Making Damped Lyman-α Systems in Semi-Analytic Models

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Abstract. The velocity profiles of weak metal absorption lines can be used to observationally probe the kinematic state of gas in damped Lyman-α systems. Prochaska and Wolfe [?] have argued that the flat distribution of velocity widths (Δv) combined with the asymmetric line profiles indicate that the DLAS are disks with large rotation velocities (∼200 km/s). An alternative explanation has been proposed by Haehnelt, Steinmetz, and Rauch (HSR) [2], in which the observed large velocity widths and asymmetric profiles can be produced by lines of sight passing through two or more clumps each having relatively small internal velocity dispersions. We investigate the plausibility of this scenario in the context of semi-analytic models based on hierarchical merging trees and including simple treatments of gas dynamics, star formation, supernova feedback, and chemical evolution. We find that all the observed properties of the metal-line systems including the distribution of Δv and the asymmetric profiles, can be reproduced by lines of sight passing through sub-clumps that are bound within larger virialized dark matter halos. In order to produce enough multiple hits, we find that the cold gas must be considerably more extended than the optical radius of the proto-galaxies, perhaps even beyond the tidal radius of the sub-halo. This could occur due to tidal stripping or supernova-driven outflows.

INTRODUCTION

Damped Lyman alpha systems (DLAS), by probing the gas content of the universe at high redshift, are powerful observational probes to study galaxy formation and evolution. Until recently the observations of DLAS included the differential density distribution f(N), its evolution with redshift, and the metalicity of the absorbers [3]. Many authors have shown that hierarchical cosmologies with models of galaxy formation can match this data. Most notable is the work of Kauffmann [4] which uses semi-analytic models (SAMs) to match f(N) and its evolution with redshift, and at the same time reproduces many features of galaxies observed locally in emission. A general prediction of Kauffmann’s models is that the galaxies
producing DLAS will typically be smaller than galaxies today.

Prochaska and Wolfe [1,5], hereafter PW, introduced new data by studying the kinematic properties of DLAS as deduced from high resolution spectroscopy of their weak metal lines. They found that DLAS seem to have a wide range of velocity widths, and are asymmetric in velocity space. The only model they tried that could explain this had thick disks with rotational velocities $\sim 220 \text{ km s}^{-1}$, which is incompatible with what is expected in models of hierarchical structure formation at the typical redshifts $z \sim 3$ of these observed DLAS. PW excluded the hierarchical single-disk model of Kauffmann.

Recently HSR showed using hydrodynamic simulations and the Press-Schechter approximation that this seeming incompatibility can be reconciled if the DLAS come from merging proto-galactic clumps. Then the DLAS are composed of a few objects, and the large velocity widths come from the motions of these objects within a larger dark matter halo. McDonald and Miralda-Escudé [6] have tested this in an analytic model. We set out to investigate if such a model is feasible in the context of SAMs, which have allowed us to include star formation and feedback, and ultimately to include also a wider range of CDM-type cosmological models.

THE SEMI-ANALYTIC MODELS

SAMs and hydrodynamical simulations have their individual strengths and weaknesses. Hydrodynamical simulations include gas dynamics and gravitation, but this makes them computationally expensive and thus limited in their ability to explore parameter space or even get adequate statistics from the small volume simulated at high resolution. Also because of this it can be difficult to understand in simple terms what is going on in the simulation. Thus while HSR showed that their model is consistent with the PW kinematic data, they only simulated one cosmology and they did not include feedback or metal production.

In contrast, SAMs attempt to capture the most essential aspects of galaxy formation, in a simplified manner. Thus instead of following the gravitational motion of particles a merger history is assigned statistically to a halo. Gas cooling, star formation, and feedback are treated by simple equations. The fact that SAMs are capable of matching many observations suggests that these simpler treatments are successful in reproducing the essential features of galaxy formation. We use the SAMs of Somerville and Primack [7] and Somerville, Primack and Faber (SPF) [8], which are similar to the work of Kauffmann [4].

In particular, we use the fiducial model of SPF, which reproduces the observed number densities of the Lyman break galaxies and $\Omega_{\text{gas}}(z)$ and metallicities $Z(z)$ measured from DLAS. In previous work such as PW’s analysis of the results of Kauffmann, it was assumed that each observed velocity width arose from the internal rotation velocity of a single disk. The main new feature here is that we explicitly investigate the implications of the substructure in the matter halos for the metal-line kinematics, and different ways of distributing gas within the proto-
Table 1: Five models of the gas distribution and their KS test results

| Model | radial profile | normalization | $\Delta V$ | $f_{mm}$ | $f_{edg}$ | $f_{tpk}$ |
|-------|----------------|---------------|------------|----------|-----------|-----------|
| 1     | $e^{-R}$ | $R_{gas} = R_{disk}$ | 0.001 | 0.008 | 0.001 | 0.001 |
| 2     | $e^{-R}$ | $R_{gas} = 7R_{disk}$ | 0.001 | 0.046 | 0.34 | 0.058 |
| 3     | $1/R$ | $N = 0.59V_c/R$ | 0.001 | 0.004 | 0.001 | 0.001 |
| 4     | $1/R$ | $R_{trunc} = 2R_{tidal}$ | 0.001 | 0.350 | 0.24 | 0.013 |
| 5     | $1/R$ | $log_{10}(N_{trunc}) = 19.3$ | 0.51 | 0.080 | 0.20 | 0.66 |

galaxies. If we are to reproduce the kinematics of DLAS then, the large velocity widths must come from a combination of the rotational motion of the gas and the relative motion between the objects in one halo.

**MAKING THE DLAS**

We analyze SCDM ($\Omega_{\text{matter}} = 1$, $\sigma_8 = 0.67$) with the star formation and feedback described in SFP’s fiducial model at a redshift of 3.2. This gives us the number of satellites in a given halo, their distances from the central object, and the amount of cold gas in each object. We position the satellites in the halo randomly in angle along circular orbits. The only quantity not specified by the SAMs is how the cold gas is distributed in each galaxy. We construct five models for the radial distribution of the gas, to explore how the radial profiles affect the observed kinematics (Table 1). We distribute the gas with an exponential of isothermal radial profile $N(R)$, and different normalizations. We compare these models to the data by passing random lines of sight through a given halo, with each halo weighted by the probability of encountering that halo as determined by the Press-Schechter formalism. Those lines of sight that intersect cold gas in excess of $2 \times 10^{20}$ cm$^{-2}$ are labeled as DLAS. Then the kinematics of these systems are investigated by assuming the gas disks have metallicities given by the SAMs and a scale height of one tenth the stellar disks scale length. Spectra are simulated and then analyzed by the same four statistics as the data was in PW, the velocity width $\Delta V$, the mean to median test $f_{mm}$, the edge leading test $f_{edg}$, and the two peak test $f_{tpk}$. We also check to see that we are getting a reasonable distribution of column densities $f(N)$ (Figure 1a). All models but the first and third fit the DLAS $f(N)$ reasonably well.

**CONCLUSIONS**

Of the models we explore only the last model comes close to matching all of PW’s kinematic data, according to the results of a Kolmogorov-Smirnov test (Table 1). The radial extent of the gas in this model is larger than the other models (Figure 1b) and this leads to its producing more multiple hits along a given line of sight than any other model.
In fact the gas extends out beyond the tidal truncation radius (the limit of the fourth model), where it would no longer be gravitationally bound. However, our method of calculating the tidal radius is only approximate, and the large radial extent of the gas can perhaps alternatively be interpreted as due to stripping or outflow. If the gas is stripped away by ram-pressure stripping, or ejected from the small proto-galaxies by supernovae, it may still cover an equivalent amount of area, just not as a disk. We are investigating this more thoroughly.

Our main conclusion is that it is possible to produce the observed kinematic properties of DLAS in SAMs based on CDM-type models by having lines of sight pass through multiple objects in the same halo; however, this requires that the cold gas in these proto-galaxies be rather large in radial extent.

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