Determining the Physical Nature of the Damped Lyα Systems by Investigating their Kinematic Characteristics

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Abstract. We report on our recent analysis on the physical nature of the damped Lyα systems. By comparing the observed kinematic properties of the damped systems with those predicted by a number of physical models, we have ruled out a number of the leading damped Lyα models. dynamics. [more] In the following, we present the new observations, summarize our techniques, and discuss and criticize the two leading models for the damped Lyα systems. In addition, we present high resolution radio and optical observations of a single damped Lyα system.

1. Introduction

The damped Lyα systems, thick layers of neutral gas observed in the spectra of background quasars, are widely believed to be the progenitors of modern galaxies (Wolfe 1995). Owing to their large neutral hydrogen column densities, they stand to be ideal targets for high redshift radio observations. Determining their physical nature remains a crucial step toward utilizing them to study the processes of galaxy formation and evolution. Over the past 3 years, we have initiated a project to analyze the kinematic characteristics of the damped Lyα systems to investigate their physical nature. The program requires very high resolution spectroscopy and has been performed entirely with HIRES on the 10m W.M. Keck Telescope. Our current data sample includes 31 damped profiles, half taken from observations performed by the Caltech group headed by W.L.W. Sargent. [Add]

In this brief report, we summarize the results of our first analysis (Prochaska & Wolfe 1997b; hereafter PW), comment on recent N-Body simulations (Haehnelt et al. 1997), and propose further observations and analysis. Finally, we contrast the kinematics of the 21cm profile of Q0458−02 with an optical depth profile taken with HIRES and discuss the observed differences.

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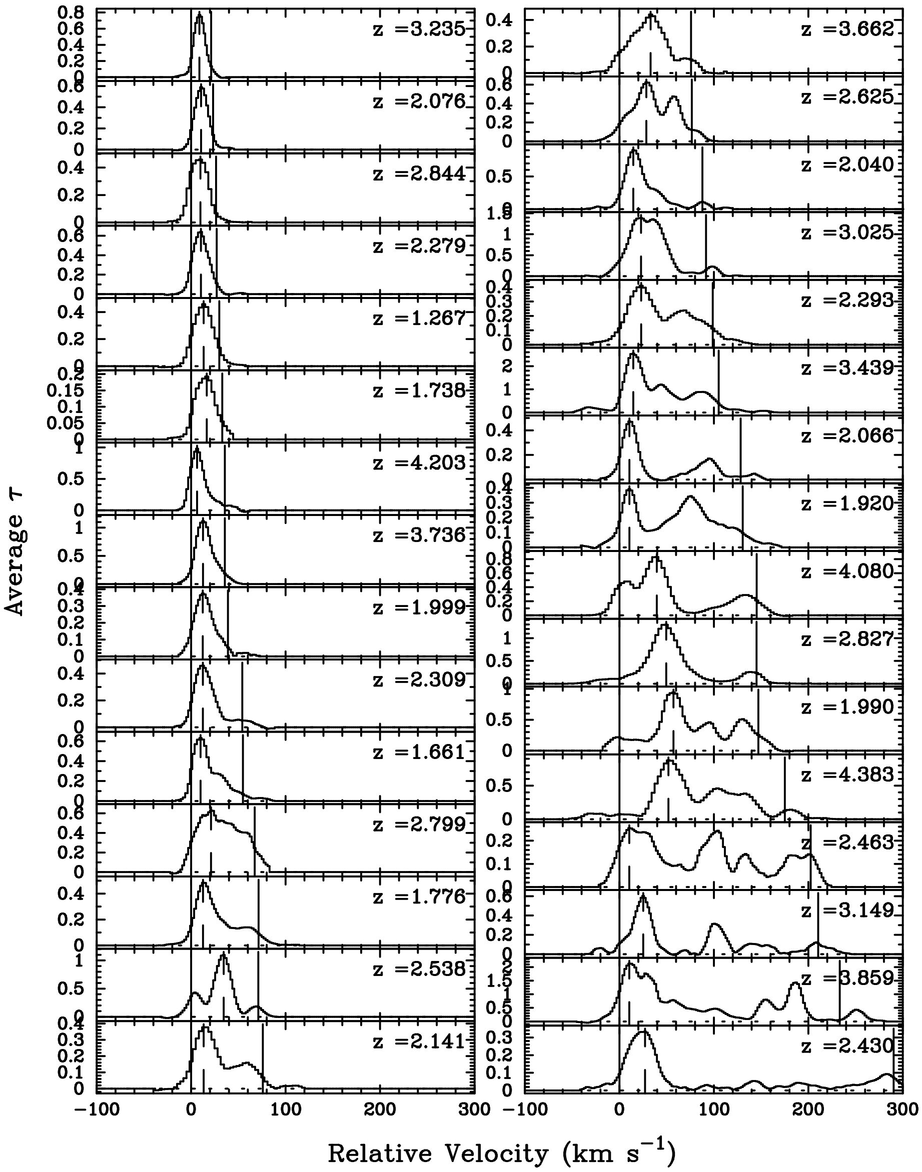

Figure 1. Average optical depth profiles of the 31 damped Lyα systems comprising our current empirical data set. The profiles exhibit a range of velocity widths and tend to show an edge-leading asymmetry. The dashed and solid vertical lines indicate the strongest feature and velocoity width respectively About half of the profiles were observed by the Caltech group headed by W.L.W. Sargent.

2. Observations

To date, over 35 damped Lyα systems have been observed with the High Resolution Echelle Spectrograph (HIRES) on the 10m W.M. Keck Telescope. In order to characterize the kinematics of these systems, we have focused on the low-ion transitions (e.g. Si II 1808, Fe II 1608) which arise from singly ionized metals like Si^+, Fe^+, Cr^+ and Zn^+. This is the dominant ionization state of these primarily neutral systems (Prochaska & Wolfe 1997a, Viegas 1995). Because the low-ion profiles from a single damped system trace one another very closely in velocity space (Prochaska & Wolfe 1996) the profiles exhibit almost exactly the same kinematic characteristics provided: (1) the transition is not so weak as to be dominated by noise and (2) the profile is not saturated.

Figure 1 plots the 31 damped Lyα profiles which comprise our current data sample. The curves are smoothed optical depth profiles and about one half have been reflected about $v = 0 \; \mathrm{km\,s^{-1}}$ such that the strongest feature always lies on the left of side of the profile. Inspecting Figure 1, we wish to note a few kinematic properties of the damped Lyα systems first recognized in the original sample of PW.

1. The velocity widths (Δv) of the profiles span from $\approx 20 - 300 \; \mathrm{km\,s^{-1}}$. The distribution peaks at $\Delta v \approx 50 \; \mathrm{km\,s^{-1}}$, but the tail out to $\Delta v = 300 \; \mathrm{km\,s^{-1}}$ is statistically significant.

2. The strongest feature tends to lie toward the edge of the profile. This is particularly true for profiles with $\Delta v > 30 \; \mathrm{km\,s^{-1}}$ where nearly 85% exhibit this edge-leading characteristic.

3. Those profiles which are edge-leading are also asymmetric in that the optical depth tends to decrease as v increases.

These characteristics are evidence that the velocity field in damped Lyα systems is dominated by systematic *not* random motions. Given this large sample of profiles, we can statistically compare these kinematic characteristics against predictions from physical models proposed for be damped systems.

3. Physical Models of Damped Systems: Disks or Clumps?

In PW, we compared 17 damped Lyα profiles with simulated profiles derived from a number of physical models proposed to describe the damped Lyα systems. The models investigated included: (1) slowly rotating disks embedded in low mass halos as predicted by the Standard Cold Dark Matter (SCDM) model and related hierarchical cosmologies (Kauffmann 1996); (2) the Bondi spherical accretion of gas onto pre-existing protogalaxies; (3) isothermal halos designed to mimic cloud motions in the halo of the Galaxy; or (4) dwarf galaxies in which random motions are comparable to the rotation speed of $v_{rot} \approx 50$ km s $^{-1}$, (5) thick rotating disks. We introduced several simple test statistics (e.g. the velocity width, Δv) to [compare] the simulated profiles derived from the damped Lyα models with the empirical profiles.

The results convincingly ruled out all but one of the models tested, including the SCDM disk model. The latter result is particularly important as this model was the leading model for damped Lyα systems within the SCDM cosmology. In a later study (Jedamzik & Prochaska 1998), we demonstrated the result is robust to CDM models with a range of normalizations and to disk models with a variety of parameters. On the other hand, we found [PW] the only model which accounts for both the distribution of velocity widths and exhibits the edge-leading asymmetry evident in the damped Lyα profiles is the thick rotating disk model. Furthermore the data required the typical rotation speeds $v_{rot} \approx 225$ km s^{-1} and that the disks are relatively thick ($h/R_d \approx 0.3$; where h is the vertical scale height and R_d is the radial scale length of the disk).

Since the publication of PW, we have nearly doubled the size of the empirical data set and have found all of our conclusions strengthened statistically (Prochaska & Wolfe 1998). In terms of the thick rotating disk model... In addition, another model has been introduced to explain the kinematics of the damped Lyα systems (Haehnelt et al. 1997). In stark contrast to the model proposed by Kauffmann and others, Haehnelt et al. (1997) suggest the damped Lyα systems are protogalactic clumps undergoing merging within a hierarchical cosmology. Specifically, they have performed high resolution ($\approx$ 1 kpc) SPH N-Body simulations (Steinmetz & Müller 1993) of a standard CDM cosmology and investigated the "clumps" which lead to damped Lyα systems. Where the Kauffmann model (i.e. disks in a SCDM cosmology) failed on account of predicting too few $\Delta v > 100$ km s^{-1}, the "clump" model succeeds in matching the Δv distribution observed for the first 17 damped systems analyzed. In the "clump" model, the profile widths result from an equal contribution of rotational, streaming, and random motions. The end result is that the median widths are $0.6 v_c$ (with v_c the circular velocity of a given dark matter halo), a factor ≈ 3 greater than the median width derived from pure rotation. [Mention how the asymmetry is explained]

Criticisims – Disk (1. Too simple, 2. Low z obs, 3. Dynamics) PGC (1. Too simple, 2. Djorgovski, 3. High ions, 4. N vs Δv)

[Table?]

4. Radio Observations

In a few cases we have both high resolution optical and radio observations of a single damped Lyα system. Comparing the 21cm line profile with the low-ion profiles reveals unique information on the kinematics of the system. Figure 2 shows the 21cm profile (Briggs & Wolfe 1985) and the Cr II 2056 low-ion profile of the $z = 2.040$ toward the radio loud quasar Q0458−02. Observe that the strongest feature in the radio profile does not correspond with that from the low-ion profile. What does this suggest about the kinematics of this system? The two sets of observations are clearly probing very different gas. One possibility is that the radio source is much larger than the optical source and therefore the radio observations provide an "average" measurement of the damped Lyα gas. On the other hand, the 21cm observations are biased toward colder gas. Therefore, the difference between the profiles may lie in the fact that the low-ion profile comes from an ISM-like warm cloud while the 21cm absorption arises in

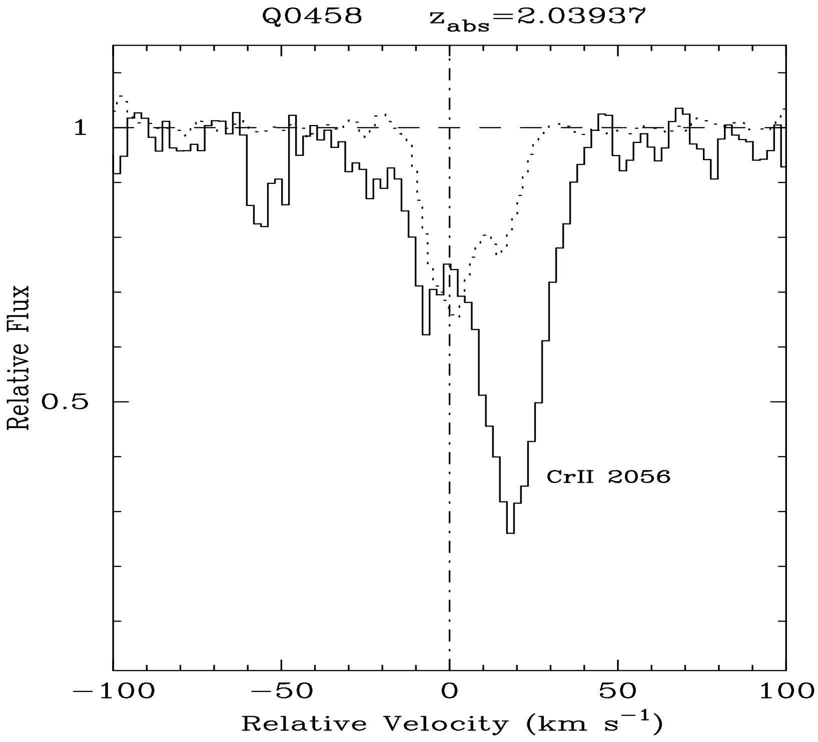

Figure 2. Radio vs Low-ion

cold clouds. In either case, the two observations offer independent measurements of the kinematics of the damped system and will be the focus of future studies.

Acknowledgments. I would especially like to thank W.L.W. Sargent and L. Lu for providing their HIRES spectra prior to publication.

References

Briggs, F.H., Turnshek, D.A., Schaeffer, J., and Wolfe, A.M. 1985, ApJ, 293, 387

Haehnelt, M.G., Steinmetz, M. & Rauch, M. 1997, astro-ph 9706201

Kauffmann, G. 1996, MNRAS, 281, 475

Jedamzik, K. & Prochaska, J. X. 1998, MNRAS, in press (astro-ph 9706290)

Prochaska, J. X. & Wolfe, A. M. 1996, ApJ, 470, 403

Prochaska, J. X. & Wolfe, A. M. 1997a, ApJ, 474, 140

Prochaska, J. X. & Wolfe, A. M. 1997b, ApJ, 486, 73 [PW]

Prochaska, J. X. & Wolfe, A. M. 1998, ApJ, submitted

Steinmetz, M., & Müller, E. 1993, A&A, 268, 391

Viegas, S.M. 1994, MNRAS, 276, 268

Wolfe, A. M. 1995, in *ESO Workshop on QSO Absorption Lines*, ed. G. Meylan, (Berlin:Springer-Verlag), p. 13