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DAMPED Lyα ABSORBER AND THE FAINT END OF THE GALAXY LUMINOSITY FUNCTION AT HIGH REDSHIFT

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ABSTRACT

We combine predictions for several hierarchical cosmogonies with observational evidence on damped Lyα systems (DLASs) to establish a correspondence between the high-redshift galaxy population and the properties of DLASs. We assume that high-redshift galaxies and damped Lyα systems are hosted by the same dark matter halos and require consistency between the predicted halo space density, the rate of incidence and the velocity width distribution of damped Lyα systems, and the observed galaxy luminosity function at the bright end. We arrive at the following results: (1) predicted impact parameters between the damped absorption system and the luminous parts of the absorbing galaxy are expected to be very small (0''.3–1'') for most galaxies; (2) luminosities of galaxies causing damped absorption are generally fainter than $m_{\mathscr{R}} = 25$, and damped Lyα systems are predicted to sample preferentially the outer regions of galaxies at the faint end of the galaxy luminosity function at high redshift. Therefore, DLASs should currently provide the best probe of the progenitors of normal present-day galaxies.

Subject headings: galaxies: kinematics and dynamics — galaxies: structure — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

The physical conditions inferred from the absorption features caused by high-redshift damped Lyα absorption systems (DLASs) are, in several aspects, similar to those in the interstellar medium of present-day galaxies. It has therefore been suggested to identify DLASs with the progenitors of such galaxies (e.g., Wolfe 1988). At low redshift DLASs show a wide variety of morphologies (Le Brun et al. 1997). At high redshift, however, few have been detected in emission (Møller & Warren 1996; Warren & Møller 1995; Djorgovski et al. 1996; Djorgovski 1997; Møller & Warren 1998), and the nature of galaxies causing the absorption remains unclear for the majority of DLASs at high redshift. The main source of information on the nature of DLASs comes from the associated metal absorption, which probes the kinematics and the chemical enrichment history of the mainly neutral gas in these systems. Motivated by the characteristic asymmetric shape of the absorption profiles of low-ionization species, Wolfe and collaborators (e.g., Wolfe et al. 1986) have suggested that high-redshift DLASs are large rapidly rotating disks akin to present-day spiral galaxies (but see also Ledoux et al. 1998). In this picture the generally low observed metallicity of high-redshift DLASs (Pettini et al. 1994; Lu et al. 1996; Pettini 1999) is taken as evidence that these are still chemically young (Lindner, Fritze–von Alvensleben, & Fricke 1999).

The conjecture that DLASs are large rotating disks is, however, at odds with the velocity width distribution, the size, and the total cross section of rapidly rotating disks predicted by hierarchical cosmogonies (Haehnelt, Steinmetz, & Rauch 1998b, hereafter HSR98). Hydrodynamical simulations (Katz et al. 1996; Haehnelt, Steinmetz, & Rauch 1996; Gardner et al. 1997a, 1997b; Rauch, Haehnelt, & Steinmetz 1997) show that gas condensations leading to damped Lyα absorption do indeed occur in such scenarios. However, the hierarchical cosmogonies predict that a significant fraction of the cross section for damped absorption is contributed by gas in halos with circular velocities as small as 50 km s^{-1} (Ma & Bertschinger 1994; Mo & Miralda-Escudé 1994; Kauffmann & Charlot 1996; Klypin et al. 1995; Kauffmann 1996; Mo, Mao, & White 1999; Gardner et al. 1999), where we define the circular velocity as $v_c = (GM/R)^{1/2}$ at a radius where the overdensity is equal to 200. In HSR98 we have shown that the shape of the absorption profiles is not unique but can be equally well produced by merging protogalactic clumps (cf. Nulsen, Barcons, & Fabian 1998; McDonald & Miralda-Escudé 1999; Maller et al. 1999). In HSR98 we further showed that the observed velocity width distribution of the absorption features of low-ionization species can be reproduced in a standard cold dark matter (SCDM) cosmology. At the same time, hierarchical cosmogonies such as SCDM have been shown to reproduce the basic properties of the observed population of high-redshift galaxies (Adelberger et al. 1998; Steidel et al. 1998; Baugh et al. 1998; Bagla 1998; Jing & Suto 1998; Haehnelt, Natarajan, & Rees 1998a; Wechsler et al. 1998; Contardo, Steinmetz, & Fritze–von Alvensleben 1998; Steinmetz 1998; Kauffmann et al. 1999; Mo et al. 1999). Here we establish a link between emission and absorption properties of high-redshift galaxies. In § 2 we briefly test whether our previous findings depend on cosmology. In § 3 we predict the luminosity and impact parameter distribution of high-redshift galaxies responsible for DLASs. Section 4 contains our conclusions.

2. THE VELOCITY WIDTH DISTRIBUTION OF DLASS

In hierarchical CDM-like cosmogonies DLASs arise naturally from the cool gas that accumulates at the center of dark matter (DM) halos (e.g., Katz et al. 1996; Gardner et al. 1997a, 1997b). Absorption features of low-ionization species like Si II are generally believed to be good tracers of the motion of this gas in a gravitational potential well

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TABLE 1

MODEL PARAMETERS

Model	σ_8	h	Ω_0	Ω_Λ	Γ	$r^0_{\rm damp}$ (kpc)	r^0_{200} (kpc)	$m^0_{\mathscr{R}}$	β
SCDM	0.67	0.5	1.0	0.0	0.5	16	50	27.1	3
ΛCDM	0.91	0.7	0.3	0.7	0.21	17	64	26.6	2.5
OCDM......	0.85	0.7	0.3	0.0	0.21	16	52	27.4	2.5
τCDM.......	0.67	0.5	1.0	0.0	0.21	26	50	25.9	3

NOTE.—σ_8 is the rms linear overdensity in spheres of radius 8 h^{-1} Mpc, and Γ is a shape parameter for CDM-like spectra; h is the Hubble constant in units of 100 km s^{-1}), and Ω_0 and Ω_Λ are the total energy density and that due to a cosmological constant. For the other quantities see the text.

(Prochaska & Wolfe 1997, 1998). One major characteristic of these absorption features is their overall width, which in HSR98 we have shown to be correlated with the circular velocity of the DM halo hosting the DLAS. However, for a halo of given circular velocity a statistical distribution of velocity widths $p(v_{\rm wid}\,|\,v_c)$ arises as a result of different orientations of the line of sight and different dynamical states of the gas of the DM halos. Halos with small circular velocities are believed to lose most of their gas because of feedback effects. The velocity width distribution of DLASs as probed by low-ionization species can thus be written as

$$p_{\rm damp}(v_{\rm wid}) = \int_{v_{\rm min}}^{\infty} p(v_{\rm wid}\,|\,v_c) p_{\rm damp}(v_c) dv_c\ . \quad (1)$$

In HSR98 we used simulated absorption profiles for a set of halos with 50 km s^{-1} $< v_c <$ 250 km s^{-1} to investigate $p(v_{\rm wid}\,|\,v_c)$ for a SCDM model and found that the distribution does not depend explicitly on v_c and depends little on redshift. We therefore assume $p(v_{\rm wid}\,|\,v_c)$ to be a function of $v_{\rm wid}/v_c$ only. In order to check whether there is a dependence on cosmology, we repeated our analysis for a ΛCDM model (see Table 1 for the assumed model parameters and HSR98 for details of the simulations). Figure 1 shows $p(v_{\rm wid}/v_c)$ averaged over different halos and lines of sight. There is little difference between the two cosmological models.

Once the cross section weighting for damped absorption is known, the velocity width distribution is readily calculated from the distribution of circular velocities $p_{\rm damp}(v_c) \propto \sigma_{\rm damp}\, p_{\rm PS}(v_c)$. It is currently difficult to infer this cross section weighting reliably from numerical simulations. Gardner et al. (1997a, 1997b), for example, found that the cross section of DM halos scales as a power law of the circular velocity as $v_c^{2.3}$–v_c^3. In their later work they found a much shallower scaling, $v_c^{0.4}$–$v_c^{1.1}$ (Gardner et al. 1999). This cross section weighting is likely to be sensitive to the energy and momentum input due to supernovae, which is difficult to include properly in these simulations.

Here we take a different approach and use the observed velocity width distribution to determine the mean cross

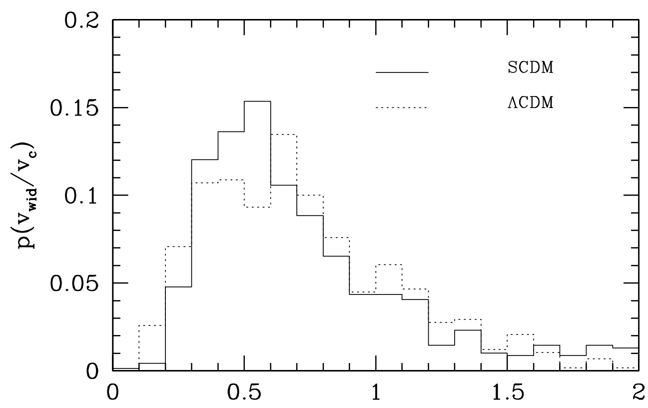


FIG. 1.—Distribution of velocity widths of absorption features of low-ionization species as a function of $v_{\rm wid}/v_c$ for two different cosmogonies. Model parameters are given in Table 1.

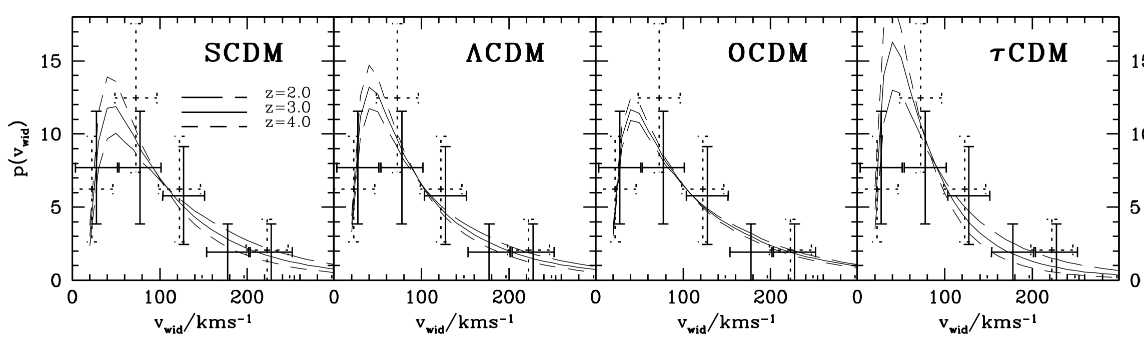


FIG. 2.—Velocity width distribution of the associated absorption of low-ionization species in DLASs. The curves are model predictions for four different cosmogonies as calculated from eq. (1) (for parameters see Table 1). The crosses are data from Prochaska & Wolfe 1997 (*dotted line:* high z, *solid line:* low z).

section weighting for damped absorption. We also choose a power-law parameterization

$$\sigma_{\rm damp}(v_c) = \pi(r^0_{\rm damp})^2(v_c/200\ {\rm km\ s^{-1}})^\beta\ . \tag{2}$$

Using the Press-Schechter formalism, we calculate $p_{\rm PS}(v_c)$ and obtain the velocity width distributions shown in Figure 2. The observed distributions are well fitted with $\beta \sim 2.5$–3 (see Table 1) and $v_{\rm min} = 50$ km s^{-1}. Note that there is little evolution with redshift in the observed or in the predicted distribution. The values of β are close to the old value but quite different from the new value of Gardner et al. (1997a, 1997b, 1999).

3. PREDICTING EMISSION PROPERTIES

3.1. *The Luminosity Distribution of DLASs*

Recently, it has become possible to determine the luminosity function for the population of star-forming galaxies detected at high redshift (Steidel et al. 1996, Steidel et al. 1999). The luminosity function at $z = 3$ can be reproduced if a simple linear scaling of the luminosity in the $\mathscr{R}$ band (Steidel et al. 1996) with mass of the DM halo is assumed,

$$m_{\mathscr{R}} = m^0_{\mathscr{R}} - 7.5\ \log\ (v_c/200\ {\rm km\ s^{-1}}) \tag{3}$$

(Haehnelt et al. 1998a). The required values of $m^0_{\mathscr{R}}$ are also shown in Table 1. The same simple model can also reproduce the clustering strength of high-redshift galaxies and its decrease with decreasing limiting UV luminosity of the galaxy sample (but see Somerville, Primack, & Faber 1999 for a somewhat different model). Note that the linear scaling of the UV luminosity with mass does not necessarily imply that the star formation rate scales linearly with the mass of the DM halo as the dust extinction of the UV luminosity is probably luminosity dependent (Steidel et al. 1999). If we make the plausible assumption that high-redshift galaxies are hosted by the same population of DM halos that are causing DLASs and assume that the linear scaling of the UV luminosity with mass can be extrapolated to smaller masses we can predict the luminosity distribution of DLASs. All we need to know is the scaling of the cross section of DM halos for damped absorption with circular velocity which we already inferred in the last section from the velocity width distribution. The result is shown in Figure 3; 80%–90% of DLASs are predicted to be fainter than $m_{\mathscr{R}} = 25.5$ (the spectroscopic limit), rather independent of cosmology (see also Fynbo, Møller, & Warren 1999). Some of these may be faint Lyα emitters (Fynbo, Thomsen, & Møller 2000) but most of them will probably be very difficult to identify reliably.

3.2. *The Impact Parameter Distribution of DLASs*

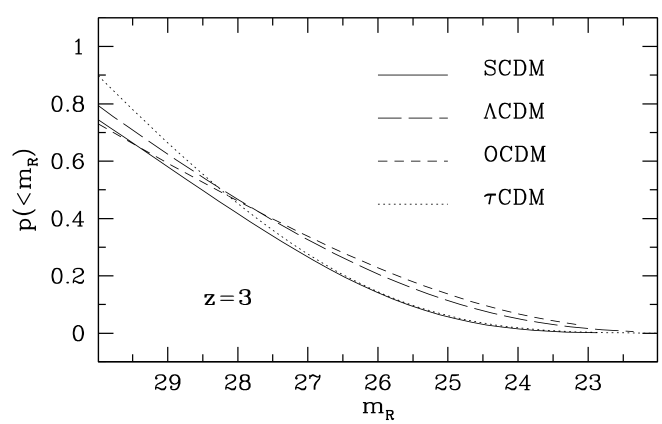
Similarly, we can also predict the impact parameter distribution (Fig. 3*b*). The overall rate of incidence, $d\mathscr{N}/dz = 0.2$ (Storrie-Lombardi, McMahon, & Irwin 1996), determines the normalization of the cross section weighting. The corresponding values of $r^0_{\rm damp} = r_{\rm damp}(v_c = 200\ {\rm km\ s^{-1}})$ are given in Table 1. The *predicted impact parameters range between 0″.3 and 1″*, rather independent of cosmology. The parameter $r^0_{200} = r_{200}(v_c = 200\ {\rm km\ s^{-1}})$, that is the radius at which the overdensity is equal to $200\rho_{\rm crit}$ is also listed in Table 1.

The typical radii of the region causing damped absorption are generally about 25%–50% of r_{200} of the corresponding DM halo. This is about a factor of 10 larger than the expected scale length of a centrifugally supported disk if the angular momentum of the gas is due to tidal torquing during the collapse of the DM halo (Mo, Mao, & White 1998). Note that with the assumed scaling of the cross section $r_{\rm damp}$ increases more steeply with circular velocity ($\propto v_c^{\beta/2}$) than r_{200} ($\propto v_c$).

4. CONCLUSIONS

In hierarchical cosmogonies DLASs are mainly caused by merging protogalactic clumps hosted by collapsed DM halos. The observed velocity width of the absorption profiles of associated low-ionization species is well reproduced for a a range of CDM variants which reproduce the present-day space density of galaxy clusters.

By combining the cross section weighting inferred from the observed velocity width distribution with the mass-luminosity relation inferred from the luminosity function and clustering properties of high-redshift galaxies, it is possible to link absorption and emission properties of DLASs. About 10%–20% of DLASs are predicted to be brighter than $m_{\mathscr{R}} = 25.5$. Expected impact parameter typically range between 0″.3 and 1″, but there is a pronounced tail of larger impact parameters. The predictions seem consistent with the luminosities and impact parameters of the small number of DLASs with spectroscopically identified emission (see, e.g., Møller & Warren 1998 for an overview). In our model these would be drawn from the tail of the distribution at the bright end and at large impact parameter, respectively. The rather faint flux levels and small impact parameter predict-



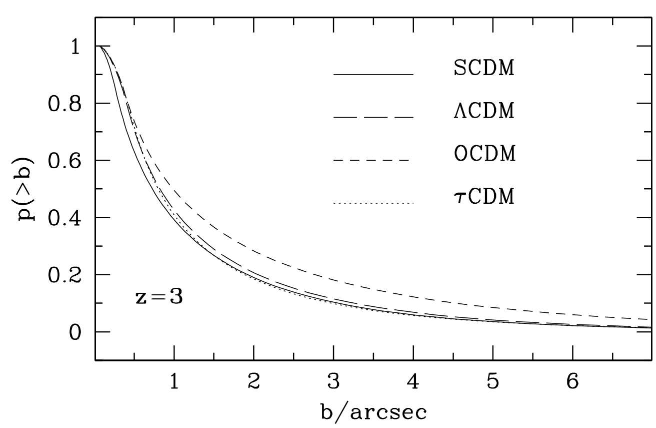


FIG. 3.—*Left:* Predicted luminosity distribution for the DLASs for the four different cosmogonies. *Right:* Predicted impact parameter distribution.

ed for the majority of DLASs explains why searches for the emission from DLASs have been notoriously difficult.

The predicted impact parameters are nevertheless about a factor of 3–5 larger than the typical radii of the luminous regions of Lyman-break galaxies. Thus, DLASs at high redshift should preferentially sample the outer regions of galaxies at the faint end of the luminosity function. This is consistent with the low observed metallicities in DLASs and the outer regions of galaxies (Ferguson et al. 1998). In our model DLASs should not be expected to show the high metallicities estimated for Lyman-break galaxies (Pettini et al. 1999); the latter are derived from emission spectra, which are dominated by the light from the more highly enriched central regions.

Hierarchical cosmogonies predict Lyman-break galaxies with $m_{\mathcal{R}} < 25$ to become part of bright galaxies in galaxy clusters at the present day. The fainter galaxies responsible for DLASs should, however, be the building blocks of more typical (L_*) present-day galaxies consistent with the findings from chemical evolution models for DLASs. Most high-redshift DLASs are predicted to be too faint to allow spectra to be obtained even with 10 m telescopes unless they are strongly magnified by gravitational lensing. The analysis of their absorption properties is currently the prime method of studying the progenitors of normal present-day galaxies.

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