Probing Galaxies through Quasar Absorption Lines
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Correlation of low z Lyman-α absorbers with HI-selected galaxies

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Abstract. In this work, observational evidence for the connection between low column density Lyman-α absorbers and large-scale structure traced by gas-rich galaxies is investigated. The H I Parkes All Sky Survey (HIPASS) galaxy catalogue is cross-correlated with known low redshift, low column density ($N_{\rm HI}$<10^{15} cm^{-2}) Lyman-α absorbers from the literature. The absorber-galaxy cross-correlation function shows that on scales from $1-10$ h^{-1} Mpc, absorbers are embedded in halos with masses similar to that of galaxy groups.

1. Introduction

Hydrodynamic simulations of galaxies and the Intergalactic Medium (IGM) predict a filamentary structure of the Universe where H I in the IGM clusters around galaxies (e.g. Davé *et al.* 1999). Observations of H I in the IGM via low column density Lyα absorption find absorbers in a variety of environments including large-scale filaments (e.g. Penton *et al.* 2002; Rosenberg *et al.* 2003), galaxy groups (e.g. Bowen *et al.* 2002), and even voids (e.g. Stocke *et al.* 1995). The cross-correction function of Lyα absorbers and galaxies can be used to measure the extent to which the two populations of objects, absorbers and galaxies, are associated. In the Press–Schechter (PS, Press & Schechter 1974) formalism, the ratio of the bias of the two populations of objects is equal to the amplitude ratio of the cross-correlation to the auto-correlation function (e.g. Mo & White 2002). Therefore, by (i) knowing the characteristic total (dark plus baryonic) halo mass (and its relative bias) of the galaxy population, (ii) measuring the galaxy auto-correlation function, and (iii) measuring the absorber-galaxy cross-correlation function, the mass of the halos in which the absorbers are embedded can be inferred. This method has been successfully used by Bouché *et al.* (2004). They cross-correlated MgII absorbers with Luminous Red Galaxies (LRGs) to show that the MgII absorbers are embedded in halos with masses $\sim 2-8\times 10^{11} M_{\odot}$, consistent with the fact that MgII absorbers arise in damped Lyα (DLA) systems, which are expected to have total halo masses of that order.

Moving from DLAs to lower column density systems, the mini-halo model (e.g. Mo & Morris 1994) predicts a weaker absorber-galaxy cross-correlation function for absorbers associated with the lower-mass mini-halos. The mini-halo model has been criticised because too many halos per unit redshift would be required to account for the observed density of absorption lines, since the mini-halos have small spatial cross sections. Observational evidence lends more support to scenarios where absorbers are embedded in large-scale filaments and galaxy groups. Furthermore, the PS formalism does not count objects that have merged into larger collapsed objects (Mo & Morris 1994).

Perhaps the PS formalism can still work for low column density absorbers, if instead they are correlated with very large structures. Here an alternative suggestion is made that if Lyα absorbers are embedded in large scale structure, then their expected clustering properties should be consistent with large-scale filaments and galaxy groups. That is, within the PS formalism, a stronger cross-correlation function amplitude is expected for Lyα absorbers on large spatial scales.

Many studies have established a positive association between absorbers and galaxies (Morris *et al.* 1993; Stocke *et al.* 1995; Tripp *et al.* 1998; Impey *et al.* 1999; Penton *et al.* 2002, 2004; Bowen *et al.* 2002), but maintain that a one-to-one correspondence between absorbers and individual galaxies does not exist in many cases (e.g. Coté *et al.* 2005). To calculate a cross-correlation function, a reasonable number of absorbers overlapping with a galaxy survey sufficient in projected distance is needed.

Morris *et al.* (1993) is the only published z=0 absorber-galaxy cross-correlation function to-date, which used 17 absorbers along the 3C 273 line-of-sight. They found that absorbers are not distributed at random with respect to galaxies, but the absorber-galaxy correlation is weaker than the galaxy auto-correlation on scales from $1 - 10$ h_{80}^{-1} Mpc. The absorber-galaxy cross-correlation function is instrumental in establishing whether absorbers are associated with individual mini-halos or large scale structure. Here, we calculate the cross-correlation function with many more absorbers.

2. Cross correlation method and results

The HI Parkes All Sky Survey (HIPASS) galaxy catalogue (Meyer *et al.* 2004; Wong *et al.* 2005) is cross-correlated with known low redshift, low column density (mostly $N_{\mathrm{HI}} < 10^{15}$ cm^{-2}) Lyα absorbers from the literature (Impey *et al.* 1999; Bowen *et al.* 2002; Penton *et al.* 2002 & 2004; Tripp *et al.* 2002; Rosenberg *et al.* 2003). HIPASS was used as its all sky coverage enables a uniform statistical comparison with the absorbers, and it identifies gas-rich dwarf and low surface brightness galaxies, often missed by magnitude-limited optical surveys. Low redshift Lyα absorption systems were chosen from the literature to overlap with HICAT, i.e. $\delta < +25°$ and heliocentric velocity less than 12,700 km s^{-1}, resulting in 141 absorbers from 36 sight-lines. There are 5,340 galaxies in the combined HIPASS catalogues.

The cross-correlation function $\xi(\sigma, \pi)$ is calculated from the Davis & Peebles (1983) estimator $\xi(\sigma, \pi) = [DD(\sigma, \pi)/DR(\sigma, \pi)][n_R/n_D] - 1$, where $DD(\sigma, \pi)$ is the number of data galaxy-data absorber pairs with projected separation σ and radial separation π, and $DR(\sigma, \pi)$ is the number of data galaxy-random absorber pairs. The function is normalised by the number of random absorbers n_R and data absorbers n_D. The projected correlation function $\Xi(\sigma)/\sigma$ is then calculated by integrating $\xi(\sigma, \pi)$ in the π direction, a power-law is then fit to give the real-space correlation function coefficients r_0 and γ. To satisfy the PS formalism condition that the slopes of the cross- and auto-correlation function γ_{ag} and γ_{gg} be equal, the coefficients $r_{0,gg}$ and γ_{gg} are calculated first, then $r_{0,ag}$ is determined by fixing γ_{ag}=γ_{gg} and using a Levenberg-Marquardt non-linear least squares fit. The errors are calculated using jackknife re-sampling.

The auto- and cross-correlation functions are given in Fig. 1. Southern HIPASS has already been used to show that H I selected galaxies are more weakly clustered than optically selected galaxies (Meyer 2003). The results here show that the absorber-galaxy cross-correlation is stronger than the HIPASS galaxy auto-correlation for the spatial range 1$-$10 h^{-1} Mpc. The median H I mass of galaxies contributing to pairs in the range $1 \leqslant \sigma \leqslant 10$ h^{-1} Mpc is $\log(M_{\mathrm{HI}}/M_{\odot})$=8.1 h^{-2}, which corresponds to a halo mass of $\log(\mathrm{M}/M_{\odot})$=10.7 h^{-1} (Mo *et al.* 2005, this volume). The ratio of the cross- to auto-correlation function $(r_{0,ag}/r_{0,gg})^{\gamma_{gg}}$ together with known halo biases at $z = 0$ (Mo & White 2002; Bouché, private communication) indicates a value of $\log(\mathrm{M}/M_{\odot}) \sim 14$ h^{-1} for the mass of halos in which Lyα absorbers are embedded. This value agrees well with

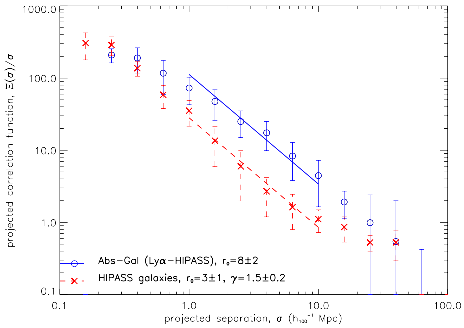

Figure 1. The absorber-galaxy cross-correlation function (circles and solid line) and the galaxy auto-correlation function (crosses and dashed line). See text for power-law fit description.

the median dynamical mass of galaxy groups in HIPASS, log(M/$M_\odot$)$\sim$13.8 h^{-1} (Stevens 2005).

3. Summary

The results show that the absorber-galaxy cross-correlation is stronger than the galaxy auto-correlation, this is opposite to what is seen by Morris *et al.* (1993, based on 17 absorbers). In the context of the PS formalism, the results suggests that on scales from 1−10 h^{-1} Mpc, Lyα absorbers are associated with dark matter halos with masses of log(M/$M_\odot$)$\sim$14 – similar to that of galaxy groups. The flattening of $\Xi(\sigma)/\sigma$ at low σ suggests that absorbers tend to avoid the densest regions of the local Universe. Although observing individual systems may reveal an association of a Lyα absorber with a particular structure, be it a galaxy group, filament, void, or galaxy halo, the statistical evidence presented here suggests that galaxy groups could be the dominant environment of low column density Lyα absorbers at z=0.

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