ARE DAMPED LY$\alpha$ SYSTEMS LARGE, GALACTIC DISKS?

JESPER SOMMER-LARSEN

Theoretical Astrophysics Center
Juliane Maries Vej 30
DK-2100 Copenhagen Ø, Denmark

Abstract. The hypothesis that the Damped Ly$\alpha$ systems (DLAs) are large, galactic disks (Milky Way sized) is tested by confronting predictions of models of the formation and evolution of (large) disk galaxies with observations, in particular the Zinc abundance distribution with neutral hydrogen column density found for DLAs. A pronounced mismatch is found strongly hinting that the majority of DLAs may not be large, galactic disks.

1. Introduction

It has been proposed that the Damped Ly$\alpha$ (DLA) systems seen as broad absorption lines with neutral hydrogen column density $N(HI) \gtrsim 2 \times 10^{20}$ cm$^{-2}$ in quasar spectra are large and massive (Milky Way sized), galactic disks with maximum circular speed $V_c \gtrsim 200$ km/s (e.g., Prochaska & Wolfe 1997, 1998). If true, this is of profound interest in relation to theories of the formation and evolution of disk galaxies, but it is obviously important to test this hypothesis in as many ways as possible. In this contribution I present a test alternative to the ones used by Prochaska & Wolfe. My test is based on fairly elaborate and realistic models of the formation and evolution (including chemical evolution) of large and massive disk galaxies, in particular on comparing the observed distribution of Zinc abundance with neutral hydrogen column density found for DLAs with model predictions.

In section 2 I briefly describe the models, in section 3 the data, in section 4 the model predictions are confronted with the data and finally section 5 constitutes a brief conclusion.
2. The models

The star-formation rate is assumed to depend on gas surface density as

\[
\frac{d\Sigma_\star}{dt} \propto w(\Sigma_{\text{gas}}) \Sigma_{\text{gas}}^N ,
\]

(1)

where \( N = 1-2 \), and the weight factor

\[
w(\Sigma_{\text{gas}}) = 1
\]

(2)

for models without a star-formation threshold and

\[
w(\Sigma_{\text{gas}}) = \begin{cases} 
1 & , \quad \Sigma_{\text{gas}} > \Sigma_{TH} \\
\approx 0 & , \quad \Sigma_{\text{gas}} \leq \Sigma_{TH}
\end{cases}
\]

(3)

for models with a star-formation threshold given by (e.g., Kennicutt 1989)

\[
\Sigma_{TH} = \alpha \frac{\kappa c}{3.36 G} \approx 11 \left( \frac{\alpha}{0.7} \right) \left( \frac{\kappa}{\kappa_\odot} \right) \left( \frac{c}{6 \text{km/s}} \right) \text{M}_\odot/\text{pc}^2 ,
\]

(4)

where \( \kappa \) is the epicyclic frequency

\[
\kappa = 1.41 \frac{V}{R} \left( 1 + \frac{R}{V} \frac{dV}{dR} \right)^{1/2} ,
\]

(5)

c is the velocity dispersion of the gas, \( \alpha \) is a dimensionless constant of the order unity and \( \kappa_\odot \) is the epicyclic frequency at the solar distance from the center of the Galaxy. I have adopted \( \alpha = 0.7 \) and \( c = 6 \text{ km/s} \) (Kennicutt 1989). Infall of primordial gas, but no gas out-flows are included in these models of large and massive disk galaxies. Chemical evolution is calculated assuming a Scalo (1986) initial mass function (IMF). Oxygen is assumed to be produced in massive stars only \( (M \gtrsim 8 \text{ M}_\odot) \) and instantaneously recycled by Type II supernova (SN) explosions. Iron is assumed to be produced partly by massive stars \( (M \gtrsim 8 \text{ M}_\odot) \) and instantaneously recycled by Type II SN explosions and partly by less massive stars and recycled by Type Ia SN explosions with a time-delay of \( t_{SNIa} = 1 \text{ Gyr} \). Unprocessed gas, locked up in stars, is assumed to be non-instantaneously recycled.

The proportionality constants in the star-formation laws (eq. [1]) are determined by applying eq. [1] to the local, solar cylinder and fitting data on the local gas fraction, G-dwarf distribution etc.

The global properties of the large disks as a function of time (or red-shift) are determined by assuming that an average, spin-parameter \( \lambda = \)
ARE DAMPED LY\(\alpha\) SYSTEMS LARGE, GALACTIC DISKS?

Figure 1. The observed distribution of \([Zn/H]_{DLA}\) vs. neutral hydrogen column density \(N(HI)\) for the 18 detections in the combined Pettini et al. sample.

0.05, galactic disk of either early or late type (see below) has an exponentially decreasing stellar profile with radius \(R\) in the disk (e.g., Freeman 1970) truncated at 4 stellar scale-lengths (e.g., van der Kruit 1987) and an exponentially decreasing oxygen gas abundance profile with radius in the disk (e.g., Zaritsky et al. 1994, Garnett et al. 1997). Early type disk galaxies (Sab/Sbc) are assumed to have an average star-formation history parameter \(b\), defined as the ratio of the current to the past average star-formation rate, of \(b \approx 0.33\) and late type disks (Scd/Sdm) to have an average \(b \approx 1.0\) (Kennicutt et al. 1994). An Ellis (1983) present day \((z=0)\) morphological mix of E/S0:Sab/Sbc:Scd/Sdm = 0.28:0.47:0.25 is assumed and the models are averaged over spin-parameter \(\lambda\). The models thereby cover the full range of morphology and global surface brightness of large, galactic
disks and are fully constrained: There are no free parameters left, except for the star-formation law index $N$ and the absence or presence of a star-formation threshold and the conclusions reached in this work turn out to be quite insensitive to this for reasonable values of $N$ ($N=1-2$) - see also below.

3. The data

Observational data on 34 DLA systems (including Zinc abundances or limits) have been taken from Pettini et al. (1994, 1997). Zinc is used because it is not or only very slightly affected by dust depletion. Figure 1 shows $[Zn/H]$ versus neutral hydrogen gas column densities $N(\text{HI})$ for the 18 DLAs with Zinc detected. They have a mean redshift of $<z>=1.91$. In-
ARE DAMPED Lyα SYSTEMS LARGE, GALACTIC DISKS?

Stellar mass return included using a Scalo 1986 IMF
Ω=0.3, z=1.91, N=1.5, dust-corr., Mix, Λ & proj. area weighted

Figure 3. Predicted DLA abundance distributions at different $N(\text{HI})$ assuming that DLAs are large, galactic disks similar to the Milky Way: For models with no star-formation threshold. Dotted line histogram: $N(\text{HI}) = 2 - 10 \times 10^{20} \text{ cm}^{-2}$, Solid line histogram: $N(\text{HI}) = 10 - 50 \times 10^{20} \text{ cm}^{-2}$.

Interestingly, higher Zinc abundance corresponds to lower $N(\text{HI})$, which is not to be expected if the DLAs are large, galactic disks, even when effects of dust obscuration of quasars are taken into account - see below. Figure 2 shows $[\text{Zn}/\text{H}]$ versus $N(\text{HI})$ for the 16 DLAs with upper limits on the Zinc abundance. The mean redshift of these is $<z>=2.56$.

4. Models versus data

Figure 3 shows the model predicted $[\text{Fe}/\text{H}]$ distributions for $N(\text{HI}) = 2 - 10 \times 10^{20} \text{ cm}^{-2}$ and $N(\text{HI}) = 10 - 50 \times 10^{20} \text{ cm}^{-2}$ for the no star-formation
Stellar mass return included using a Scalo 1986 IMF
\( \Omega = 0.3, z = 1.91, N = 1.5(\text{TH}), \text{dust-corr., Mix, } \lambda \& \text{proj. area weighted} \)

Figure 4. Same as in Figure 3, but for models with a star-formation threshold

threshold models with star-formation law index \( N = 1.5 \). The distributions have been weighted over morphological mix, spin-parameter (and hence effectively global surface brightness) and projected area and corrected for the effects of dust obscuration of quasars using the clever methodology developed by Fall & Pei (1993). Figure 4 shows the same thing, but for the models with a star-formation threshold (and still \( N = 1.5 \)).

Neither of the two sets of model distributions appear to match the data at all (assuming that \([Zn/H] \simeq [Fe/H]\) as is the case for Galactic stars of all abundances). More quantitatively, Komolgorov-Smirnov (KS) tests show that both sets of model distributions can be ruled out as fits to the data with more than 99% confidence (this result is more generally obtained for all values \( N = 1-2 \) and also for Wyse & Silk (1989) type star-formation
Figure 5. Predicted number of DLAs per redshift interval for the models with no star-formation threshold - see text for details. Points with errorbars: Data, Lines: Models.

The mismatch between the data and the models is further illustrated by Figure 5. The figure shows the number of predicted DLA systems per redshift interval with Zinc detected, $dN/dz$, for $N(\text{HI}) = 2-10^{20}$ cm$^{-2}$ and $N(\text{HI}) \geq 10^{21}$ cm$^{-2}$ versus redshift $z$. The models have been normalized using observational information about the luminosity function and sizes of present day ($z=0$), large and massive disk galaxies (with $V_c \gtrsim 200$ km/s). The model predictions have been weighted and corrected as described above and furthermore corrected for the effect of a Zinc detection threshold as a function of $N(\text{HI})$. Figure 5 is for the models with star-formation law index $N=1.5$ and no star-formation threshold. Also shown are APM survey based observational results of Storrie-Lombardi et al. (1996) corrected by an ob-
Observationally deduced Zinc detection probability as a function of redshift $z$ and $N(HI)$ derived from the Pettini et al. (1994, 1997) data. As can be seen from the figures the two sets of model predictions lie more than two orders of magnitude below the observations - the situation is even worse for the models with a star-formation threshold (not shown).

5. Conclusion

The analysis presented above suggests that the DLA systems may not in general be accounted for by large and massive disk galaxies with $V_c \gtrsim 200$ km/s, not even when account is taken for the existence of some very large and low surface brightness disk galaxies (physically: high $\lambda$ galactic disks). The true situation is most likely quite complicated, but it is tempting to associate the DLAs at low redshift with the large population of faint, blue dwarfs and at higher redshift with the large number of smaller galaxies expected at such redshifts ($z \sim 2-4$) in hierarchical galaxy formation scenarios (e.g., Kauffmann 1996, Mo et al. 1998). DLAs with indications of large internal velocities ($\sim 200$ km/s) may, at least partly, be dynamically unrelaxed systems (e.g., Haehnelt et al. 1998).

Acknowledgements

I have benefited from discussions with Mike Edmunds, Don Garnett, Bernard Jones, Bernard Pagel and Max Pettini.

References

Ellis, R. S.: 1983, in The Origin and Evolution of Galaxies ed. B. J. T. Jones and J. E. Jones (Dordrecht: Reidel), 255
Fall, S. M., Pei, Y. C.: 1993, Astrophys. J. 402, 479
Freeman, K. C.: 1970, Astrophys. J. 160, 811
Garnett, D. R., Shields, G. A., Skillman, E. D., Sagan, S. P., Dufour, R. J.: 1997, Astrophys. J. 489, 63
Haehnelt, M. G., Steinmetz, M., Rauch, M.: 1998, Astrophys. J. 495, 647
Kauffmann, G.: 1996, MNRAS 281, 475
Kennicutt, R. C.: 1989, Astrophys. J. 344, 685
Kennicutt, R. C., Tamblyn, P., Congdon, C. W.: 1994, Astrophys. J. 435, 22
Mo, H. J., Mao, S., White, S. D. M.: 1998, MNRAS 295, 319
Pettini, M., Smith, L. S., Hunstead, R. W., King, D. L.: 1994, Astrophys. J. 426, 79
Pettini, M., Smith, L. S., King, D. L., Hunstead, R. W.: 1997, Astrophys. J. 486, 665
Prochaska, J. X., Wolfe, A. M.: 1997, Astrophys. J. 487, 73
Prochaska, J. X., Wolfe, A. M.: 1998, Astrophys. J. 507, 113
Scalo, J. M.: 1986, Fundamentals of Cosmic Physics 11, 1
Storrie-Lombardi, L. J., Irwin, M. J., McMahon, R. G.: 1996, MNRAS 282, 1330
van der Kruit, P. C.: 1987, Astron. Astrophys. 173, 59
Wyse, R. F. G., Silk, J.: 1989, Astrophys. J. 339, 700
Zaritsky, D., Kennicutt, R. C., Huchra, J. P.: 1994, Astrophys. J. 420, 87