Overall, the statistical evolution of these various populations is due to some combination of evolution in the metallicities, ionization conditions, and kinematic structuring of the absorbing clouds. A separation of these effects awaits detailed study of the individual absorption line systems.

To better appreciate the inferences about the physical conditions of the gas based upon absorption lines, we would like to know what type of galaxy and what part of the galaxy is being probed by the QSO light path. Specifically relevant to this proceedings is the question of when we are looking through part of a Milky Way–like disk, high velocity cloud, LMC–like satellite, and/or something like the LMC Stream. A good strategy for sorting this out is to study nearby galaxies and the Milky Way itself, to draw inferences on the kinematic, chemical, and spatial distribution of the clouds from the absorption lines they produce, and to ascertain what fraction of each absorber “population” is presented by a galaxy of known type and morphology. Deep imaging of \( z \leq 1 \) galaxies allows us to go further back in time and to determine what luminosity and type of galaxy is associated with particular QALs. With the addition of theoretical modeling of the expected absorption conditions arising from various processes (eg. winds, fountains, superbubbles, and infalling material), the evolution of strengths, overall shapes, and subcomponent structures of the absorption line profiles will allow us to infer a time sequence in the Milky Way’s history.

This article begins with a review of the insights that are likely to be gained through absorption studies of the Milky Way and of nearby galaxies. The third section is a discussion of observations of Mg\( \text{II} \) absorbing galaxies at \( 0.3 < z < 1.0 \) that also focuses on studies designed to discern the overall geometric cross sections of low ionization galactic gas. In the fourth section, we present HIRES (Vogt et al. 1994) spectra of a number of Mg\( \text{II} \) absorbers (Churchill 1996a) and discuss what we hope to learn from the variety of substructures that are

\(^1\)The co–moving number is parameterized by \( N(z) \propto (1 + z)^\gamma \). For no evolution, \( \gamma = 0.5 \) in a \( q_0 = 0.5 \) universe and \( \gamma = 1.0 \) in a \( q_0 = 0.0 \) universe.
observed. The use of C iv systems at high $z$ in developing a picture of the history of the early Milky Way galaxy is discussed in section five, as is the relevance of damped Ly $\alpha$ systems for understanding the evolution of the Milky Way disk. We conclude with speculations on the physical nature of the objects that give rise to various types of QALs.

2. Lines of Sight Through the Milky Way

A sampling of lines of sight the Milky Way show a variety of structure in the observed low and high ionization species. The line of sight to the low halo star HD 167756, which samples the inner galaxy and disk, shows low ionization gas with velocities $-25 \leq v \leq +30$ km s$^{-1}$ (Cardelli, Sembach, & Savage 1995). Looking toward two halo stars, Savage and Sembach (1994) find highly ionized gas with C iv/Nv $> 6$ toward the first and C iv/Nv $\sim 1–3$ toward the second. The latter is consistent with the conditions predicted to exist in superbubbles and galactic fountains. The line of sight toward 3C 273 passes through Galactic superbubbles which exhibit large C iv and N v column densities (Lu, Savage, & Sembach 1994). From the line of sight to the star HD 156359, which samples the outer warp of the disk, a scale–height of 1 kpc for N v and of 3–5 kpc for C iv has been inferred. This line of sight passes through several spiral arms whose gas is seen to have a large velocity dispersion due to turbulent mixing from supernova–related processes (Sembach, Savage, & Lu 1995). The punch line here is that even looking through this specific galaxy at a particular stage in its evolutionary history, we see substantial variation in the absorption properties.

Savage et al. (1993) compared the range of abundances of various ionic species in the population of $z > 2$ damped Ly $\alpha$ absorbers to those derived from lines of sight through the Milky Way. They found overlap between the two samples, with a trend toward larger line strengths arising in the damped Ly $\alpha$ absorbers and a smaller number of strong lines from high ionization species in the Milky Way. Since all lines of sight used to study absorption through our galaxy must pass through our region of the disk and through the lower halo, the Milky Way sample is likely to be biased toward low ionization conditions. Nonetheless, it is interesting to speculate if redshift evolution in the ionization conditions is occurring.

How often does a line of sight through the Milky Way pass through a high velocity cloud (HVC)? The line of sight through the Milky Way toward NGC 3783 passes through an HVC of $v \sim 240$ km s$^{-1}$ and a metallicity of 15% solar (Lu, Savage, & Sembach 1994). In a recent survey, Murphy, Lockman, and Savage (1995) found an HVC covering factor (for lines of sight passing through half the Milky Way) of 38%. However, Bowen, Blades and Pettini (1996a) surveyed for Mgii HVCs (which should trace the Lyman limit H1) and found that many are consistent with co–rotation in the Galactic disk, and a covering factor much smaller than 38%. Regardless, the population of Milky Way HVCs is not sufficient to produce anywhere close to the unity covering factor of Mgii absorbing gas that is inferred from studies of $z \leq 1$ galaxies. The high frequency with which galaxies at intermediate redshifts are found to produce Mgii absorption is an indication that either there is strong evolution of the HVC population around galaxies, or other galactic components contribute significantly to the
cross-section of absorption. It is interesting to note that Bowen, Blades and Pettini find the LMC H\textsc{i} “double disk” in Mg\textsc{ii} at impact parameter 7 kpc as well as Galactic Mg\textsc{ii} along the line of sight to Q0637–725.

3. The Geometry of Mg\textsc{ii} Absorbing Gas

In a GHRS survey of 17 lines of sight through nearby galaxies, Bowen, Blades, and Pettini (1996b) find that lines of sight that pass within 10 kpc of a galaxy center usually exhibit absorption while lines of sight at impact > 30 kpc do not. (Unfortunately, the paucity of known bright quasars at impact parameters 10–30 kpc from the centers of nearby galaxies prevents a robust determination of local galaxy absorption covering factors.) There are exceptions to such a simple picture. Lines of sight with QSO–galaxy impact parameters < 10 kpc toward the early type galaxies Leo I and NGC 1380 do not exhibit absorption. On the other hand, the highly inclined disk toward galaxy G1543+4856 (smallest impact candidate) seems to be producing strong Mg\textsc{ii} absorption ($W_0 = 0.6$ Å) at an impact parameter of 45 kpc. Based upon their overall study, Bowen, Blades, and Pettini go on to suggest that the environment of the absorbing galaxies has affected the characteristics of the absorption, the strength of the lines, the complexity of individual line components, and the ionization state of the gas.

For $z \leq 1$, Steidel, Dickinson, and Persson (1994, hereafter SDP) used imaging and spectroscopy to identify the population of Mg\textsc{ii} absorbing galaxies that may represent predecessors to the Milky Way. In a sample of 58 absorbers in 51 QSO fields, they identified galaxies that have the same redshift as seen in Mg\textsc{ii} absorption. In a plot of the impact parameter $D$ versus the rest frame $K$ luminosity, these 58 systems were found to define an absorption cross-section “boundary”, given by $D = 38h^{-1}(L_K/L_K^*)^{0.15}$ kpc (Steidel 1995, hereafter S95). Apparently, nearly all galaxies produce Mg\textsc{ii} absorption within ~ 40 kpc, and very rarely is absorption seen at larger distances from a luminous ($> 0.05L_K^*$) galaxy. The most straightforward interpretation is that the gaseous galaxy halos have a relatively sharp edge within which Mg\textsc{ii} absorbing clouds are distributed with a nearly unity covering factor.

In light of the above described studies of local galaxies, we ask “what is the contribution of galactic disks to the absorption cross section”? It would appear that if Mg\textsc{ii} absorption was produced by disks, some galaxies with highly inclined disks would fail to produce absorption at small impact parameters. However, in these inclined disks, the path length of the line of sight is increased due to the orientation. For H\textsc{i} disks that extend well beyond the optical radius of the galaxy, the effect of passing further out in the disk where the column density is smaller can be compensated by the increased path length. Realistically, a disk responsible for Mg\textsc{ii} absorption would be thick and consist of discrete absorbing clouds. Even in the saturated regime, orientation can lead to an increased equivalent width if the larger number of clouds along the path in an inclined galaxy disk are spread over a larger range of velocities.

The argument that Mg\textsc{ii} absorption is often produced in the outer disks of spiral galaxies is confirmed by 21 cm maps that show H\textsc{i} at radii of tens of kpc (Irwin 1995, Corbelli, Schneider, & Salpeter 1989, van Gorkom et al. 1993). Also, Bowen, Blades, and Pettini (1995b) demonstrated that the radius for H\textsc{i}...
absorption at $N(\text{H}i) = 10^{20}$ cm$^{-2}$ increases with a larger power of the luminosity $R = 16(L/L^*_B)^{0.56}$ kpc than at the $10^{19}$ cm$^{-2}$ contour level, for which $R = 23(L/L^*_B)^{0.36}$ kpc. If this trend continues to lower $N(\text{H}i)$, the disks of relatively low luminosity spiral galaxies likely make a significant contribution to the Mg\textsc{ii} absorption cross section. Radio maps are not sensitive down to the H\textsc{i} column densities of $10^{17}$ cm$^{-2}$, the level at which Mg\textsc{ii} is known to be associated, yet even the contour level of $10^{19}$ cm$^{-2}$ shows that many galaxy disks will present a significant cross section for Mg\textsc{ii} absorption. The shape of the radial cutoff for Mg\textsc{ii} disks depends on the physics of the photoionization (Maloney 1993, Corbelli & Salpeter 1993, Dove & Shull 1994), so the cross section of a “population” of Mg\textsc{ii} disks is uncertain by about a factor of two.

Figure 1. The distribution of impact parameter versus normalized $K$ luminosity for three random realizations of a spherical cloud model (upper panels) and of a disk model (lower panels). Open circles denote absorbing galaxies and filled triangles denote non–absorbing galaxies. These realizations sample the number of fields required to produce 58 absorbing galaxies, as observed by SDP. The model then yields the number of non–absorbers for this same number of fields, unbiased with respect to whether absorption occurs in a field or not. The solid line is the S95 best–fit “boundary” to the SDP data, $D = 38h^{-1}(L_K/L^*_K)^{0.15}$ kpc.

These ideas motivated us to design Monte–Carlo simulations that would compare the expected absorption properties of populations of Mg\textsc{ii} clouds in spherical and in disk geometries (Charlton and Churchill 1996). In Figure 1, we illustrate results for absorbing and non–absorbing galaxies in a simulated SDP study. Both the spherical and disk geometry models yield predicted numbers of
non-absorbing galaxies at small impact parameters and of absorbing galaxies at large impact parameters than are larger than what is observed. Spherical cloud models with a unity covering factor are discrepant with the observed distribution of Mg\textsc{ii} equivalent widths, producing relatively too many large values. We predict that spherical cloud models have only a covering factor of 70–80\%, which is, in fact, similar to the effective covering factor of the population of model disks.

![Figure 2](image)

Figure 2. Predictions from Monte–Carlo models for a randomly oriented population of absorbing disks. — (a) expected equivalent width of Mg\textsc{ii} as a function of the inclination. — (b) relative number of absorbers as a function of the position angle of the QSO with respect to the projected inclined disk major axis.

If galaxy disks play a significant role in defining the geometric cross–section for Mg\textsc{ii} absorption there should be a correlation between the equivalent width of the absorber and the disk inclination (due to the increased path length and resulting increased velocity dispersion of the clouds in highly inclined disks). A Monte–Carlo model realization illustrating the expected trend is given in Figure 2a. Hubble Space Telescope WFPC2 images will allow the orientations and morphologies of the absorbing galaxies at $z < 1$ to be determined. With a sample of $\sim 20$ such images (being obtained by Steidel and collaborators), it should be possible to utilize this test to determine if disks make a significant contribution to the overall cross–section for Mg\textsc{ii} absorption. A second prediction for the disk population is illustrated in Figure 2b. The cross section for absorption is highest when the angle, $\theta$, subtended between the QSO line of sight and the major axis of an inclined disk projected on the sky, is zero or $\pi$.

We “calibrated” our simulated fields to account for the selection and observational procedure employed by SDP. First, we considered that the observa-
tional sample was not unbiased in that it contained a larger fraction of absorber fields than “control” fields and thus was deficient in the total number of non-absorbing galaxies. Second, we considered that redshifts were not obtained (in the S95 results for all galaxies at large distances from the quasar in the absorber fields (i.e. once the galaxy responsible for absorption was identified the search was often stopped). When the selection procedures of S95 are applied to our model results we find little distinction between either geometry, i.e. for both only a few to several non-absorbing galaxies at impact parameters less than $38h^{-1}(L_K/L_K^*)^{0.15} \text{kpc}$ are observed in the model fields. Discrepancy in these numbers are further reduced when possible misidentifications of absorbing galaxies are incorporated into the statistics. We conclude that both the spherical and the disk models are consistent with the current observations of the population of MgII absorbers. In fact, disk gas, halo gas, and satellite gas all surely play a role in shaping the MgII absorption profiles, and the overall geometric cross section of an absorbing galaxy is unlikely to be the same at all column density levels.

4. The Variety of MgII Absorbers

The idea that galaxy disks, clouds in galaxy halos, and satellite galaxies all contribute to MgII profiles is reinforced by the great variety of substructure in Keck/HIRES spectra of MgII absorbers at 6 km s$^{-1}$ resolution. A sampler of the kinematic substructure exhibited by the $(\lambda 2796)$ transition of the MgII doublet is presented in Figure 3.

These spectra are likely to be showing us absorption from satellites of $L^*$ galaxies, rotating galaxy disks, multiple clumps in galaxy halos, groups of galaxies, superbubbles, infall of gaseous fragments, and/or outflow. Using the observational clues from the Milky Way and nearby galaxies in tandem with theoretical models of the processes (such as fountains, winds, and tidal stripping) that give rise to the absorption, we hope to learn to recognize what galactic substructures are giving rise to these complex profiles.

As described in §2, the Milky Way itself exhibits large differences in absorption along different lines of sight. Undoubtedly, very different profiles in Fig. 3 could represent lines of sight through different regions of galaxies that were similar to each other in their gross properties. Images of the absorbing galaxies (allowing determination of impact parameters, luminosities, morphologies, and orientations) will be a key to interpretation of the absorption signatures (Churchill, Steidel, & Vogt 1996, Churchill 1996b). If the absorption profiles can be decoded, such that the internal dynamics, chemical compositions, and ionization states of galactic gas can be inferred, the ultimate contribution of QAL studies would be realized. The processes by which galaxies of various types form and evolve could be studied in detail back to the highest redshifts.

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2The SDP survey is still in progress. It is their goal to obtain all redshifts within a well defined angular separation from the QSO.
Figure 3. The HIRES Mg\textsc{ii} profiles ($R = 45000$) of a sample of Mg\textsc{ii} absorbers at $0.4 < z < 1.5$. Absorption profiles have also been obtained for the low ions Mg\textsc{i}, Fe\textsc{ii}, and Ca\textsc{ii}. The full sample will be presented elsewhere (Churchill 1996a).

5. **Clues from C\textsc{iv} and Damped Ly\textsc{\alpha} for Milky Way Evolution**

Here, we briefly comment on other examples of the power of QALs in understanding the dynamical, chemical, and ionization evolution of the gaseous components of the Milky Way.

If the Milky Way is any indication, C\textsc{iv} and other high ions can be used to trace processes such as galactic fountains and high velocity clouds. For example, the number of strong C\textsc{iv} doublets decreases with increasing redshift, but the weaker lines increase in number back to at least a redshift of $z = 3.7$ (Steidel 1990). This is interpreted as an increase in abundance of carbon by a factor of three in a typical galaxy halo in just one billion years. This interpretation, however, is not definitive in light of the recent detection of a strong Mg\textsc{ii} absorption system at $z > 4$ (Elston et al. 1996). Since C\textsc{iv} is observable from the ground at these high redshifts, the discovery of bright high redshift QSOs may facilitate a study of the buildup of the first metals.

Wolfe (1995, references therein) has continued to suggest that damped Ly\textsc{\alpha} systems are the high redshift predecessors of Milky Way–like disks. This view is supported by the observation that the H\textsc{i} contribution to the total mass density of the Universe from the population of damped Ly\textsc{\alpha} absorbers decreases with time, consistent with the expectation that gas is being converted into stars (Wolfe et al. 1995). Will further study of damped Ly\textsc{\alpha} absorbers and their metal content be key to understanding the past evolution of the Milky Way?
disk? Unfortunately, there are several serious complications that must first be considered: 1) The several nearby \((z < 1)\) damped Ly\(\alpha\) systems are not ordinary spirals, but are instead found to be low surface brightness galaxies and dwarfs (Steidel, private communication). 2) Dust obscuration could seriously bias samples by eliminating from quasar catalogs those that are obscured by the largest column density damped Ly\(\alpha\) systems (Fall & Pei 1995). 3) Gravitational lensing could bias samples, adding to the numbers of the largest column density absorbers (Bartelmann & Loeb 1996). 4) It is quite rare to observe damped systems with values of \(N(\text{H}i)\) as large as the stellar surface density in the centers of galaxy disks at present (Salpeter 1996). These facts suggest that either infall plays a key on-going role in the evolution of spiral disks, or that many of the high redshift damped Ly\(\alpha\) systems are also low surface brightness galaxies. These complications will substantially delay definitive conclusions for the Milky Way disk evolution based on the study of damped Ly\(\alpha\) absorbers.

6. Speculations on the Origins of QALs

We conclude with general hypotheses about the types of gaseous systems that give rise to the various populations of QALs:

1. Damped Ly\(\alpha\) systems may mostly consist of the thick predecessors of galaxy disks, but there is likely to be a non-negligible contribution from lower surface brightness disks that do not evolve into Milky Way–like galaxies.

2. It is likely that Lyman limit/Mg\(\text{II}\) systems usually have an absorption contribution from the extended disk of a spiral galaxy. The multiple components of these systems, extending over a range of \(\sim 100\) km s\(^{-1}\), provide information about the environment of the dominant absorbing galaxy. We should occasionally see galaxy pairs and groups in Mg\(\text{II}\) absorption. This will provide a way of observing the evolution of the environments and satellite systems of galaxies back to early times.

3. C\(\text{IV}\) systems trace a more diffuse, more ionized component that may allow study of high velocity clouds and halo structure. The substructure observed in C\(\text{IV}\) systems may relate to the infall mechanisms and merger processes during the formation of galaxy halos.

4. Ly\(\alpha\) forest systems are flattened and filamentary structures (extending over hundreds of kpc) that form almost everywhere at high redshifts and persist out to large distances around galaxies and galaxy groups at present.

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