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The Physical Nature of the Damped Lyα Systems

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Abstract. I review the latest results on the low-ion kinematics of the damped Lyα systems and their implications for the processes of galaxy formation at high redshift. While these observations are most easily explained by thick, rapidly rotating disks, they are also consistent with two CDM scenarios based on merging subsystems. We describe these models and discuss several ongoing programs to further investigate the physical nature of the damped Lyα systems.

1. Introduction

The damped Lyα (DLA) systems are the redwoods of the Lyα forest. With HI column densities (N(HI) $> 2 \times 10^{20}\,\mathrm{cm}^{-2}$) far exceeding all of the other trees combined, these systems truly dominate the neutral hydrogen content of the universe at all epochs. Because the damped systems are the reservoirs of neutral gas which feed star formation and because their large N(HI) values imply overdensities $\delta\rho/\rho \gg 100$, they are widely accepted as the progenitors of present-day galaxies. Therefore, observations of the DLA systems provide an efficient means for studying galaxy formation and cosmology in the early universe. In the following, we review our studies on the kinematics of the DLA systems and the insight we have gained on the nature of these systems. Through this research, we aim to reveal the physical processes which drive galaxy formation investigate the cosmological implications.

2. Low-ion Kinematics

There is essentially no kinematic information in the damped Lyα profile or the higher order lines in the Lyman series, so one must look to the low-ion metal profiles to reveal the kinematic characteristics of the damped systems. The term "low-ion" refers to the dominant ionization state of an element in a neutral HI region. Because the DLA systems have extremely large optical depths to ionizing radiation with $h\nu > 1$ Ryd, they are presumed primarily neutral. Therefore the low-ion transitions should trace the kinematics of the hydrogen gas. Note that provided we restrict ourselves to unsaturated metal-line profiles and to global kinematic properties (e.g. the width of the profile in velocity space), the results we derive are independent of the low-ion transition used. Figure 1 presents our current complete sample of 40 low-ion DLA profiles. They are FeII, SiII, AlII,

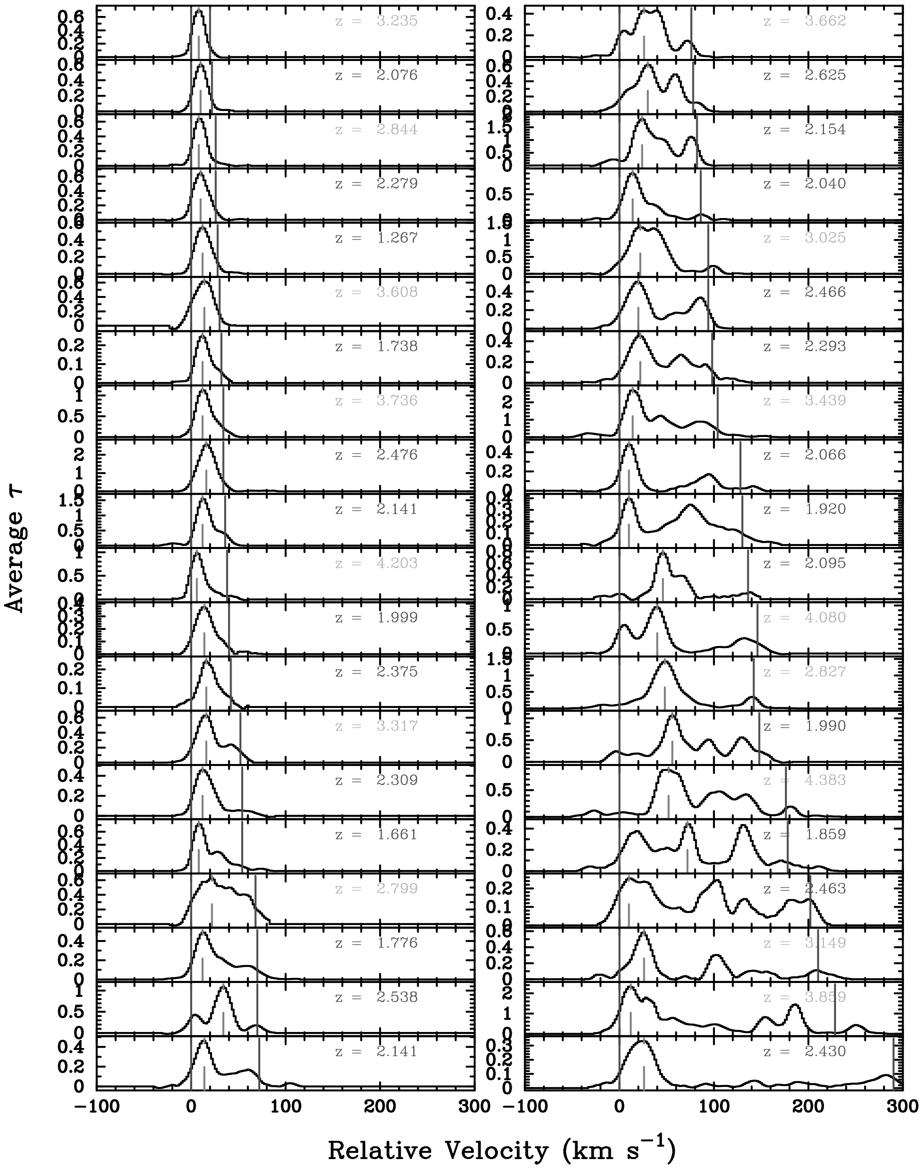

Figure 1. Average optical depth profiles of the 40 damped Lyα systems comprising our current empirical data set. The profiles exhibit a range of velocity widths and tend to show an edge-leading asymmetry. The dashed and solid vertical lines indicate the strongest feature and velocity width respectively. 23 of the profiles were reflected so that the strongest feature always lies toward $v = 0\ \mathrm{km\,s}^{-1}$.

NiII, and CrII profiles observed at high resolution (FWHM $\approx 8\,\mathrm{km\,s}^{-1}$) with HIRES on the W.M. Keck I 10m telescope.

Examining this empirical dataset, we characterize the kinematics of the DLA systems as follows. First, the systems exhibit a range of velocity widths, $\Delta v = 20$ to 300 km s^{-1} with a statistically significant tail out to at least 220 km s^{-1} . Second, the narrowest profiles are highly symmetric with the majority of absorption contained in a single component. Finally, profiles with $\Delta v >$ 40 km s^{-1} tend to show significant asymmetry with the majority of absorption occurring towards one edge of the profile. We refer to this profile characteristic as an 'edge-leading' asymmetry. To quantify these kinematic characteristics, we have introduced several test statistics which gauge the velocity widths and profile shapes in a rigorous fashion. In Figure 2, we plot three of the test statistics from Prochaska & Wolfe (1997) for [i] the full sample, [ii] a low redshift sample, $z_{low} = [1.5, 2.7]$ with median $\tilde{z}_{low} = 2.14$, [iii] a high redshift sample, $z_{high} = (2.7, 5]$ with $\tilde{z}_{high} = 3.44$, and [iv]−[vii] the four DLA models described below. Examining the empirical distributions we note: (1) the full sample exhibits a range of velocity widths from $20-300$ km s^{-1} with median ≈ 75 km s^{-1}, (2) the profiles yield nearly uniform distributions of the symmetry and edge-leading test statistics. (3) we find no significant differences over the three statistical tests when comparing the distributions for the two redshift cuts, i.e., no significant redshift evolution.

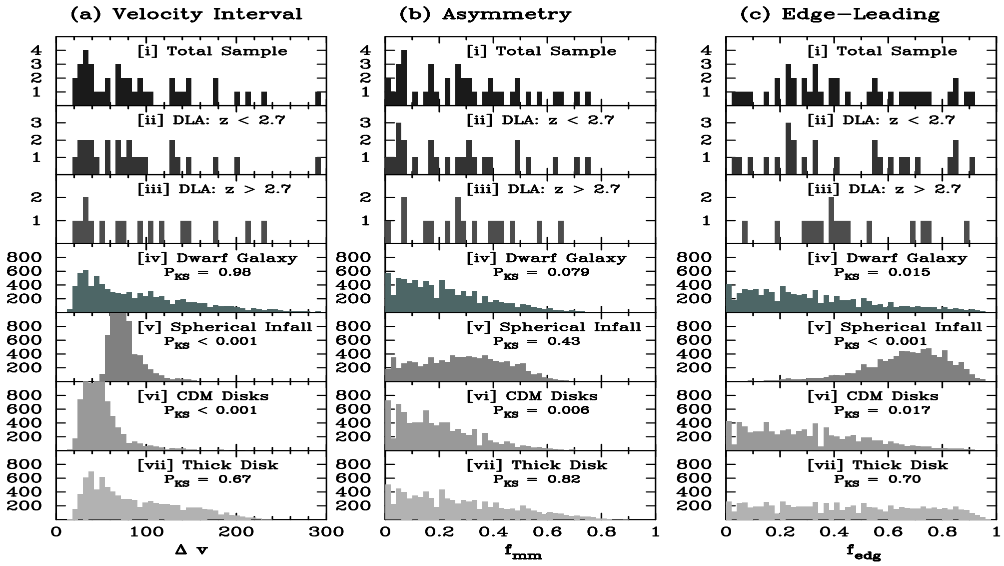

Figure 2. Plots of the kinematic characteristics for the damped Lyα systems for [i] the full sample, [ii] a low redshift sample, and [iii] the high redshift sample. Compare the empirical distributions with the best results for [iv] dwarf galaxy, [v] spherical infall, [vi] CDM, and [vii] thick disk models. The P_{KS} values were derived with the KS test by comparing the given model with the empirical distributions of [i].

We probe the physical nature of the DLA systems by comparing predictions from theoretical models with the empirical distributions presented in Figure 2. In our first analysis (Prochaska & Wolfe 1997), we concluded that velocity fields dominated by random motions (e.g. a dwarf galaxy model; [iv] in Figure 2) and spherical infall ([v] in Figure 2) are inconsistent with the DLA observations. In particular, these models cannot match the asymmetry and/or the 'edge-leading' characteristics of the empirical sample. Furthermore, we considered the semi-analytic predictions of Kauffmann (1996) for the DLA systems (model [vi]) within the CDM cosmology and found they are inconsistent with the DLA systems at $> 99.9\%$ c.l. In particular, if one assumes the systems are centrifugally supported disks (e.g. Mo, Mao, & White 1998), the CDM scenario vastly underpredicts the typical DLA low-ion velocity width irrespective of normalization, cosmological constant, and baryonic fraction (Jedamzik & Prochaska 1998). In turn, the only model we tested that is consistent with the observations, is a thick ($h > 0.1 R_d$) rotating disk model with typical rotation speed $v_{rot} \approx 200 \ \mathrm{km\,s^{-1}}$ ([vii] in Figure 2). Encouraged by these initial results, we considered disk models with more realistic physical properties (e.g. warping, photoionized edges, physical rotation curves) and demonstrated that the thick disk model is robust to the DLA observations, again provided $v_{rot} \approx 200 \ \mathrm{km\,s^{-1}}$ (Prochaska & Wolfe 1998). The problem remains, however, that the distribution of rotation speeds required to match the observations is similar to the present-day spiral distribution and in complete disagreement with CDM predictions at $z \approx 2$. Because these rotation speeds are very difficult to motivate cosmologically, it was important to further consider alternative models within the hierarchical cosmogonies.

Inspired by these results, Haehnelt et al. (1998) analyzed high resolution SPH numerical simulations of a small sample of DLA systems at high redshift. They found that the DLA systems in their simulations have kinematics resulting from a combination of infall, random motions and rotation in contrast to the assumption of pure rotation for the traditional semi-analytic models (SAM's). Furthermore, their results offered tentative evidence that the CDM cosmology is consistent with the DLA observations. Owing to the large expense of these high resolution simulations, however, the statistical significance of these results are limited. Recently, Maller et al. (this volume) have applied the UCSC SAM framework to the DLA observations. They find they can explain the DLA observations if the disk gas profile is very extended and one considers multiple subhaloes within a virialized halo. While the robustness of this DLA model remains to be fully addressed, it establishes a second working CDM model for the damped systems.

3. Future Investigation into the Physical Nature of the DLA Systems

Presented with three working models which may account for the low-ion DLA kinematics, we look to other observations and theoretical tests to distinguish between them as well as provide further clues to the processes of galaxy formation. We are pursuing the following avenues among others: (1) increase the high redshift low-ion sample to investigate the kinematic evolution at high redshift; (2) analyze the kinematics of the CIV gas associated with the DLA systems; and (3) perform a complete survey of $z > 3$ DLA systems in emission.

In terms of the low-ion kinematics, by increasing our high redshift sample we hope to robustly establish the evolution (if any) in the kinematic characteristics from $z = 2 - 4.5$. While the thick disk model is consistent with no kinematic evolution, the CDM scenarios need to be tested against these observations. We are currently pursuing our own numerical simulations using the Moving Mesh Hydro code developed by U. Pen to address exactly this issue. In addition, we will simulate a large number ($N > 100$) of protogalaxies at high resolution (≈ 1 kpc) to achieve the high statistical significance that previous studies lack.

An independent test of the DLA models can be made using observations of the high-ion (CIV) absorption lines arising in the DLA systems (Wolfe & Prochaska 2000). The CIV profiles are kinematically disjoint from the low-ion profiles and therefore provide unique kinematic information on the velocity fields of the DLA systems. For the CIV profiles, we examine kinematic characteristics similar to the low-ion analysis but also make use of correlations observed between the two ionization states. This treatment will place tight constraints on the models discussed here. For example, the observed correlation between the centers of the low and high-ion profiles may rule out the zeroth order model of a rotating disk within a symmetric dark matter halo.

Finally, we have begun a survey of the DLA systems in emission using the Lyman break technique (Steidel & Hamilton 1992). Djorgovski et al. (1996) have demonstrated that there are luminous galaxies associated with the DLA systems, yet their observational strategy has concentrated on only a few systems. Our goal is to image *every* $z > 3$ DLA QSO field and systematically follow-up every $R > 25.5$ dropout candidate. Not only do we aim to identify and examine the properties of the galaxies responsible for the DLA absorption, we will also study the clustering properties of the galaxies in the field. Therefore, we will address whether the DLA systems exhibit clustering properties similar to the Lyman break galaxies (Adelberger, this volume). Although our results will be based on significantly fewer systems than most Lyman break surveys, these observations will enable us to roughly determine the relative mass, star formation rate, dust content and luminosity function of the DLA and Lyman break galaxies.

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