

Towards an understanding of the physical nature of Mg II absorption systems

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Abstract. We discuss issues concerning the physical nature of intervening Mg II quasar absorption systems in light of results from our recent surveys using SDSS EDR QSO spectra and data obtained at the MMT. These surveys indicate an excess of weak ($W_0^{\lambda 2796} \lesssim 0.3\text{\AA}$) systems relative to the exponential $\partial N/\partial W_0$ distribution of stronger systems. The incidence of intermediate-strength lines shows remarkably little evolution with redshift, thereby constraining models for the nature of the clouds comprising these absorbers. The total distribution does evolve, with the incidence decreasing with decreasing redshift in a $W_0^{\lambda 2796}$ -dependent rate (the strongest systems evolve the fastest). This suggests that multiple populations that evolve at different rates contribute to the incidence in a $W_0^{\lambda 2796}$ -dependent manner. We also present two images of fields containing unprecedented “ultra-strong” ($W_0^{\lambda 2796} \geq 4.0\text{\AA}$) Mg II absorbers.

1. Introduction

Boksenberg & Sargent (1977) demonstrated that some quasar absorption lines arise in intervening galaxies with the discovery of the Ca II H and K absorption lines from NGC 3067 in the spectrum of 3C 232. In the subsequent decades, much progress has been made in the understanding of the physical conditions, such as abundances (Nestor *et al.* 2003; Prochaska *et al.* 2003), temperatures (e.g. Lane, Briggs & Smette 2000), and kinematics (Churchill & Vogt 2001, hereafter CV01) of the gas responsible for intervening low-ion/neutral-gas-rich absorption. However, an overall physical description of the structures giving rise to the absorption has been more elusive. Do these absorbers select extended galaxy disks, halos, stripped gas, galactic winds, clouds condensing from ionised gas surrounding galaxies, enriched IGM gas not directly associated with a specific galaxy, some combination of processes, or do they have other natures altogether? More importantly, what does the answer to this question tell us about the *physical nature of galaxies*, and how the properties of galaxies *evolve with cosmic time*? In this contribution we address these issues in light of the results of our recent surveys for Mg II absorbers in the Sloan Digital Sky Survey (SDSS) Early Data Release (EDR) quasar spectra and in data obtained at the 6.5 m MMT on Mount Hopkins, AZ.

2. Incidence of intervening Mg II absorption systems

Perhaps the most fundamental result from absorption line surveys is the determination of the incidence of absorbers. As regards Mg II systems, an important early survey was Lanzetta, Turnshek & Wolfe (1987). The survey of Steidel & Sargent (1992, hereafter SS92) determined the incidence of systems over the interval $0.2 < z < 2.1$ for absorbers with Mg II $\lambda 2796$ rest equivalent width $W_0^{\lambda 2796} \geq 0.3\text{\AA}$. Churchill *et al.* (1999, hereafter CRCV99) determined the incidence of “weak” ($W_0^{\lambda 2796} < 0.3\text{\AA}$) systems.

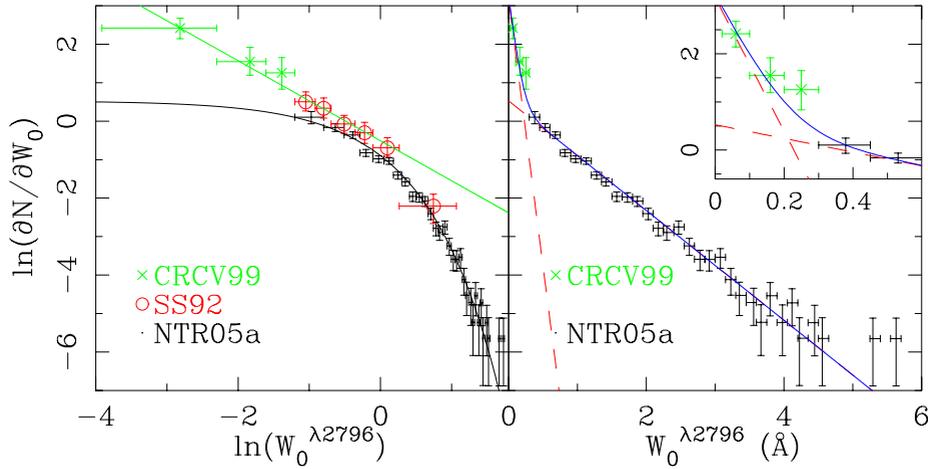


Figure 1. Dependence of the incidence of Mg II absorbers on $W_0^{\lambda 2796}$. Left: the surveys of SS92, CRCV99, and NTR05a. Right: fitting the data with a sum of two exponentials.

It is both traditional and useful to consider the incidence (proportional to total cross section, which is the integrated product of absorber cross section and co-moving number density) of systems $\partial^2 N / \partial z \partial W_0$, as it depends on $W_0^{\lambda 2796}$ and redshift separately.

2.1. Incidence as a function of line strength

The incidence as a function of Mg II $\lambda 2796$ line strength, $\partial N / \partial W_0^{\lambda 2796}$, from the SS92 and CRCV99 surveys are shown in the left panel of Fig. 1. SS92 fitted their data equally well with a power law or an exponential, but the combined SS92 and CRCV99 results suggested that $\partial N / \partial W_0^{\lambda 2796}$ was best described by a power law. In Nestor, Turnshek & Rao (2005a, hereafter NTR05a), we presented the results of a detailed Mg II survey using the SDSS EDR quasar spectra. Though the redshift coverage and minimum $W_0^{\lambda 2796}$ of this survey were similar to SS92, it was more than an order of magnitude larger which not only provided smaller statistical errors but allowed for the measurement of systems with $W_0^{\lambda 2796}$ up to almost 6 \AA . The incidence determined from this survey, also shown in Fig. 1, indicates that the distribution for $W_0^{\lambda 2796} \gtrsim 0.3 \text{ \AA}$ is very well fit by an exponential. Power law fits drastically over-predict the incidence of the strongest systems. However, extrapolating our exponential fit to the weak regime drastically under-predicts the CRCV99 results.

Rigby, Charlton & Churchill (2002, hereafter RCC02) demonstrated that the number of clouds (kinematic sub-components) comprising a Mg II absorber is consistent with a Poissonian distribution, *except* for the excess of single-cloud systems, which are optically-thin in neutral hydrogen and comprise $\approx 2/3$ of “weak” systems. It thus appears that these single-cloud systems are indeed a distinct population. Therefore, we fitted the combined $W_0^{\lambda 2796}$ incidence data with a sum of two exponentials, shown in the right panel of Fig. 1. Indeed, the extrapolation of the shallow exponential accounts for $\approx 1/3$ of the expected number of weak systems consistent with the fraction of multi-cloud weak systems found by RCC02.

Since the CRCV99 data does not overlap with the SS92 or NTR05a data, it is a concern that the upturn below $W_0^{\lambda 2796} \approx 0.3 \text{ \AA}$ is due to some unknown systematic difference in the surveys. We were able address this concern with our MMT survey, which achieved greater sensitivity allowing the study of weaker lines. The incidence as a function of $W_0^{\lambda 2796}$ determined from the MMT survey (Nestor, Turnshek & Rao 2005b, hereafter

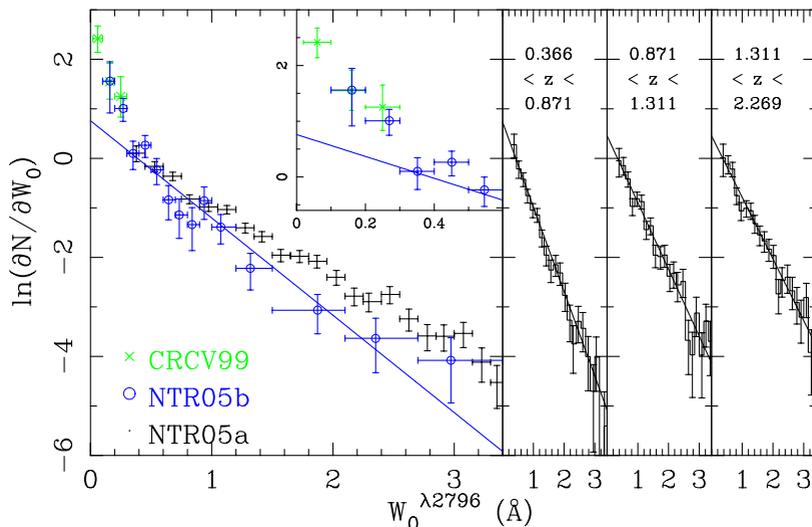


Figure 2. Left: $\partial N/\partial W_0^{\lambda 2796}$ from the EDR, MMT, and CRCV99 surveys. Right: redshift dependence of $\partial N/\partial W_0^{\lambda 2796}$ from the EDR survey.

NTR05b) is shown in the left panel of Fig. 2. Also shown is the EDR and CRCV99 results. One can see that the $W_0^{\lambda 2796} < 0.3\text{\AA}$ MMT results are quite consistent with CRCV99 and significantly above the extrapolation of the exponential fit to the stronger systems. However, the slope of the exponential measured in the MMT data is steeper than that determined from the EDR data due to the difference in mean redshift of the surveys: $\langle z \rangle_{MMT} = 0.589$ and $\langle z \rangle_{EDR} = 1.108$. As can be seen in the right panels of Fig. 2 which show the EDR results divided into three redshift ranges, $\partial N/\partial W_0^{\lambda 2796}$ steepens with decreasing redshift. The MMT results for $W_0^{\lambda 2796} > 0.3\text{\AA}$ are consistent with the lower-redshift EDR results.

2.2. Incidence as a function of redshift

Multi-cloud systems span a large range of strengths, and thus velocity spreads (since $W_0^{\lambda 2796}$ for saturated lines is primarily a measure of line-of-sight velocity complexity). Insight into the nature of the stronger systems can be gained by considering how their incidence depends on redshift, and thus cosmic time.

The same results on incidence presented above can be shown as a function of redshift for $W_0^{\lambda 2796}$ ranges as opposed to as a function of $W_0^{\lambda 2796}$ for a range of z . This is shown in Fig. 3 for the results of the SDSS EDR, MMT, and CRCV99 studies.

There are two notable trends apparent in Fig. 3. First, $\partial N/\partial z$ is consistent with no evolution over a long period of cosmic time, to within strong limits, for intermediate-strength ($0.3\text{\AA} \lesssim W_0^{\lambda 2796} \lesssim 2.0$) systems. The redshift interval $[2 : 0.4]$, for example, corresponds to 6 Gyrs. There are various possible interpretations of this result: (a) the timescales/lifetimes governing the structures are $\gtrsim 6$ Gyrs; (b) the creation/destruction of the structures is regulated by feedback, producing a nearly steady-state; or (c) a range of formation epochs, together with evolution, conspire to keep the total absorption cross-section constant. Several authors (e.g. SS92; Mo & Miralda-Escudé 1996; CV01) have discussed the difficulties associated with long lifetimes from effects including evaporation, hydrodynamic and Rayleigh-Taylor instabilities, and cloud-cloud collisions. Thus, feedback and creation/destruction balance have been favoured over long lifetimes (see e.g. NTR05a). Balanced formation/evolution without feedback seems somewhat contrived,

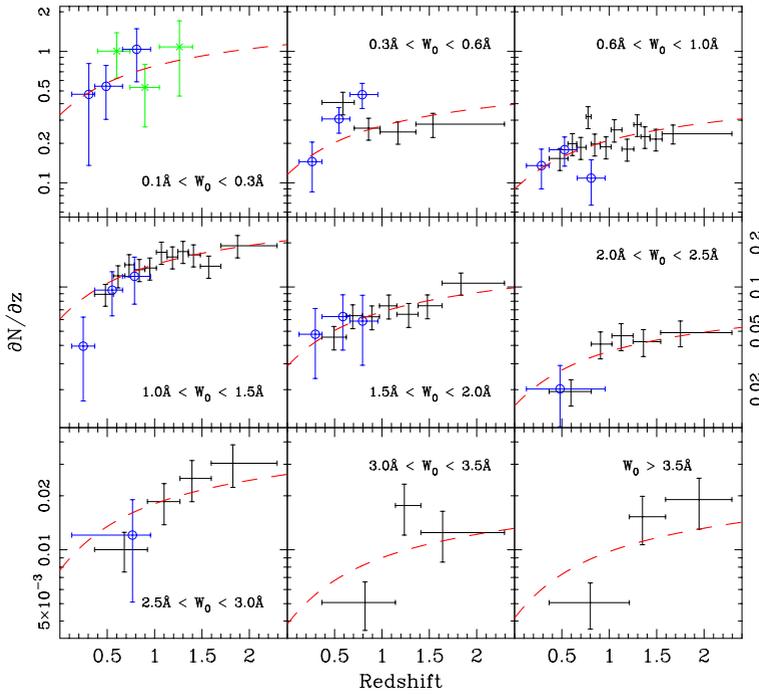


Figure 3. Incidence as a function of z for ranges of $W_0^{\lambda 2796}$. The horizontal bars represent the redshift-bins and the vertical bars the one-sigma uncertainty. Circles are from the MMT survey, and \times -symbols from CRCV99. The other points represent the EDR results. Also shown as the dashed lines is $\partial N/\partial z$ for a non-evolving population in a $(\Omega_\Lambda, \Omega_M, h) = (0.7, 0.3, 0.7)$ cosmology, normalised to the EDR (or CRCV99 in the top-left panel) results.

though it should be noted that this is precisely what is predicted for the low-mass end of the halo mass function in Λ CDM simulations (see e.g. Reed *et al.* 2003). However, without a clear picture of the physical nature of the absorbers, it is difficult to completely eliminate any of the scenarios. Finally, Fig. 3 indicates that the total absorption cross-section for systems with $W_0^{\lambda 2796} \gtrsim 2\text{\AA}$ decreases with decreasing redshift, especially at $z \lesssim 1$. The evolution is such that the rate is a function of $W_0^{\lambda 2796}$, or a steepening of $\partial N/\partial W_0^{\lambda 2796}$ with decreasing z . This can be understood if: (1) various physically-distinct structures contribute to the incidence of Mg II absorbers; (2) their relative contributions are $W_0^{\lambda 2796}$ -dependent; and (3) they evolve in time at different rates. Thus, determining the relative contribution of each type as a function of $W_0^{\lambda 2796}$ can tell us about the time evolution of each type (and perhaps vice-versa).

3. Direct study of individual absorbers

Individual Mg II systems can be studied in more depth using high-resolution spectroscopy to uncover the line-of-sight kinematic structure of the absorption. Much of these results are due to Churchill and collaborators (Churchill, Steidel & Vogt 1996; Charlton & Churchill 1998; Churchill *et al.* 2000; CV01) who have reported that: (a) intermediate-strength ($0.3 \lesssim W_0^{\lambda 2796} \lesssim 1.5\text{\AA}$) systems consist of multiple kinematic subsystems usually containing a dominant group and weak kinematic outliers; (b) such systems have multiphase ionisation structures; (c) disk+halo models have partial/limited success describing the absorption kinematics; and (d) such systems show no correlation between gas kinematics and galaxy properties. Also, direct study of galaxies associated

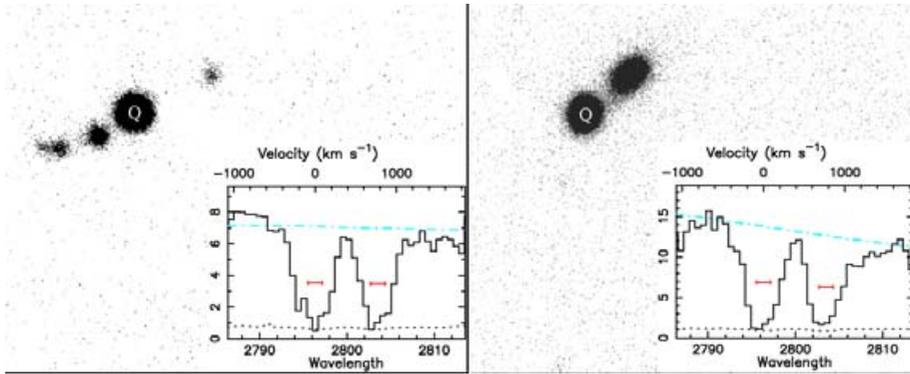


Figure 4. “Ultra-strong” Mg II absorber fields. Quasars are marked with a “Q”. Insets show the SDSS spectrum of the Mg II $\lambda\lambda 2796, 2803$ absorption doublet with the FWHM resolution marked. Left: field of 0902+372, with $W_0^{\lambda 2796} = 4.1\text{\AA}$ and $z = 0.670$. If at $z = z_{abs}$, the three galaxies have $L \approx 1.2L^*$, $b = 35$ kpc (compact galaxy close to LOS), $L \approx 0.8L^*$ and $b = 72$ kpc (disturbed companion); and $L \approx 0.4L^*$ and $b = 81$ kpc. Right: field of 1520+611 with $W_0^{\lambda 2796} = 4.2\text{\AA}$ and $z = 0.423$. If at $z = z_{abs}$, the galaxy has $L \approx 2L^*$ and $b = 20$ kpc.

with the absorber is possible at relatively low ($z \lesssim 1$) redshift. Such work in the 1990s (e.g. Bergeron & Boissé 1991; Le Brun *et al.* 1997) found that intermediate-strength Mg II absorber galaxies span a range of properties and impact parameters consistent with normal, relatively luminous ($L \gtrsim 0.3L^*$) galaxies. In addition, authors (e.g. Steidel *et al.* 2002) have combined imaging and galaxy spectroscopy with high-resolution spectroscopy of the absorption (though for only a small number of systems that were exclusively nearly edge-on spirals), finding that extrapolated disk rotation is consistent with the absorption kinematics, though could not explain it in full. Furthermore, work presented at this colloquium (e.g. Tripp 2005; Kacprzak *et al.* 2005) gave new clues to the nature of Mg II absorbers. For example, the covering factor for intermediate-strength systems may be much smaller than previously thought ($f_c \approx 0.5$ as opposed to $f_c \approx 1$) and absorption properties show no correlation with galaxy orientation, but *are* correlated with galaxy asymmetry.

3.1. A new kinematic regime

Until recently, very few strong ($W_0^{\lambda 2796} \gtrsim 2\text{\AA}$) Mg II absorbers with relatively low-redshift were known, and no “ultra-strong” systems with $W_0^{\lambda 2796} \gtrsim 4\text{\AA}$ were known. Thus, the nature of the extreme end of the $W_0^{\lambda 2796}$ distribution, which exhibits mostly saturated absorption over a *huge* kinematic spread ($\approx 500 \text{ km s}^{-1}$), has not been investigated. Our surveys with the SDSS data, however, have uncovered a large number of such systems at redshifts low enough for direct study. Fig. 4 shows the sight-lines toward two such systems. The 0902+372 field appears to contain an interacting group of three galaxies spanning a projected distance of ≈ 150 kpc. There are other galaxies at larger impact parameters, spanning ≈ 500 kpc, including a pair of interacting spirals and a large bright galaxy. These galaxies that have magnitudes which are consistent with $L \approx 1 - 3L^*$ if they are at the absorption redshift, suggesting that the three galaxies are part of a larger group. The apparent interaction is evidence for gas-stripping being responsible for the extreme velocity spread seen in absorption. The 1520+611 field, contrastingly, reveals a lone bright galaxy at lower impact parameter. Spectroscopy of the galaxy will be necessary to test models based on superbubbles or rotating disk/halo absorption.

4. Conclusions

Evidence from both large statistical surveys and smaller direct-observation studies provide evidence that various physically distinct types of systems give rise to intervening Mg II absorbers. Single-cloud weak systems are likely associated with enriched Ly α clouds, as proposed by RCC02, in the vicinity of galaxies. The nature of the more kinematically complex systems has been difficult to determine with confidence. It seems that disks and halo clouds do contribute, though cannot explain the kinematics in full. We know that a significant fraction of the strong Mg II absorbers harbour damped Ly α systems; this has been discussed separately by Rao (2005) and Turnshek *et al.* (2005) at this colloquium. Interaction-stripped gas and superwinds may have important contributions, especially at large values of $W_0^{\lambda 2796}$. It is intriguing that the various populations contribute to the incidence of these absorbers such that $\partial N/\partial W_0$ is described extremely well by a single exponential out to the largest $W_0^{\lambda 2796}$ values detected in recent large surveys. Detailed study of a large, uniform, unbiased sample of systems is necessary to determine the relative contributions, which will hopefully lead to a consistent understanding of their evolution in time with the determined nature of $\partial^2 N/\partial z \partial W_0$.

Acknowledgements

We thank members of the SDSS collaboration who made the SDSS a success. We acknowledge support from NSF, NASA-LTSA, and NASA-STScI on various projects to study QSO absorption lines. Funding for creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, Participating Institutions, NASA, NSF, DOE, the Japanese Monbukagakusho, and the Max Planck Society.

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