Probing Galaxies through Quasar Absorption Lines
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Measuring the halo mass of Mg II absorbers from their cross-correlation with Luminous Red Galaxies

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Abstract. We study the cross-correlation between 716 Mg II quasar absorption systems and $\sim 100{,}000$ Luminous Red Galaxies (LRGs) selected from the Sloan Digital Sky Survey Data Release 3 in the redshift range $0.4 \leqslant z \leqslant 0.8$. The Mg II systems were selected to have $\lambda\lambda 2796$ & 2803 rest-frame equivalent widths $\geqslant 1.0$ Å and identifications confirmed by the Fe II $\lambda 2600$ or Mg I $\lambda 2852$ lines. Over co-moving scales 0.2–$13h^{-1}$ Mpc, the Mg II–LRG cross-correlation has an amplitude 0.69 ± 0.09 times that of the LRG–LRG auto-correlation. Since LRGs have halo-masses of $10^{13}\,\mathrm{M}_\odot$, this strong cross-correlation signal implies that the absorber host-galaxies have halo-masses 1–$2 \times 10^{12}\,\mathrm{M}_\odot$.

1. Introduction

The connection between quasar (QSO) absorption line (QAL) systems and galaxies (first established by Bergeron & Boissé 1991) is important to our understanding of galaxy evolution. QALs provide detailed information about the physical conditions and kinematics of galaxies out to large impact parameters ($R > 100$ kpc), regardless of the absorber's intrinsic luminosity (e.g. Steidel *et al.* 2002, ; Churchill *et al.* 2005; Kacprzak *et al.* 2005, these proceedings). Past results show that Mg II absorbers are biased towards late-type galaxies which do not evolve strongly from $z \simeq 1$ (Steidel & Sargent 1992; Steidel *et al.* 1994). These results also show that Mg II absorber host-galaxies have K-band luminosities consistent with normal $0.7L_B^*$ Sb galaxies. The cross-section of Mg II absorbers with $W_\mathrm{r}^\mathrm{MgII} \geqslant 0.30$ Å appears to be $R_\times \sim 70h^{-1}$ kpc (co-moving) (e.g. Steidel 1995). These systems are associated with H I absorbers in the Lyman limit regime up to the damped Ly-alpha absorber (DLA) regime (see also Rao *et al.* 2005, these proceedings).

In Bouché *et al.* (2004), we used the Sloan Digital Sky Survey (SDSS) data release 1 (DR1; Abazajian *et al.* 2003) to constrain the mass of the halos associated with the Mg II absorbers. Specifically, we used the absorber-galaxy cross-correlation to measure the mass ratio of the halos associated with Mg II since in a hierarchical galaxy formation scenario, the amplitude ratio of the Mg II–LRG cross-correlation to the LRG–LRG auto-correlation is also their bias ratio. The reader is referred to Bouché *et al.* (2004) and Bouché *et al.* (2005a) for the details. Fig. 1 (left) illustrates the methodology. Using 212 Mg II absorbers and $\sim 20{,}000$ Luminous Red Galaxies (LRGs), Bouché *et al.* (2004) found that the bias ratio $b_{\mathrm{Mg\,II}}/b_\mathrm{LRG}$ is 0.67 ± 0.09 on scales $r_\theta > 200h^{-1}$ kpc, implying a halo mass for the Mg II host galaxies of 0.5–$2.5 \times 10^{12}\,\mathrm{M}_\odot$ (for $10^{13}\,\mathrm{M}_\odot$ LRG halos).

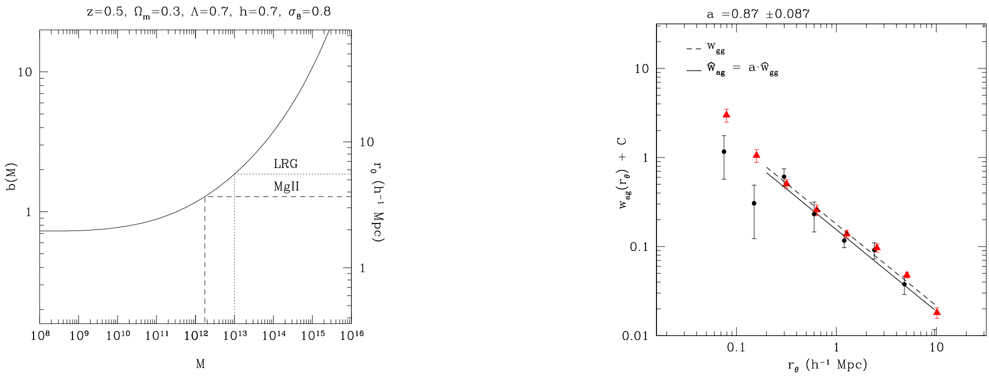

Figure 1. *Left :* the bias $b(M)$ as a function of the halo mass M, Mo & White (2002) (solid line). The right y-axis shows the auto-correlation length r_0. LRGs have $r_{0,\mathrm{gg}} \simeq 6\ h^{-1}$ Mpc, and thus masses of $\simeq 10^{13}\,\mathrm{M}_\odot$. *Right*: filled circles show the Mg II–LRG cross-correlation $w_{\mathrm{ag}}(r_\theta)$ between 716 Mg II absorbers and 94,649 LRGs. Filled triangles show the LRG–LRG auto-correlation, w_{gg}. The dashed line shows a power-law fit to w_{gg}. The solid line shows the fit $\hat{w}_{\mathrm{ag}} = a \times \hat{w}_{\mathrm{gg}}$ for $r_\theta > 200h^{-1}$ kpc since the smallest scales will be affected by the finite cross-section of the absorbers. The raw relative amplitude is $a = 0.87 \pm 0.08$. The left panel therefore implies that our Mg II absorbers have halos 7–10 times less massive than LRG halos, i.e. our Mg II absorbers have halos with mass $1\text{–}2 \times 10^{12}\,\mathrm{M}_\odot$.

2. Results

Here, we extend our DR1 results using SDSS Data Release 3 (DR3; Abazajian *et al.* 2005). We selected 716 Mg II absorbers from SDSS/DR3 with $z_{\mathrm{abs}} \leqslant 0.8$ using an automated technique that included the following criteria: (i) $W_{\mathrm{r}}^{\mathrm{MgII}} \geqslant 1.0\,\text{Å}$; (ii) we require that $W_{\mathrm{r}}^{\mathrm{MgI}} \geqslant 0.2\text{Å}$, and that $W_{\mathrm{r}}^{\mathrm{FeII}} \geqslant 0.5$ following the DLA criteria of Nestor *et al.* (2003) and Rao & Turnshek (2000) (see Rao *et al.* 2005, these proceedings, for an updated discussion). We remove spurious candidates by visually inspecting each Mg II spectrum.

For each absorber, we selected $\sim$ 1,300 Luminous Red Galaxies (LRGs) from the SDSS/DR3 using colour criteria following Scranton *et al.* (2003), and in a slice of width $W_z = 0.1$ using photometric redshifts calculated with the code of Csabai *et al.* (2003). There are a total of 94,649 LRGs meeting these criteria, within $12.8h^{-1}$ Mpc, our largest bin.

For the cross-correlation, w_{ag}, we used the estimator $1 + w_{\mathrm{ag}}(r_\theta) = \mathrm{AG}/\mathrm{AR}$, where AG is the total observed number of absorber–galaxy pairs between $r_\theta - \mathrm{d}r/2$ and $r_\theta + \mathrm{d}r/2$ and AR is the total absorber–random galaxy pairs. This estimator is necessary to account for the non-symmetric situation: Mg II absorbers have precise redshifts, while the LRGs have photometric redshifts with an accuracy of $\sigma_z \ \simeq\ 0.1$ (see Bouché *et al.* 2005a, for a discussion). Fig. 1 (right) shows our results (see caption). The errors in w_{ag} and w_{gg} were computed using $N_{\mathrm{jack}} = 10$ jack-knife realisations.

The amplitude of the Mg II-LRG cross-correlation relative to that of the LRG–LRG auto-correlation is $0.69 \pm 0.07 \pm 0.06$, after applying a correction of 25 ± 10 percent discussed in Bouché *et al.* (2004). The two error terms reflect the statistical and systematic uncertainty, respectively. By adding the errors in quadrature, the bias ratio is

$$a = 0.69 \pm 0.09\,. \tag{2.1}$$

Within the context of hierarchical galaxy formation, Eq. 2.1 implies that our Mg II absorbers have halo masses 7–10 times smaller than the LRGs. For $10^{13}\,\mathrm{M}_\odot$ LRG halos, the Mg II absorbers have halos of $1\text{–}2 \times 10^{12}\,\mathrm{M}_\odot$.

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It is important to realise that this method (i.e. measuring the halo mass from the ratio of projected correlation functions) has the following advantages (see also Bouché *et al.* 2004): (i) it constrains the mass of the Mg II/DLA host-galaxies in a statistical manner without directly identifying them; (ii) it is free of systematics from contaminants (e.g. stars); and (iii) it does not require knowledge of the true width of the redshift distribution of the galaxies used. The last two points are a consequence of the fact that we use the same galaxies for $w_{gg}(r_\theta)$ and for $w_{ag}(r_\theta)$.

3. Discussion

Our results are consistent with those of Bergeron & Boissé (1991) and Mo & Miralda-Escudé (1996). For instance, Mo & Miralda-Escudé (1996) indicate that the majority of Mg II absorbers reside in systems with V_{circ} = 150–300 km s^{-1} with a median at $\sim$ 200 km s^{-1}. Our mass measurement appears to corroborate that of Steidel *et al.* (1994) who found that Mg II absorbers with $W_r^{\rm MgII} \geqslant 0.3$ Å are associated with late-type $\sim 0.7 L_B^*$ galaxies, since the expected amplitude ratio between early and late type galaxies is $\sim$0.70 (see Bouché *et al.* 2004).

Are our results consistent with ΛCDM? That is, are there enough massive halos to account for dN/dz? From $\mathrm{d}N/\mathrm{d}z = n(M)\ \sigma(M)\ \mathrm{d}r/\mathrm{d}z$, $R_X \simeq 70$ kpc (co-moving) (Steidel 1995), $n(M) = 10^{-2} h^{-3}$ Mpc^{-3}, $\mathrm{d}N/\mathrm{d}z = 0.3\ (n/10^{-2})\ (R_X/70\ \mathrm{kpc})^2 \simeq \mathrm{d}N/\mathrm{d}z(\mathrm{obs})$, and we can conclude that there are enough massive 10^{12} M$_\odot$ halos. While we defer a more detailed analysis of these results to Bouché *et al.* (2005b), preliminary results also indicate little dependence of the halo mass on the equivalent width.

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