Damped Ly$\alpha$ Systems in Semi-Analytic Models:
Sensitivity to dynamics, disk properties, and cosmology.

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1. Introduction

Previously (Maller et al. 1999, hereafter MSPP) we have shown that it is possible to account for the kinematic properties of damped Lyman alpha systems (DLAS) as measured by Prochaska & Wolfe (1997, 1998, hereafter PW97 and PW98) in the context of semi-analytic models (SAMs) (Somerville & Primack 1999, hereafter SP99). In these models, hierarchical structure formation is approximated by constructing a merger tree for each dark matter halo. A natural consequence is that every virialized halo may contain not only a central galaxy, but also a number of satellite galaxies as determined by its merging history. Thus the kinematics of the DLAS arise from the combined effects of the internal rotation of gas disks and the motions between gas disks within a common halo. Here we investigate the sensitivity of this model to some of the assumptions made in MSPP, including the modeling of satellite dynamics, the scale height of the gas, and the cosmology.

2. Satellite Dynamics

In the SAMs, a merger tree represents a halo’s growth through the mergers of smaller halos (see Somerville 1997). When halos merge, the central galaxy of the largest progenitor halo becomes the central galaxy of the new halo, and all other galaxies become satellites. These satellites then fall in towards the central galaxy due to dynamical friction, and eventually merge with it (see SP99). Because the treatment of the dynamics of the satellites is necessarily simplified in the usual semi-analytic spirit, and since the kinematics of the DLAS arise from both the rotation of disks and the motions of satellite galaxies in the common halo, it is important to test whether our results are sensitive to the details of our modeling.
Figure 1. A halo of circular velocity 156 km s\(^{-1}\) with its satellite galaxies. The ellipses mark where the cold gas is truncated, in Model A (left) with thin disks and Model B (right) with thicker disks. The dashed line is the virial radius of the parent halo.

In the models presented in MSPP, all satellites were assumed to start falling in from the virial radius of the newly formed halo, and all satellites were assumed to be on circular orbits. These assumptions will tend to maximize the dynamical friction timescale of the satellites, and correspond to the assumptions made in some earlier versions of the SAMs (e.g. Somerville 1997). In the models presented here, we have modified these assumptions in two ways. We initially place the satellites at one half of the virial radius, and assign the orbits from a random distribution as observed in N-body simulations by Navarro, Frenk, & White (1995). They found that the “circularity” parameter \( \epsilon \) has a flat distribution, where \( \epsilon \equiv J/J_c \) is defined as the ratio of the angular momentum of the satellite to that of a circular orbit with the same energy. The dynamical friction time scale is then scaled by a factor \( \epsilon^{0.78} \) (Lacey & Cole 1993). This causes some of the satellites to fall in faster than in our previous modeling. In addition, we have changed from the SCDM cosmology used in MSPP to a more fashionable \( \Omega_0 = 0.4, \Omega_\Lambda = 0.6 \) cosmology. These ingredients are compatible with the models that were shown to produce good agreement with both local galaxy observations (SP99) and the high redshift Lyman-break galaxies (Somerville, Primack, & Faber 1999).

We find that the combined effect of these changes has a negligible effect on our results. Although we do see fewer satellites within a halo of a given mass, the number of satellites in the inner part of the halo is similar. These are the satellites most likely to give rise to multiple hits, which as we argued in MSPP is the crucial factor in matching the observed kinematics of the DLAS. As in MSPP, we still find that the gaseous disks must have very large radial extents in order to match the observations.

3. Disk Thickness

Another important feature of the models is the assumed distribution of the gas within the disks. In MSPP, we investigated several radial profiles and obtained
Model vertical scale height normalization $\Delta V_{\text{sym}}$ $t_{\text{edg}}$ $t_{\text{pk}}$
\hline
A & $0.1R_*$ & $\log N_t = 19.3$ & 0.35 & 0.10 & 0.56 & 0.26 \\
B & $0.5R_*$ & $\log N_t = 19.6$ & 0.41 & 0.24 & 0.54 & 0.71 \\
\hline

Table 1. The properties of our two models and the KS probabilities for the four statistics of PW97.

The best results with an assumed gas distribution of the form

$$n(R, z) = \frac{N_t R_t}{2h_z R} \exp\left(-\frac{|z|}{h_z}\right) \quad (R < R_t)$$

where the truncation density $N_t$ is an adjustable parameter. The vertical scale height of the gas disks is another uncertainty. In MSPP we assumed it to be one tenth of the stellar disk scale radius, i.e. $h_z = 0.1R_*$ where $R_*$ is the stellar disk scale length as given by the SAMs (see SP99). Because the gas disks in the successful models tend to have a large radial extent, much larger than the stellar disk, this leads to very thin gaseous disks. When the scale height is increased to half the stellar scale radius ($h_z = 0.5R_*$), we are able to use more physically plausible values for the truncation density $N_t$ (see Table 1), and the gas disks are now typically contained within the truncation radius of the dark matter sub-halos surrounding the satellites. This model therefore seems to be more physical, yet still produces good agreement with all four of the diagnostic statistics of PW97 (see Table 1). Note that PW98 have shown that the effect of including a warp in the gas disk is the same as increasing its thickness, so our exploration of thicker disks can also be thought of as including warps in the disk.

Figure 2 shows the distribution of thicknesses and inclinations for the disks that contribute to DLAS in the two models. We find that the disks that produce damped systems in model B are more likely to have a face-on geometry. With thinner disks, more of the cross section comes from an inclined geometry as $n \sim h_z^{-1}$. The total cross section in the two models is roughly the same; in model A, more of it comes from extended highly inclined disks, while in model B, denser, face-on disks are more important.

Thus the need for gas disks with large radial extent can be reduced by using thicker disks, though not by a large amount. Increasing the thickness by a factor of five only reduces the radial truncation value by 30%. The gaseous disks in model B are still quite large compared to the stellar component.

4. Conclusions

In MSPP we argued that the observed kinematics of DLAS can be reproduced in hierarchical models if a significant fraction of the lines of sight pass through multiple disks orbiting within a common dark matter halo. However, we found that in order to obtain a high enough cross section for multiple hits, we had to assume very large radial extents for the gaseous disks in our models. We have tested the robustness of these conclusions by modifying several of the uncertain ingredients of our models. We find that modifying the dynamical friction
timescale of the satellites by assuming a different initial radius or orbit has a small effect on our results. Similarly, our results do not seem to be sensitive to the assumed cosmology. Increasing the vertical scale height of the disks has a larger effect and leads to models that are more physically plausible and still produce good agreement with the diagnostic statistics of PW. Our results suggest that in order to reconcile the observed kinematics of DLAS with hierarchical theories of structure formation, gaseous disks at high redshift must be large in radial extent and thickened or warped. The physical cause of these properties remains obscure, however we speculate that tidal encounters or outflows could be responsible.

References

Lacey, C. & Cole, S. 1993, MNRAS, 262, 627

Maller, A. H., Somerville, R. S., Prochaska, J. X., & Primack, J. R. 1999, in After the Dark Ages: When Galaxies were Young, ed. S. Holt & E. Smith (AIP Press), 102

Navarro, J. F., Frenk, C. S., & White, S. D. M. 1995, MNRAS, 275, 56

Prochaska, J. X. & Wolfe, A. M. 1997, ApJ, 487, 73

——. 1998, ApJ, 507, 113

Somerville, R. S. 1997, PhD thesis, Univ. California, Santa Cruz

Somerville, R. S. & Primack, J. R. 1999, MNRAS, accepted, astro-ph/9802268

Somerville, R. S., Primack, J. R., & Faber, S. M. 1999, MNRAS, accepted, astro-ph/9802268