CORRELATIONS BETWEEN $O\,\text{vi}$ ABSORBERS AND GALAXIES AT LOW REDSHIFT

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Received 2007 November 6; accepted 2008 March 27; published 2008 April 11

ABSTRACT

We investigate the relationship between galaxies and metal-line absorption systems in a large-scale cosmological simulation with galaxy formation. Our detailed treatment of metal enrichment and nonequilibrium calculation of oxygen species allow us, for the first time, to carry out quantitative calculations of the cross-correlations between galaxies and $O\,\text{vi}$ absorbers. We find the following: (1) The cross-correlation strength depends weakly on the absorption strength but strongly on the luminosity of the galaxy. (2) The correlation distance increases monotonically with luminosity from $\sim 0.5$–$1\,h^{-1}$ Mpc for $0.1L_\odot$ galaxies to $\sim 3$–$5\,h^{-1}$ Mpc for $L_\odot$ galaxies. (3) The correlation distance has a complicated dependence on absorber strength, with a luminosity-dependent peak. (4) Only 15% of $O\,\text{vi}$ absorbers lie near $>L_\odot$ galaxies. The remaining 85%, then, must arise “near” lower luminosity galaxies; however, the positions of those galaxies is not well correlated with the absorbers. This may point to pollution of intergalactic gas predominantly by smaller galaxies. (5) There is a subtle trend that for $>0.5L_\odot$ galaxies, there is a positive correlation between absorber strength and galaxy luminosity in the sense that stronger absorbers have a slightly higher probability of finding such a large galaxy at a given projection distance. For less luminous galaxies, there seems to be a negative correlation between luminosity and absorber strength.

1. INTRODUCTION

Cosmological hydrodynamic simulations have shown that most of the so-called missing baryons (Fukugita et al. 1998) may be in a filamentary network of warm-hot intergalactic medium (WHIM; Cen & Ostriker 1999; Davé et al. 2001). Visual inspection of simulations suggests that the WHIM is spatially correlated with galaxies. This is consistent with the observed large-scale structure of galaxies, as well as the physical expectation that both galaxies and intergalactic medium (IGM) are subject to the dominant gravitational force of dark matter which tends to lead to such large-scale structures (Zel’dovich 1970).

Moreover, the WHIM may provide a primary conduit for matter and energy exchanges between galaxies and the IGM. Thus, a detailed understanding of the WHIM may shed useful light on galaxy formation (e.g., Cen et al. 2005). The $O\,\text{vi}$ $\lambda\lambda 1032, 1038$ absorption line doublet in the spectra of low-redshift QSOs provides a valuable probe of the WHIM (e.g., Lehner et al. 2007; Shull & Danforth 2008; Tripp et al. 2008). In this Letter we use cosmological hydrodynamic simulations to make predictions of the correlations between $O\,\text{vi}$ absorbers and galaxies, which may be used for detailed comparisons with upcoming Hubble Space Telescope Cosmic Origins Spectrograph observations.

2. SIMULATION AND CONSTRUCTION OF ABSORBER AND GALAXY CATALOGS

We use the simulation from Cen & Ostriker (2006) and Cen & Fang (2006) to make predictions of the relationship between $O\,\text{vi}$ WHIM absorption and the presence of galaxies. This cold dark matter simulation assumes $\Omega_m = 0.31$, $\Omega_b = 0.048$, $\Omega_{\Lambda} = 0.69$, $a_s = 0.89$, $H_0 = 100\,h = 69\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$, $n_s = 0.97$, comoving box size $85\,h^{-1}$ Mpc, and 1024$^3$ cells.

The simulation follows star formation using a physically motivated prescription and includes feedback processes from star formation to the IGM in the form of UV radiation and galactic superwinds carrying energy and metal-enriched gas (Cen & Ostriker 2006). In star formation sites, “star particles” are produced at each time step, which typically have a mass of $10^6 M_\odot$. Galaxies are identified post facto using the HOP grouping scheme (Eisenstein & Hut 1998; see Nagamine et al. 2001 for details) on these particles. This grouping scheme provides a catalog of galaxies containing 3D positions, peculiar velocities, stellar masses, and ages. The catalog consists of 33,887 galaxies. Stellar population synthesis models from Bruzual & Charlot (2003) are used to compute luminosities in all SDSS bands. For the purposes of this Letter, we focus on the Sloan $z$ band, which is centered at 9100 Å and has a width of 1200 Å (Fukugita et al. 1996). For galaxies, the flux in this band is most tightly correlated (of all the Sloan bands) with the total stellar mass (e.g., Kauffmann et al. 2003). We find that the luminosities of field galaxies in this simulation follow a Schechter function down to $\sim 10^{-3} L_\odot$ ($L_\odot = 3 \times 10^{10} L_\odot$; R. Ganguly et al. 2008, in preparation).

We extract a 100 × 100 grid of sight lines uniformly separated by $850\,h^{-1}$ kpc. For each sight line, a synthetic spectrum of $O\,\text{vi}$ $\lambda 1032$ absorption is generated, taking into account effects due to peculiar velocities and thermal broadening. For each sight line, we decompose the spectrum into individual Gaussian-broadened components with an algorithm similar to AUTOVP (Davé et al. 1997). Finally, we associate grouped components into systems; this is important since, physically, it does not serve our purpose to treat individual components separately when comparing to the locations of galaxies. (A single physical system such as a galactic disk/halo is often composed of multiple components. This is a result of complicated velocity structures and the clumpiness of gas. Historically, older surveys did not have the spectral dispersion needed to resolve individual components. Therefore, it is desirable to...
Fig. 1.—We show the cumulative fraction of O\textsc{vi} absorbers that have galaxies at least as luminous as $L/L_*$, within a cylindrical volume centered on the absorber. We show results for cylinders of two different radii and a velocity depth of 2000 km s$^{-1}$. In the top panel, we show different cuts in the integrated O\textsc{vi} column density. In the bottom panel, we show cuts in $l_{1032}$ equivalent width. In each panel, a horizontal line is drawn where 50% of the absorbers are accounted for. A vertical line is drawn where each of the curves crosses this fiducial. Black dashed lines show the results for uncorrelated absorber and galaxy positions.

Fig. 2.—We show the cumulative fraction of O\textsc{vi} absorbers as a function of projected distance to the closest galaxy with luminosity $\geq L_*$. The absolute velocity separation is required to be $|\Delta v| \leq 1000$ km s$^{-1}$. We show different cuts in O\textsc{vi} column density (top) and $l_{1032}$ equivalent width (bottom). In both panels, four families of curves are shown corresponding to different luminosity cuts: $L/L_* \geq 0.03, 0.1, 0.3$, and 1. Black lines show the results for uncorrelated absorber and galaxy positions. Note that vertical cuts at $D_{\text{min}} = 1, 3 \, h^{-1}$ Mpc plotted against luminosity reproduce Fig. 1.

3. ANALYSIS AND RESULTS

We consider the probability that an O\textsc{vi} absorber of a given equivalent width or column density lies within some distance of a galaxy with a certain luminosity. We take three approaches to address this question, but we must first tackle the problem of assigning galaxies to O\textsc{vi} absorbers. Due to peculiar velocity effects, the exact 3D separation between an O\textsc{vi} absorber and a galaxy cannot be precisely known, although the projected distance in the sky plane can be directly measured. Thus, we simply limit absorber-galaxy associations to within the physically motivated line-of-sight separation of 1000 km s$^{-1}$, corresponding approximately to the velocity dispersion of clusters of galaxies.

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regroup these components back to physically independent systems.) We accomplish this by computing the one-dimensional two-point correlation function of components and identify a characteristic velocity scale. We find that, on small scales, absorption-line components are correlated out to a velocity separation of $\sim 300$ km s$^{-1}$, which we adopt as the characteristic velocity interval to identify systems. For each system, we record the integrated flux-weighted centroid redshift, O\textsc{vi} column density, and $l_{1032}$ rest-frame equivalent width. A total of $\sim 180,000$ components were found to be grouped into $\sim 21,000$ systems with $W_{\alpha}(\lambda 1032) \geq 1$ mA.
in that volume. We do this for two subsamples of absorbers, those with $\lambda 1032$ equivalent width larger than 30 mA (typical detection limit for HST STIS and FUSE spectra) and 10 mA (expected limit for HST COS observations). In addition to the equivalent width cuts in the absorber sample, we also make luminosity cuts in the galaxy sample. Current catalogs are typically able to reach galaxy luminosities of $0.1L_*$ for statistically interesting volumes (e.g., Stocke et al. 2006).

Taking Figures 1 and 2 together, we first address the question of which galaxies, and on what scales, are correlated (if any) with O vi absorption. In Figure 1, at luminosities fainter than (0.3–0.5$L_*$), the curves lie below the equivalent curves for randomly placed galaxies. That is, finding a lower luminosity galaxy near an O vi absorber is less probable than if galaxies were uncorrelated with the O vi absorbers for $D = 1–3 h^{-1}$ Mpc. This merely implies that the correlation distance, defined to be the distance within which there is positive enhancement of pairs compared to random distributions, is smaller than $1 h^{-1}$ Mpc for these low-luminosity galaxies, consistent with results summarized in Table 2 (see below). At higher luminosities, the curves are above the random galaxies. This implies that galaxies with $\geq 0.3L_*$ are correlated with O vi WHIM absorption with the correlation distance larger than $3 h^{-1}$ Mpc, again consistent with results summarized in Table 2. This same information may be seen, in a different way, in Figure 2, as the families of curves for fainter galaxies lie below equivalent ones for random galaxies, but the converse is true for higher luminosity galaxies. A perhaps somewhat counterintuitive result in Figure 1 is that an absorber is more likely to find a faint galaxy within the $D = 1 h^{-1}$ Mpc cylinder, if the galaxies were randomly distributed, and ~30% of absorbers do not find any galaxy to the faintest limit simulated. This is due to the fact that the galaxies themselves are more strongly clustered than absorbers among themselves or between galaxies and absorbers. Therefore, absorbers will have a lower probability of finding neighboring galaxies than when the latter are randomly distributed, beyond the cross-correlation distance.

An interesting feature immediately visible from Figures 1 and 2 is that the association between galaxies and O vi absorbers depends weakly on either the O vi column density or $\lambda 1032$ equivalent width. This suggests that, while overall galaxies and O vi absorbers are correlated on small scales, the physical properties of O vi absorbers (e.g., strength, kinematics, number of components) themselves do not display any tight correspondence with nearby galaxies. It seems that the strengths of O vi absorbers do not provide useful indicators for the properties of nearby galaxies. Physically, it suggests that O vi absorbers may arise in the vicinities of galaxies in a wide variety of ways through complex feedback and thermodynamic processes. Complex interactions involving gravity-induced shocks, feedback, and photoionization appear to have erased or smoothed out any potential trend with respect to O vi column density or equivalent width. This finding is in accord with observations (e.g., Prochaska et al. 2006).

From Figure 2 it appears that the distance out to which O vi absorbers are correlated with galaxies is a function of both galaxy luminosity and absorber strength (even though the mere presence of a galaxy is not tightly correlated with absorber strength as from Fig. 1). Comparison of the black curves in Figure 2, showing the results of uncorrelated absorber and galaxy positions, with the equivalent families of the curves for the simulated galaxies and absorbers shows that there is typically a distance beyond which it is more probable to find an uncorrelated galaxy. This distance changes depending on the galaxy luminosity and the absorption strength. In the extreme case, there is no distance at which the strongest absorbers are correlated with the least luminous galaxies. In Table 2 we list the correlation distances as a function of galaxy luminosity and absorption strength. We note two interesting features from the table: (1) For a given equivalent width limit, the correlation distance is a monotonic function of the limiting luminosity. (2) However, for a given limiting luminosity, the correlation distance is not a monotonic function of equivalent width limit. This may also point toward the eclectic nature of the absorbers as mentioned above.

It is interesting, however, to consider the number of galaxies that may be responsible for producing O vi absorption. While the intragroup/intracluster medium (ICM) is typically too hot ($T \sim 10^7$ K) for O vi to survive in appreciable quantities, the interfaces between warm, denser, photoionized clouds of temperature $T \sim 10^5$ K and the ICM are potential locations for O vi production. Examples of such interfaces include the boundaries between Milky Way high-velocity clouds and the hot Galactic corona (e.g., Fox et al. 2005; Sembach et al. 2003). From Table 1 we find that 85% of O vi absorbers, regardless of absorption equivalent width, do not lie near $L_*$ galaxies. Furthermore, the remaining 15% have at most 3 nearby $L_*$ galaxies, comparable to the Local Group. This is not surprising given that $L_*$ galaxies are not common. However,

**Table 1**

| $W_0(1032)$ | $L/L_*$ |
|-------------|--------|
| $W_0(1032) \geq 10$ mA, $\sim 6500$ Absorbers | $L/L_*$ |
| $0$ | 0.15 | 0.36 | 0.56 | 0.74 | 0.84 | 0.99 |
| $1$ | 0.04 | 0.17 | 0.40 | 0.62 | 0.75 | 0.98 |
| $2$ | 0.01 | 0.08 | 0.28 | 0.52 | 0.67 | 0.96 |
| $3$ | 0.00 | 0.04 | 0.20 | 0.43 | 0.60 | 0.94 |
| $4$ | 0.00 | 0.02 | 0.14 | 0.36 | 0.52 | 0.92 |
| $5$ | 0.00 | 0.02 | 0.10 | 0.30 | 0.47 | 0.89 |
| $10$ | 0.00 | 0.00 | 0.02 | 0.12 | 0.26 | 0.75 |

**Notes.**—The first column denotes the number of galaxies, $n$, that lie within a cylindrical volume of radius $3 h^{-1}$ Mpc and depth 2000 km s$^{-1}$ centered on an O vi absorber. For the remaining columns, $f$ denotes the galaxy luminosity in units of $L_*$, (i.e., $L = fL_*$). The numbers in these columns indicate the fraction of $\geq L_0(1032)$ O vi absorbers that have $>n$ galaxies with luminosities $\geq L_*$.

**Table 2**

| $W_0(1032)$ | $L/L_*$ |
|-------------|--------|
| $W_0(1032) \geq 30$ mA, $\sim 3000$ Absorbers | $L/L_*$ |
| $0$ | 0.15 | 0.35 | 0.55 | 0.74 | 0.84 | 0.99 |
| $1$ | 0.05 | 0.17 | 0.39 | 0.61 | 0.75 | 0.98 |
| $2$ | 0.01 | 0.08 | 0.27 | 0.51 | 0.67 | 0.96 |
| $3$ | 0.00 | 0.05 | 0.19 | 0.42 | 0.59 | 0.94 |
| $4$ | 0.00 | 0.02 | 0.14 | 0.35 | 0.52 | 0.92 |
| $5$ | 0.00 | 0.02 | 0.10 | 0.29 | 0.46 | 0.89 |
| $10$ | 0.00 | 0.00 | 0.02 | 0.11 | 0.25 | 0.75 |

**Notes.**—The first column denotes the luminosity of galaxies in units of $L_*$, (i.e., $L = fL_*$). The numbers in the remaining columns indicate the distance in Mpc out to which $\geq W_0(1032)$ O vi absorbers are correlated with $\geq 2L_*$ galaxies. Galaxies are required to lie within 1000 km s$^{-1}$ of the absorber.
99% of absorbers do lie near galaxies of lower luminosity, even if the presence of those galaxies is not correlated over what is expected from randomly placed galaxies.

Figure 2 shows that \( \lesssim 20\% \) of O \( \text{\textsc{vi}} \) absorbers should find an \( L_\ast \) galaxy within a projected distance of \( 5 \, h^{-1} \) Mpc. Of course, one would not likely associate O \( \text{\textsc{vi}} \) absorbers with \( L_\ast \) galaxies at such large projected separations, since, for example, one would have already found a nearby \( \gtrsim 0.03L_\ast \) galaxy within \( 1 \, h^{-1} \) Mpc, or \( \gtrsim 0.1L_\ast \) galaxy at closer distance with comparable probability. In any case, it seems unlikely that \( L_\ast \) galaxies at such remote distances are responsible for creating the O \( \text{\textsc{vi}} \) absorbers. The rapid rise of probability in Figure 2 from \( D_{\min} = 0 \) to \( D_{\min} \sim 1 \, h^{-1} \) Mpc from galaxies \( \gtrsim (0.03-0.1)L_\ast \) may reflect a ubiquitous physical connection between O \( \text{\textsc{vi}} \) absorbers and these relatively small galaxies, perhaps a result of galactic superwinds being able to transport metals to a distance of \( \lesssim 1 \, h^{-1} \) Mpc from these galaxies. This, however, does not necessarily exclude larger galaxies from being able to do the same. The slower rise of probability in Figure 2 from \( D_{\min} = 0 \) to \( D_{\min} \sim 5 \, h^{-1} \) Mpc for galaxies \( \gtrsim (0.3-1)L_\ast \) may be a result of the intrinsic correlation of large galaxies and small galaxies on these scales. These more detailed issues will be examined subsequently elsewhere. Our results appear to be in broad agreement with observations (e.g., Stocke et al. 2006, 2007; Tripp et al. 2006).

We take a more detailed look at the dependencies of probability on the O \( \text{\textsc{vi}} \) column density or equivalent width. Closer examination of the curves in Figure 1 (lower right corner of both panels) and in Figure 2 (solid curves, lower left corner of bottom panel) reveals that the probability of finding a \( \sim L_\ast \) galaxy is higher for O \( \text{\textsc{vi}} \) absorbers with a higher column density equivalent width. In particular, \( N(\text{O} \, \text{\textsc{vi}}) \gtrsim 10^{13} \text{ cm}^{-2} \) or \( W_v \gtrsim 100 \text{ mÅ} \) absorbers deviate noticeably from the weaker absorbers. This is a reversal of the trends from other parts of those figures. For smaller galaxies, e.g., \( \gtrsim 0.5L_\ast \) galaxies (the set of dotted curves in the bottom panel of Fig. 2), the trend is considerably weaker although still visible. For still smaller galaxies, the trend is reversed, with weaker absorbers having a higher probability than stronger ones. These results seem to suggest that these very strong O \( \text{\textsc{vi}} \) absorbers tend to be produced in richer, high-density environments where the probability of finding massive galaxies is enhanced (we will examine this physical link elsewhere). The fact that weaker O \( \text{\textsc{vi}} \) absorbers have a higher probability of finding a galaxy than stronger absorbers, for galaxies less luminous than \( \sim (0.2-0.5)L_\ast \) (Fig. 1), once again suggests that these relatively weaker O \( \text{\textsc{vi}} \) absorbers \( (W_v \lesssim 50 \text{ mÅ}) \) are probably produced by galaxies of \( \sim 0.1L_\ast \), not by more luminous galaxies. This is consistent with the trend in Figure 2.

4. CONCLUSIONS

We investigate the relationship between galaxies and metal-line absorption systems in a large-scale cosmological simulation with galaxy formation included. Our detailed treatment of metal enrichment and nonequilibrium calculation of oxygen species allow us, for the first time, to carry out quantitative calculations of the cross-correlations between galaxies and O \( \text{\textsc{vi}} \) absorbers. We examine the cross-correlations between O \( \text{\textsc{vi}} \) absorbers and galaxies as a function of projection distance, with the line-of-sight velocity separation between an absorber and a galaxy constrained to within \( \pm 1000 \text{ km s}^{-1} \). Here are some major findings: (1) The cross-correlation strength depends only weakly on the strength of the absorber but strongly on the luminosity of the galaxy. This result suggests that O \( \text{\textsc{vi}} \) absorbers are produced ubiquitously and their physical/thermal properties and history vary widely, presumably due to the combined effects of gravitational shocks, feedback, photoionization, and cooling processes. (2) The correlation length, however, does depend on both the galaxy luminosity and on the absorber strength from \( \sim 0.5-1 \, h^{-1} \) Mpc for 0.1\( L_\ast \) galaxies to \( \sim 3-5 \, h^{-1} \) Mpc for \( L_\ast \) galaxies. While the dependence on luminosity is monotonic, the dependence on limiting equivalent width appears to peak at some luminosity-dependent value and then falls. (3) Only 15% of O \( \text{\textsc{vi}} \) absorbers lie near \( 2L_\ast \) galaxies. Thus the remaining 85% must be produced by gas ejected from fainter galaxies. The positions of lower luminosity galaxies are not well correlated with absorbers (i.e., in comparison with randomly placed galaxies). This may point toward pollution of intracluster gas by many galaxies, rather than a single high-luminosity galaxy. (4) For \( \gtrsim 0.5L_\ast \) galaxies, there is a positive correlation between absorber strength and galaxy luminosity (stronger absorbers have a slightly higher probability of finding such a large galaxy at a given projection distance). The reverse seems true for less luminous galaxies. On average, these results indicate that very strong O \( \text{\textsc{vi}} \) absorbers tend to be produced in richer, high-density environments where one is more likely to find massive galaxies.

The spatial resolution of our simulation is \( \sim 80 \, h^{-1} \) kpc. While this is adequate for resolving large galaxies, it becomes marginal for galaxies in halos of total mass less than \( \sim 10^{11} \, M_\odot \). Therefore, some of the smaller galaxies of luminosities (0.01–0.03\( L_\ast \)) may be significantly affected and their abundances underestimated. In addition, O \( \text{\textsc{vi}} \) systems that would have been produced from these underresolved galaxies may be absent. As a result, one should treat the cross-correlation strength between O \( \text{\textsc{vi}} \) absorbers and the low-luminosity galaxies as a lower bound. But we hope that the preliminary results presented here will provide a useful framework for comparison with upcoming imaging campaigns of galaxies in the field of quasars and spectroscopic observations with the Cosmic Origins Spectrograph.

We thank Ken Nagamine for providing simulated galaxy catalogs, and the referee for thoughtful comments. We gratefully acknowledge financial support by grants AST 05-07521 and NNG05GK10G. This work was partially supported by the National Center for Supercomputing Applications under MCA04N012.

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