The Distribution of Gas In and Around Galaxies

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Abstract. A consensus is developing on the nature of various populations of absorbers at different redshift regimes and in particular on their relationships to galaxies at those epochs. As one example we discuss the population of $z < 1$ Mg II absorbers. Kinematic models are presented that show this population to be consistent with some combination of halo and disk kinematics and not with a pure disk or halo model. In contrast, the $2 < z < 3$ C IV absorbers are likely to represent a mix of already formed halos and protogalactic clumps in the process of assembly. Clues could be provided by the level at which S IV traces the same kinematic components as C IV (relative to how it traces lower ionization gas) and this is illustrated by a simple application of principal components analysis. It remains uncertain how much unambiguous information it will be possible to extract about the detailed properties of the gas along the line of sight through an individual absorption profile. However, ratios of various low and high ionization transitions along the line of sight can be combined with insights gained from kinematic models and from observations of galaxy properties. There is reason for optimism that we will progress toward a point when we will someday study the interstellar medium and gaseous halos and environments of absorbing galaxies at close to the same level as we study these components in the Milky Way.

1 Introduction

The past decade of research in quasar absorption lines had the theme of establishing the basic nature of various classes of absorbers, such as the Lyα forest clouds, the damped Lyα absorbers, the C IV systems, and the Mg II systems. The emphasis has been on the relationship between a population of absorbers and the population of galaxies. For example, common questions are whether they are produced by a particular component of galaxies, and whether absorbers are clustered with respect to galaxies? The answer for a particular population can vary as a function of time and thus quasar absorption lines provide a basic understanding of the assembly of gas into galaxies and of the evolution of the gaseous content of the Universe. Although significant controversy remains (eg. the high redshift damped Lyα clouds, see both Wolfe and Haehnelt in this volume), we can be confident that this basic understanding will soon be achieved.

Even with this significant advance, a major potential of quasar absorption lines remains untapped. Absorption line studies of the Milky Way Galaxy provide detailed information about its gaseous components, eg. disk vs. halo composition, high velocity clouds, and supershells. Will quasar absorption line studies ever allow such detailed information to be extracted about other individual galaxies? In any one case, can we understand the physical conditions in internal structures present along a line of sight through a galaxy?
Figure 1: An ensemble of Mg II(λ 2796) absorption profiles for absorbers at $0.4 < z < 1.0$ at resolution 6 km s$^{-1}$ from Keck/HIRES. The Voigt profile model fits are superimposed upon the data and the locations of those components are marked with ticks.

2 Diagnosing the Conditions in Mg II Absorbers at $z < 1$

As our first example we present in Fig. 1 Keck/HIRES spectra of the Mg II(λ 2796) profiles for a population of Mg II absorbers at $0.4 < z < 1.0$. We would like to be able to identify in these profiles the signatures of spirals and ellipticals, of disk/halo interplay, of satellite galaxies, of supershells, etc. This section discusses the ensemble of absorbing galaxies that produce the variety of profiles displayed and sketches out some considerations that have potential for diagnosing their individual properties.

We have generated ensembles of simulated spectra for lines of sight through model populations of galaxies with various spatial and kinematic distributions of Mg II gas. The details of these models and the results will be presented in Charlton and Churchill (1997). In each case a galaxy was created by placing some number of clouds in a halo and/or disk component, with the velocity vector of each cloud chosen from a given distribution, e.g. rotation or radial infall with an additional random component. The choice of which populations of galaxies were considered in our models was guided by what we know about the properties of nearby galaxies. The cloud Mg II column densities and Doppler b parameters were chosen from input distribution functions so as to produce output cloud properties that match those extracted from the ensemble of observed $z < 1$ Mg II profiles presented in Fig. 1. In this way we remove the ambiguities caused by lack of knowledge of chemical abundance and ionization conditions and are able to focus on distinguishing spatial and kinematic distributions of clouds.
Figure 2: Ensembles of simulated spectra for three different kinematic models. The parameters of these models were tuned in order to reproduce the flux distribution of the observed $z < 1$ Mg II profiles. For the first ten profiles, all clouds were placed within a thick rotating disk that becomes thicker with increasing radius, and that has a velocity dispersion of 30 km s$^{-1}$ in the vertical direction. For the second set of ten, all clouds are spread at random in a spherical halo and have constant magnitude radial infall, and for the “mix” model half the clouds were placed in the disk and half in the halo.

Fig. 2 presents examples of profiles generated from lines of sight through rotating disks and through halos with radial infall. In most cases we could guess from which kinematic law a given profile was chosen, but in some cases we cannot. It is clear from inspection of these profiles that neither of these simple pure disk or pure halo models produces sufficient variety to match the observed ensemble. The pure halo models do not produce a large enough fraction of simple, narrow (< 100 km s$^{-1}$) profiles, and the pure disk models do not produce enough complex profiles with large velocity spreads. An ensemble of model galaxies in which half the Mg II clouds are in the disk and half are in the halo produces a much more realistic set of profiles. We performed many statistical tests to distinguish what types of kinematic models best fit the data. For example, the two point clustering function is defined as the distribution of differences in velocity between all pairs of subcomponents (the ticks in Fig. 1 and 2). This function is too narrow compared to the data for pure disk models and too wide for pure halo models. This test and others showed that some Mg II clouds must exist in a narrow kinematic distribution such as a disk and others in a wider distribution in order to match the observations. It is interesting that agreement can be obtained either from a model in which half of the clouds in each galaxy are in the halo and half in the disk or from a model in which half the galaxies had pure disk and half had pure halo contributions.
In reality the galaxy population responsible for Mg II absorbers is likely to be a continuum of relative halo/disk proportions just as would be expected from the gas distributions in nearby galaxies.

Figure 3: On the left, the Keck/HIRES absorption profile showing the variation of Fe II/Mg II with velocity in the \( z = 1.3250 \) system of Q0117+212. (Note the small Fe II/Mg II at +140 km s\(^{-1}\).) On the right, two simulated spectra of Mg II(\( \lambda 2796 \)) profiles from a combined halo/disk model with the place of origin identified for individual clouds. This shows that without additional information there is considerable ambiguity in the kinematic profiles.

Monte–Carlo variations between different lines of sight through galaxies drawn from the same model parameters can go a long way toward explaining the variations in observed profiles of the \( z < 1 \) Mg II population. The variations between different galaxies may not be so large as the variations within them. Thus it appears that in any one case we cannot definitively extract the nature of the absorbing galaxy from the profiles of low ionization gas. However, additional information provided by the ratio of Fe II/Mg II has the potential to provide more leverage. The example in Fig. 3 shows that the ratio can vary dramatically across individual systems. The observed ratios may allow us to distinguish halo clouds from disk clouds, and starbursting dwarfs (smaller Fe II/Mg II) or quiescent dwarfs (larger Fe II/Mg II) from material associated with a bright galaxy. Information from deep images of the field can provide considerable further leverage. Finally, Churchill has shown (in these proceedings) that the distribution of high ionization gas can provide information about the kinematic components of \( z < 1 \) Mg II absorbers. The velocity spread of the Mg II profiles tends to be larger (at a 3.8\( \sigma \) level) for systems with a larger C IV equivalent width, suggesting a picture of an extended C IV halo with embedded Mg II clouds. The additional fact that the Mg II equivalent width is not so strongly correlated with the Mg II kinematics leads us
to consider that a dominant fraction of the Mg ii column may be produced in the galaxy disk. HST/STIS observations at high resolution are needed to determine just how much of the C iv is in the disk, in the halo, and in outer layers surrounding individual Mg ii clouds.

3 Diagnosing the Conditions in C iv Absorbers at z > 2

As our second example, we briefly consider the population of C iv absorbers at z > 2. For these systems the issue is whether a given one is a collection of protogalactic clumps expanding with the Hubble flow, or part of an already collapsed structure. As with the Mg ii absorbers, an important question is whether one can distinguish these two possibilities by examining an individual set of profiles for a C iv system. Here the most important clue could be whether the Si iv (an intermediate ionization state transition) is distributed more like the lower ionization transitions (such as Mg ii, C ii, or Fe ii) or like the higher ionization transitions (such as C iv or N v). Here we present a technique for quantifying the degree to which two ions trace one another in velocity space. Principal components analysis allows us to represent the observed transitions in terms of a set of basis functions. A successful PCA analysis will describe the variations between the transitions with many fewer basis functions than there are transitions. This technique is illustrated in Fig. 4 for two example C iv systems. Most of the variation between the profiles can be explained by two principal components that resemble the profiles for the C iv and for a lower ionization species, respectively. In one system the Si iv is distributed similarly to the C ii, and this can be quantified by considering the coefficients of the principal components. In the second system, the Si iv has nearly identical principal component coefficients as C iv. As with the Fe ii/Mg ii ratios, the Si iv/C iv ratio is found to vary across some profiles. This can be diagnostic of changing abundance ratios, ionization parameters, or spectral shapes (with large values for stellar rather than power law), however again there is considerable ambiguity (see also Boksenberg in this volume).

4 Future Plans for Investigating z > 2.5 Mg ii Absorbers

The properties of z < 1 Mg ii absorbers are consistent with clouds within the usual kinematic components of galaxies, i.e. halos and disks. C iv absorbers at high redshift show signatures of coalescence of protogalactic clumps. Do the higher redshift Mg ii absorbers already show kinematic signatures of disks, or are they more consistent with the distribution of higher ionization gas? This question can only be addressed with near–IR spectroscopy for the z > 2.5 Mg ii absorbers. Using the JCAM, a R = 10,000 spectrograph planned for the 8–m Hobby–Eberly Telescope, we will conduct a survey for Mg ii doublets to a rest equivalent width limit of 0.15 Å. For detected systems we plan to
determine the kinematic structure of Mg II systems up to a $z = 4$ using a $R = 20,000$ mode of the JCAM. In this important redshift regime we may find evidence for the assembly of galaxies and for the gradual development of their gaseous components.

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