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ON THE EVOLUTION OF DAMPED Lyα SYSTEMS TO GALACTIC DISKS

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ABSTRACT

The mean metallicity of the thick disk of the Galaxy is 0.5 dex higher than that of the damped Lyα systems. This has been interpreted to argue that stars in the former do not arise out of gas in the latter. Using new metallicity and H I column density data, we show that metal-rich damped systems do contain sufficient baryons at the thick-disk metallicity to account for the stellar masses of thick disks. Comparing our kinematic data with the metallicities, we show that damped Lyα systems exhibiting the largest profile velocity widths, Δv, span a narrow range of high metallicities, while systems with small Δv span a wider range of metallicities. This is naturally explained by the passage of the damped Lyα sight lines through rapidly rotating disks with negative radial gradients in metallicity. The systematically lower N(H I) of systems with high Δv indicates (1) that the gaseous disks have centrally located holes and (2) an apparent inconsistency with the protogalactic clump model for damped Lyα systems. The higher metallicity of systems with low N(H I) further implies that stars rather than gas dominate the baryonic content of the most metal-rich damped systems.

Subject headings: cosmology: miscellaneous — galaxies: evolution — quasars: absorption lines

1. INTRODUCTION

The collapse of a spheroidal protogalaxy to the centrifugally supported disk of the Galaxy was inferred from correlations between the metallicities and the kinematics of old stars in the solar neighborhood (Eggen, Lynden-Bell, & Sandage 1962). But subsequent studies have not sorted out the sequence of events leading to the formation of stellar populations comprising the halo, the thick disk, and the thin disk (see, e.g., Majewski 1993). The damped Lyα absorption systems, a population of H I layers widely believed to be the gaseous progenitors of current galaxies (see Wolfe 1995), provide an independent perspective for studying these events because (1) they occur in objects comprising the bulk of the galaxy population at high redshifts and (2) the ranking of redshifts yields an unambiguous time sequence. Detected in the redshift interval $z = [0,\ 4.5]$, the damped Lyα systems trace the evolution of neutral gas in galaxies from their protogalactic phase to the present. However, the chemical properties of the gas may be incompatible with those of existing stellar populations. At $z = [1.6,\ 4.5]$, the metallicity of the gas is low compared with the thin disk metallicity (Pettini et al. 1997), indicating that stars in the thin disk do not arise directly from high-z damped systems (Lanzetta et al. 1995). The possible enhancement of alpha-rich elements suggests that the gas gives rise to halo stars (Lu et al. 1996), but the kinematics of the gas are inconsistent with this hypothesis (Prochaska & Wolfe 1997). More recently, Pettini et al. (1997) argued that the metallicities of the damped systems are too low to explain the thick disk (Gilmore et al. 1989; Carney et al. 1996).

In this Letter we reconsider the scenario in which star formation in damped Lyα systems results in the formation of the thick disk. Combining metallicities and column densities with new kinematic data obtained with the Keck I 10 m telescope, we suggest a plausible scenario in which the thick disk forms out of damped Lyα gas.

2. COSMIC METALLICITY DEPENDENCE ON BARYON DENSITY

We wish to find out whether the mass content and metal abundances of gas in damped Lyα systems can account for the mass density and metallicities of thick stellar disks. Let us define the cosmic metallicity $\langle \mathcal{Z} \rangle \equiv \Omega_{\rm metals}/\Omega_g$, where $\Omega_{\rm metals}$ and Ω_g are the comoving densities of metals and neutral gas in damped Lyα systems (Lanzetta, Wolfe, & Turnshek 1995). Let the number of damped systems in the metallicity and column density intervals $(Z',\ Z' + dZ')$ and $(N,\ N + dN)$ be given by $h(Z', N)dZ'dN$. The latter is related to the frequency distribution of H I column densities by $f(N) = \int h(Z', N)dZ'$ (Lanzetta et al. 1995), and the frequency distribution of metallicities by $g(Z') = \int h(Z', N)dN$. Suppose $h(Z', N)$ spans the metallicity interval $Z' = [Z_{\rm min}, Z_{\rm max}]$ and column density interval $N = [N_{\rm min}, N_{\rm max}]$, and $\Omega_g(Z)$ is the density of damped Lyα baryons in the metal-rich subinterval $Z' = [Z, Z_{\rm max}]$. Then $\Omega_g(Z)$ and the corresponding $\langle \mathcal{Z}(Z) \rangle$ are given by

$$\Omega_g(Z) = \Omega_g \frac{\int_{Z_{\rm max}}^{Z} dZ' \int_{N_{\rm min}}^{N_{\rm max}} dN N h(Z', N)}{\int_{Z_{\rm max}}^{Z_{\rm min}} dZ' \int_{N_{\rm min}}^{N_{\rm max}} dN N h(Z', N)}\,, \tag{1}$$

$$\langle \mathcal{Z}(Z) \rangle = \frac{\int_{Z_{\rm max}}^{Z} dZ' \int_{N_{\rm min}}^{N_{\rm max}} dN Z' N h(Z', N)}{\int_{Z_{\rm max}}^{Z} dZ' \int_{N_{\rm min}}^{N_{\rm max}} dN N h(Z', N)}\,, \tag{2}$$

where the order of Z integration is reversed. In the discrete limit $h(Z', N) = \sum_i \delta(Z' - Z_i)\delta(N - N_i)$, where the sum extends over all the N_i, Z'_i pairs in the sample. As a result,

$$\Omega_k = \Omega_g \frac{\sum_{i=1}^{k} N_i}{\sum_{j=1}^{i_{\rm min}} N_j}\,, \quad \langle \mathcal{Z}_k \rangle = \frac{\sum_{i=1}^{k} N_i Z'_i}{\sum_{j=1}^{k} N_j}\,, \tag{3}$$

where the indices $i = 1$, k, and $i_{\rm min}$ correspond to $Z_{\rm max}$, Z, and $Z_{\rm min}$. Because the sums in equation (3) are over an array of damped Lyα gas layers ordered according to *decreasing* metallicity, $\langle \mathcal{Z}(Z) \rangle$ decreases with *decreasing* Z while $\Omega_g(Z)$ increases. We can determine $\Omega_g(Z)$ corresponding to the mean

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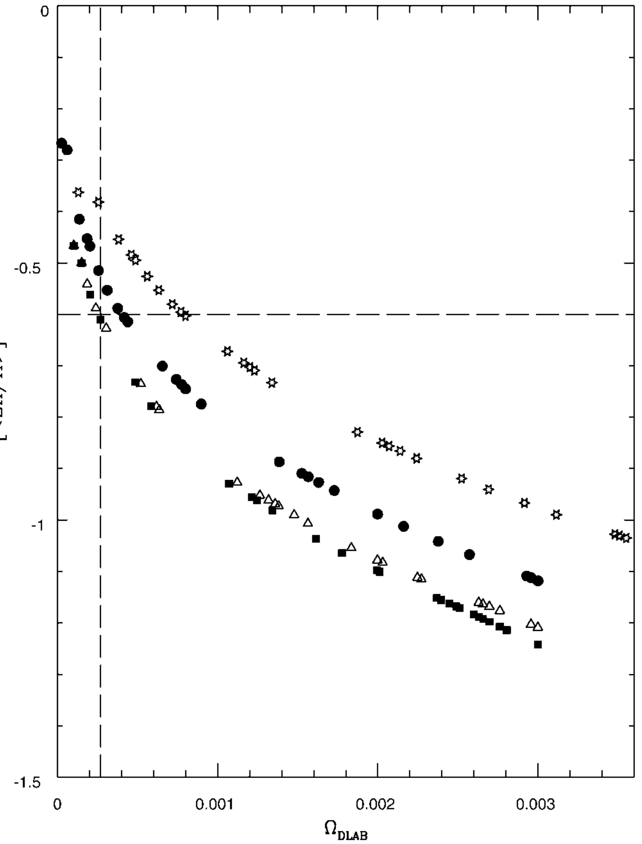

FIG. 1.—Log of mean cosmic metallicity vs. the comoving density of damped Lyα baryons for damped systems with metallicities $Z' = [Z, Z_{\rm max}]$. Circles computed assuming upper limits equal true values of [Zn/H]. Triangles and squares computed assuming upper limits minus 0.5 and 1.0 equal true values of [Zn/H]. In latter cases all baryons are assumed to be gas. Thus, eq. (3) is used to compute $\Omega_{\rm DLAB}(Z) = \Omega_k$ and $[\langle {\rm Zn/H} \rangle] = \log(\langle \mathcal{Z}_k \rangle / Z_\odot)$. Stars include correction for the presence of baryons in stars. In this case, eqs. (4)–(6) are used to compute $\Omega_{\rm DLAB}(Z)$ and $[\langle {\rm Zn/H} \rangle]$. Vertical and horizontal dashed lines correspond to cosmic density and metallicity of the thick stellar disk.

metallicity of the thick disk, provided the latter is less than $Z_{\rm max}$.

To determine $\langle \mathcal{Z}(Z) \rangle$ as a function of $\Omega_g(Z)$, we turn to the [Zn/H], N(H I) pairs that Pettini et al. (1997) acquired for 34 damped systems, where $Z = Z_\odot 10^{[{\rm Zn/H}]}$. We focus on Zn rather than Fe as a metallicity indicator, because this is the largest recorded sample of damped Lyα metal abundances, and Zn is less depleted than Fe by dust that may be present (Fall & Pei 1993). We select the 27 pairs in the redshift range $z = [1.6,\ 3.0]$. Systems with $z > 3.0$ are excluded, since the metallicities in this redshift range are systematically lower than those of the thick disk. The sample comprises 16 systems with detected [Zn/H] and 11 with upper limits. Two of the detections, which come from our Keck HIRES observations, replace the upper limits of Pettini et al. (1997).

We used equation (3) to determine the points in Figure 1, which plots $[\langle {\rm Zn/H} \rangle]$ $[\equiv \log(\mathcal{Z}_k/Z_\odot)]$ versus Ω_k for $k = [1, i_{\rm min}]$. We let $\Omega_g = 0.003$, the value inferred by Storrie-Lombardi & Wolfe (1998) in the redshift interval $z = [1.8,\ 3.5]$ for $H_0 = 50$ km s^{-1} Mpc^{-1} (which is adopted throughout this Letter). The circles were computed by letting the upper limits equal the true values of [Zn/H]. In this case $\Omega_g(Z) = 0.0004$ when $[\langle {\rm Zn/H} \rangle] = -0.6$, the mean metallicity of the thick disk (Carney et al. 1986). The triangles and squares were computed by equating the upper limits minus 0.5 and 1.0 with the true values of [Zn/H]. In both cases $\Omega_g(Z) \approx 0.0003$ when $[\langle Zn/H \rangle] = -0.6$, indicating that the result is robust. Assuming bulges and disks contribute equally to the density of visible matter (Schechter & Dressler 1987), which is given by 0.0054 (Gnedin & Ostriker 1992), and that the mass of the thick disk is 0.1 times that of the thin disk (Majewski 1993), we find the thick-disk mass density, $\Omega_{\rm thick} = 0.00027$. Although the error bars associated with $\Omega_{\rm thick}$ are of order 50%, it is reasonable to conclude that the damped Lyα systems contain sufficient baryons to account for the masses of thick stellar disks (see Fig. 1).

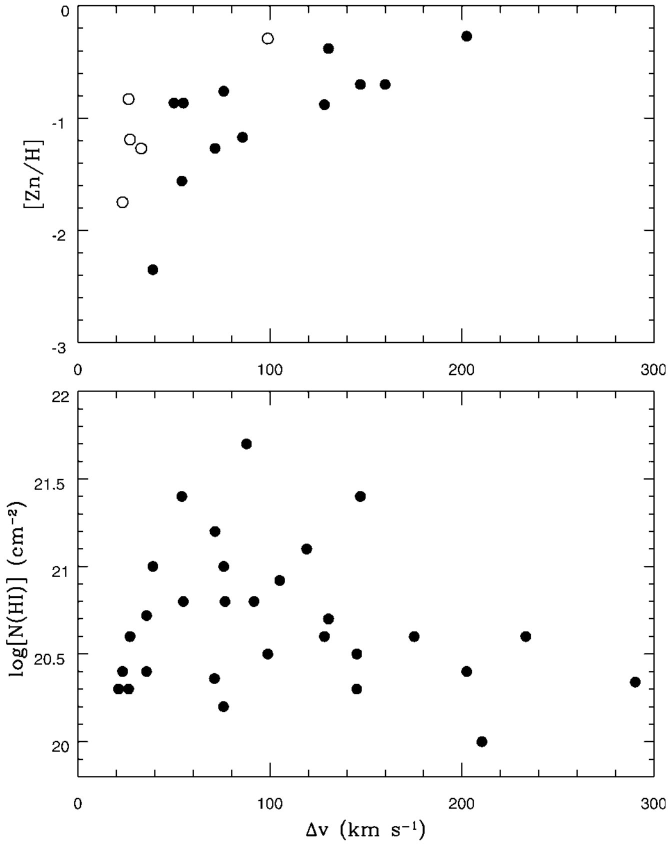

FIG. 2.—*Top*: metallicity vs. Δv for damped systems with $z = [1.6,\ 3.0]$. Filled and empty circles correspond to detections and upper limits. *Bottom*: log N(H I) vs. Δv.

3. KINEMATICS, METALLICITIES, AND STARS

To learn more about the metal-rich damped systems, we turn to the kinematics of the gas. Analysis of the velocity profiles of weak metal lines in over 30 damped Lyα systems shows the frequency distribution of profile velocity widths, Δv, and other statistics that test for asymmetries exhibited by the profiles are consistent with absorption by thick disks with rotation speeds $v_{\rm rot} \approx 250$ km s^{-1} (Prochaska & Wolfe 1997). The CDM simulation of Haehnelt, Steinmetz, & Rauch (1998), in which infall, random motions, and rotation of protogalactic clumps contribute equally to Δv, may be likewise consistent. Here we focus on rotating disks.

Figure 2 (*top*) plots 17 [Zn/H], Δv pairs drawn from our kinematic sample with $z = [1.6,\ 3.0]$. The figure shows that systems with high Δv and low metallicity are *not* detected in this redshift range. Specifically, metallicities $[{\rm Zn/H}] < -1.0$ are

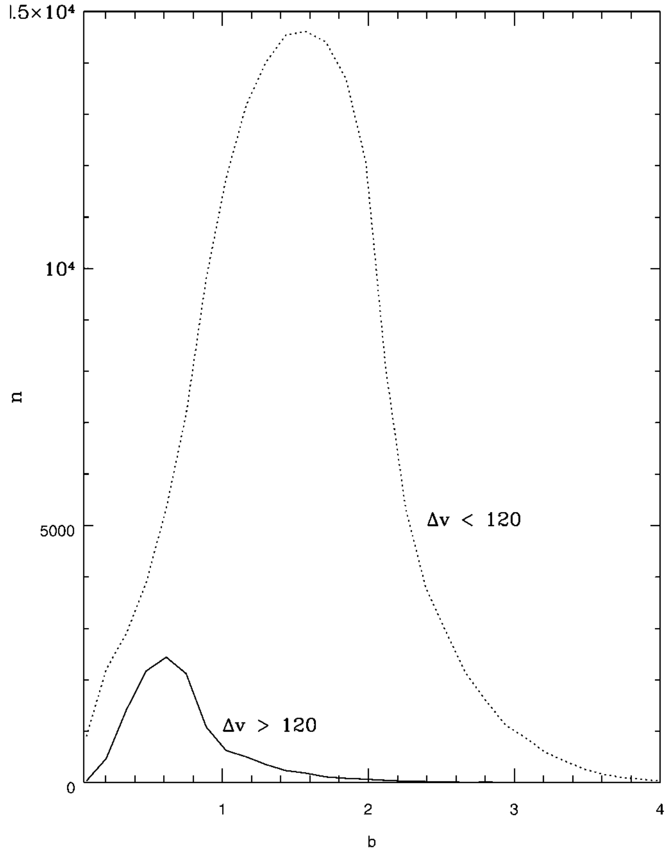

FIG. 3.—Distribution of impact parameters resulting from the numerical simulation described in text. Solid curve corresponds to impacts leading to $\Delta v > 120$ km s^{-1}, and the dotted curve to $\Delta v < 120$ km s^{-1}. Impact parameters in units of radial scale length, R_d.

absent in all five systems with $\Delta v > 120$ km s^{-1} but present in 7 out of 12 systems with $\Delta v < 120$ km s^{-1}. The effect is real and is not an artifact due to observational selection, since systems with high Δv and low metallicity are detected at $z > 3.0$. Nor is dust likely to be a contributing factor, since dust would remove the metal-rich rather than metal-poor systems missing from Figure 2 (*top*). The reality of this effect is further supported by its presence in a [Fe/H] versus Δv diagram. We also find possible evidence for a correlation between [Zn/H] and Δv, exceeding 3.5 σ significance when the true [Zn/H] equals the upper limits minus 1.0.

The systematic pattern in Figure 2 (*top*) can be explained by negative radial gradients in metallicity. Monte Carlo simulations of absorption profiles produced by sight lines penetrating randomly oriented disks indicate that a necessary condition for large Δv is a small impact parameter. This is evident in Figure 3, which plots the distribution of impact parameters, b (where b is in units of radial scale length, R_d, of an assumed exponential gas distribution), resulting from simulating identical exponential disks with rotation speed $v_{\rm rot} = 250$ km s^{-1} and vertical scale height $h = 0.3R_d$. Whereas 86% of impacts leading to $\Delta v > 120$ km s^{-1} are confined to $b < 1$, 1% are at $b > 2$. Therefore, the absence of low metallicities at $\Delta v >$ 120 km s^{-1} requires high element abundances at small radii. On the other hand, 26% of impacts leading to $\Delta v < 120$ km s^{-1} are at $b < 1$, while 16% are at $b > 2$. The wide range of impact parameters can explain the broader distribution of metallicities at $\Delta v < 120$ km s^{-1}, if impacts at large b yield low metallicities, i.e., if metallicity decreases with radius. None of these results change significantly when we use a more realistic model in which $v_{\rm rot}$ is drawn from a distribution of rotation speeds characterizing present-day spiral galaxies.

Damped Lyα systems with large Δv also exhibit systematically lower N(H I). This is shown in Figure 2 (*bottom*), which plots log N(H I) versus Δv for 29 damped Lyα systems drawn from our kinematic sample. Whereas 1 out of 10 systems with $\Delta v > 120$ km s^{-1} has log N(H I) > 20.6, 12 out of 19 systems with $\Delta v < 120$ km s^{-1} have log N(H I) > 20.6. Figure 2 (*bottom*) includes systems with $z > 3.0$, because the effect is independent of redshift. Suppose the gas distribution has a central hole. At high Δv the impact parameters are so small that the sight lines encounter the low column densities present at small radii. A wider range of N(H I) occurs at low Δv, because the sight lines sample a broader range of impact parameters. Preliminary results from simulations with central holes are in better agreement with the log N(H I) versus Δv data than standard exponential disks.

Deficiency of neutral gas occurs often in the central regions of spiral galaxies (Broiels & van Woerden 1994), the same regions where enhancements in metallicity are also common (Edmunds & Pagel 1984). Thus, there is empirical support for the idea that damped Lyα systems comprise gaseous disks with central holes and negative radial gradients in metallicity, if they evolve into current spirals. The increased metallicity is a signature of enhanced star formation, which also helps to explain the deficit of gas, either through direct gas consumption or the loss of gas through energetic outflows from supernovae. In either case a significant fraction of baryons in the metal-rich damped systems may be locked up in stars. As a result, the expression for cosmic metallicity in equation (3) will underestimate the contribution from the gas-poor metal-rich systems.

When stars are present, Ω_k and $\langle \mathcal{Z}_k \rangle$ are given by

$$\Omega_k = \Omega_g \times \frac{\sum_{i=1}^{k} (N_i + N_i^s)}{\sum_{j=1}^{i_{\rm min}} N_j},$$

$$\langle \mathcal{Z}_k \rangle = \frac{\sum_{i=1}^{k} (N_i \times Z_i' + N_i^s \times Z_i^s)}{\sum_{j=1}^{k} (N_j + N_j^s)}, \qquad (4)$$

where Ω_k is the comoving mass density of baryons in stars plus gas. Because N_i^s and Z_i^s are the column density and metallicity of matter in stars, $\langle \mathcal{Z}_k \rangle$ is the comoving mass density of metals in stars plus gas divided by Ω_k. Although $\langle \mathcal{Z}_k \rangle$ in equation (4) differs from the standard definition for metallicity, it is the appropriate quantity, because metals in stars as well as gas in damped Lyα systems supply metals to stars comprising the current thick disk. And the thick-disk metallicity is inferred solely from stars.

To solve equation (4), we first adopt the chemical evolution model of Larson (1972) to compute the fraction of baryons in stars. The model assumes that the star formation rate is balanced by the rate of mass infall to the disk, and as a result the gas content of the galaxy does not change. This agrees with the observed constancy of $\Omega_g(z)$ in the redshift range $z =$ [1.6, 3.3] (Storrie-Lombardi & Wolfe 1998) in which stars of the thick disk are assumed to form. We have

$$N_i^s/N_i = \ln\left(\frac{y + Z_f - Z_{\rm init}}{y + Z_f - Z_i'}\right), \qquad (5)$$

where y is the chemical yield, and Z_f and $Z_{\rm init}$ are the metallicities of the infalling material and of the ‘initial’ disk at $z > 3.0$. We determine Z_i^s from the constraint

$$Z_i^s N_i^s + (Z_i' - Z_{\rm init}) N_i = y N_i^s \tag{6}$$

(see Tinsley 1980). We combined equations (4)–(6) to compute log $(\mathcal{Z}_k/Z_\odot)$ versus Ω_k in the presence of stars. The solution, shown as stars in Figure 1, was computed assuming $y = 0.5Z_\odot$, $Z_{\rm init} = Z_f = 0.01Z_\odot$. In one case where $Z_i' < 0.01$, we let $Z_{\rm init} = Z_f = Z_i'$. We estimated $Z_{\rm init}$ and Z_f from the lowest metallicities found for damped Lyα systems at $z > 3.0$, and y from standard models (Tinsley 1980). In this case, $\Omega_k = 0.0008$, i.e., $3\Omega_{\rm thick}$, when log $(\mathcal{Z}_k/Z_\odot) = -0.6$. The increase in Ω_k at the metallicity of the thick disk results from the significant stellar corrections in baryonic mass for the metal-rich damped Lyα systems.

4. DISCUSSION AND CONCLUSIONS

Our results suggest that, contrary to previous claims (Pettini et al. 1997), the damped Lyα systems contain more than enough baryons at suitable metallicity and rotation speed to form thick stellar disks in spiral galaxies. The kinematic/metallicity data further imply that (1) stars in the thick disk form in the inner metal-rich regions of rapidly rotating gaseous disks and (2) these stars may dominate the baryonic content of the most metal-rich damped systems. We conjecture that vertical contraction of the metal-rich, thick gaseous disk leads to the formation of the inner thin disk. The metal-poor gas of the outer disk, i.e., the ~90% of the damped Lyα baryons that remain in gas after the formation of the thick disk, could supply the remaining thin-disk mass through radial contraction driven by angular momentum transport mediated by high-amplitude spiral density waves (Roberts & Shu 1972). The metallicity of this gas may increase as a result of mass loss by stars in the inner regions.

By contrast, stars forming in the protogalactic clumps considered by Haehnelt et al. (1998) end up in spheroidal bulges and halos, which are supported by virial motions, rather than in rotationally supported disks. The reason is that the short merger timescale inferred for protogalactic clumps indicates significant randomization of stellar orbits in most clumps. Formation of the thick disk occurs at $z < 1$, after merging ceases, and when the mean metallicity equals -0.6. But the age of the thick disk is unlikely to be less than 12 Gyr (B. W. Carney 1997, private communication), which exceeds the lookback time to $z = 1$ in all $\Lambda = 0$ cosmologies and spatially flat cosmologies in which $\Omega_\Lambda < 0.8$, when $H_0 > 50$ km s^{-1} Mpc^{-1}. Second, edge-leading asymmetries of the velocity profiles arise because clumps with the highest volume and column density move fastest with respect to the surrounding gas. This may occur because ram-pressure deceleration by ambient gas is less effective in decelerating denser clumps. The predicted correlation between N(H I) and Δv is in conflict with the detection of systems having high Δv (i.e., >120 km s^{-1}) and low log N(H I) (<20.6) (see Fig. 2, *bottom*).

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