Maps of the Cosmos
ASP Conference Series, Vol. 216, 2005
M. Colless, L. Staveley-Smith, R. Stathakis

Damped Lyman-α Absorbers in Cosmological SPH Simulations: the "Metallicity Problem"

Kentaro Nagamine

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, U.S.A.

Volker Springel

Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, 85740 Garching bei München, Germany

Lars Hernquist

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, U.S.A.

Abstract. We study the distribution of star formation rate (SFR) and metallicity of damped Lyman-α absorbers (DLAs) using cosmological smoothed particle hydrodynamics (SPH) simulations of the Λ cold dark matter (CDM) model. Our simulations include a phenomenological model for feedback by galactic winds which allows us to examine the effect of galactic outflows on the distribution of SFR and metallicity of DLAs. For models with strong galactic winds, we obtain good agreement with recent observations with respect to total neutral hydrogen mass density, $N_{\rm HI}$ column-density distribution, abundance of DLAs, and for the distribution of SFR in DLAs. However, we also find that the median metallicity of simulated DLAs is higher than the values typically observed by nearly an order of magnitude. This discrepancy with observations could be due to shortcomings in the treatment of the supernova feedback or the multiphase structure of the gas in our current simulations. Recent observations by Wolfe et al. (2003a,b) seem to point to the same problem; i.e. the observed DLA metallicities are much lower than those expected from the (either observed or simulated) DLA star formation rates, a puzzle that has been known as the "missing metals"-problem for the globally averaged quantities.

1. Introduction

Damped Lyman-α Absorbers (DLAs) are considered to be important reservoirs of neutral hydrogen in the universe at $z \sim 3$ (Storrie-Lombardi & Wolfe 2000). Studying the physical properties of DLAs, such as the distribution of their star formation rates (SFRs) and metallicity, will therefore provide us with important information on the history of star formation, galaxy formation, and chemical enrichment of the universe. As such, this information complements that provided by the emitted light from stars in high-redshift galaxies in a powerful and independent way.

Here we use cosmological SPH simulations of the ΛCDM model with varying resolution and feedback strength to study the physical properties of DLAs. In our first study (Nagamine, Springel, & Hernquist 2004a), we showed that the ΛCDM model is able to account for the observed abundance of DLAs at redshift $z = 3 - 4.5$ quite well. Another important conclusion of our study was that earlier numerical work overestimated the DLA abundance significantly. This was due to insufficient numerical resolution, lack of efficient feedback processes, and inaccuracies introduced in cooling processes when conventional formulations of SPH are used, giving rise to an overcooling problem.

In this conference proceedings, we focus our attention on the metallicity and the SFRs of DLAs. In particular, we discuss the "metallicity problem" that we currently face in both simulations and observations. We refer the readers to Nagamine, Springel, & Hernquist (2004b) for the details of our work.

2. Simulations

In this section, we briefly describe the SPH simulations that we use for our study. Our simulations include radiative cooling and heating with a uniform UV background, star formation, and supernova (SN) feedback, as well as a phenomenological model for feedback by galactic winds. The latter allows us to examine, in particular, the effect of galactic outflows on the distribution of the SFR and metallicity of DLAs. For the details of these models, we refer readers to Springel & Hernquist (2003a) and a concise summary in Nagamine et al. (2004b).

We employ a "conservative entropy" formulation (Springel & Hernquist 2002) of SPH which alleviates numerical overcooling problems that affected earlier simulations. In addition, we utilize a series of simulations of varying boxsize and particle number to investigate the impact of numerical resolution on our results. The simulation parameters are summarized in Table 1. The adopted cosmological parameters of all runs are $(\Omega_m, \Omega_\Lambda, \Omega_b, \sigma_8, h) = (0.3, 0.7, 0.04, 0.9, 0.7)$.

3. DLA Metallicity in the Simulations

In Figure 1, we show the projected gas metallicity versus neutral hydrogen column density $N_{\rm HI}$ for random sight-lines in the 'Q5'-run at $z = 3$. We show the results from the 'Q5'-run because it has the highest resolution at $z = 3$. Each point in the figure represents one sight-line, and the contours are equally spaced on a logarithmic scale. The solid square symbols give the median value in each $\log N_{\rm HI}$ bin, with error bars indicating the quartiles on both sides. The median metallicity increases as $N_{\rm HI}$ increases, reaching solar metallicity at $\log N_{\rm HI} \sim 23$. This trend is expected because star formation is more vigorous in high $N_{\rm HI}$ systems.

An important result is that the median metallicity we find for DLAs in our simulations is much higher than the observed value. Note that observers typically find DLAs with $20 < \log N_{\rm HI} < 22$ to have a metallicity of $\log(Z/Z_\odot) \sim -1.5$ (e.g. Boissé et al. 1998; Pettini et al. 1999; Prochaska & Wolfe 2000), as indicated by the shaded region.

Another point to notice is the existence of systems that have both high $N_{\rm HI}$ and high metallicity; these systems tend to be absent in observations. Dust

Table 1. Simulations employed in this study.[a]

Run	Boxsize	N_p	m_{DM}	m_{gas}	ϵ	z_{end}	wind
R3	3.375	2×144^3	9.29×10^5	1.43×10^5	0.94	4.00	strong
R4	3.375	2×216^3	2.75×10^5	4.24×10^4	0.63	4.00	strong
O3	10.00	2×144^3	2.42×10^7	3.72×10^6	2.78	2.75	none
P3	10.00	2×144^3	2.42×10^7	3.72×10^6	2.78	2.75	weak
Q3	10.00	2×144^3	2.42×10^7	3.72×10^6	2.78	2.75	strong
Q4	10.00	2×216^3	7.16×10^6	1.10×10^6	1.85	2.75	strong
Q5	10.00	2×324^3	2.12×10^6	3.26×10^5	1.23	2.75	strong
D4	33.75	2×216^3	2.75×10^8	4.24×10^7	6.25	1.00	strong
D5	33.75	2×324^3	8.15×10^7	1.26×10^7	4.17	1.00	strong
G4	100.0	2×216^3	7.16×10^9	1.10×10^9	12.0	0.00	strong
G5	100.0	2×324^3	2.12×10^9	3.26×10^8	8.00	0.00	strong

[a]The box-size is given in units of h^{-1}Mpc, N_p is the particle number of dark matter and gas (hence $\times 2$), m_{DM} and m_{gas} are the masses of dark matter and gas particles in units of $h^{-1}M_\odot$, respectively, ϵ is the comoving gravitational softening length in units of h^{-1}kpc, and z_{end} is the ending redshift of the simulation. The value of ϵ is a measure of spatial resolution. The 'strong-wind' simulations form a subset of the runs analyzed by Springel & Hernquist (2003b).

obscuration is sometimes invoked to reconcile this result with observations, however, recent observational tests suggest that the dust extinction effect is not so strong (Ellison et al. 2001; Prochaska & Wolfe 2002), and the solution could rather lie in a more adequate treatment of star formation and supernova feedback. For example, Schaye (2001) argues that the conversion of neutral hydrogen atoms into a molecular form, which we have not yet implemented in our simulations, would introduce a physical limit to the highest N_{HI} that can be attained. This process would eliminate the highest N_{HI} systems, but would not reduce the metallicity of low N_{HI} systems because it would make the star formation even more efficient than in our current simulations. Other possibilities include the existence of metal-loaded winds, which we will discuss in more detail in Section 5. It hence remains to be seen whether future cosmological simulations with a more sophisticated modeling of star formation and SN feedback processes confirm the existence of high-metallicity, high-N_{HI} systems, which could then turn into an interesting challenge for the CDM model.

4. Star Formation Rates in DLAs

In Figure 2, we show the distribution of sight-lines in the 'Q5'-run at $z = 3$ on the plane of metallicity versus projected star formation rate surface density Σ_{SFR} (in proper units of $M_\odot$ yr^{-1}kpc^{-2}). The shaded area roughly indicates the region of recent observational estimate by Wolfe et al. (2003b).

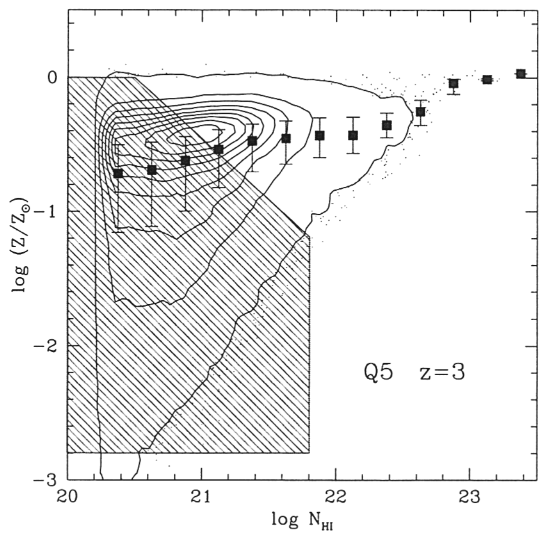

Figure 1. Gas metallicity vs. $\mathrm{H_I}$ column density at $z = 3$ in the 'Q5'-run. Each point in the figure represents one line-of-sight. Contours are equally spaced on a logarithmic scale. The solid square symbols give the median value in each $\log N_{\mathrm{HI}}$ bin, with error bars indicating the quartiles on both sides. Current observational data points fall into the shaded region.

The shape of the simulated distribution is easy to understand. Because Σ_{SFR} is tightly correlated with N_{HI} in our simulation (as shown in Figure 3; the Kennicutt [1998] law), the distribution seen in Figure 2 is simply a reflection of Figure 1 around a diagonal line. The star formation model adopted in our simulation depends only on local physical quantities; e.g. the local gas density. The free parameter of the model was chosen to reproduce the Kennicutt law in isolated disk galaxies at low redshift, but was kept fixed as a function of time. We hence implicitly assumed that the Kennicutt law holds at all redshifts, and our simulation results reflect this assumption.

The observational estimates of SFR by Wolfe, Gawiser, & Prochaska (2003b) agree well with the simulation, although they do not follow the Kennicutt law tightly. Using the DLA abundance information, Wolfe et al. (2003b) have estimated the volume-averaged SFR density of DLAs and found that it is comparable to that of the Lyman-break galaxies (LBGs). This leads to the so-called global "missing metals"-problem (e.g. Pagel 2002; Pettini 2004), where the total amount of metals seen in DLAs are not sufficient to account for all the metals expected from the observed SFR density at $z = 3$. However, even before taking the volume-average, both our simulations and the observations by Wolfe, Prochaska, & Gawiser (2003a) and Wolfe et al. (2003b) seem to be pointing to the same problem; i.e. the observed DLA metallicities are much lower than those expected from the (either observed or simulated) DLA star formation rates.

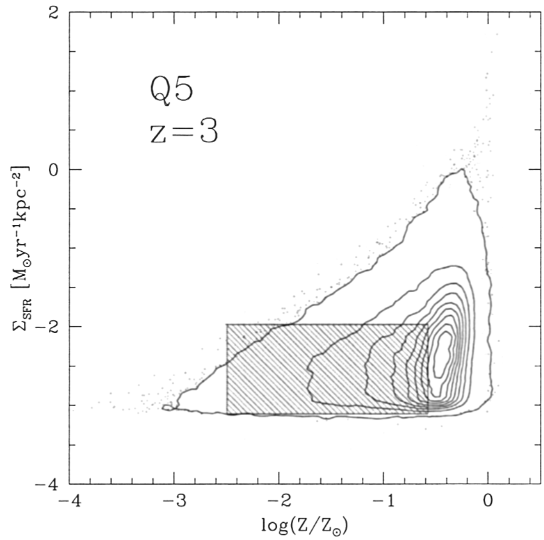

Figure 2. Projected SFR density vs. gas metallicity at $z = 3$ for the 'Q5'-run. Each point in the figure represents one line-of-sight. Contours are equally spaced on a logarithmic scale. The shaded area indicates the region of observed data points by Wolfe et al. (2003b).

5. Discussion

While the projected SFR density at $z = 3$ in our simulations is plausible and agrees well with current observations, the median metallicity of DLAs appears to be too high compared to the values typically observed for DLAs. There are a number of possible explanations for this problem, and we will briefly discuss some of the most prominent possibilities.

One potential reason for high metallicity in DLAs is that the feedback by galactic winds is not efficient enough in blowing out metals from DLAs. Clearly, if the feedback by winds were stronger, then star formation and hence metal creation in DLAs would be more strongly suppressed. However, simply making the winds stronger and blowing out more gas will not necessarily decrease the metallicity of DLAs much, because in our current simulation model, the winds transports away metals *and* gas at the same time; i.e. the winds' initial metallicity is assumed to be equal to that of the gas of the DLA, leaving the ratio of metal and gas mass in the DLA unchanged.

It is, however, quite plausible that the wind is *metal-loaded* compared to the gas in the DLA, as is for example suggested by simulations of SN explosions (e.g. MacLow & Ferrara 1999; Bromm, Yoshida, & Hernquist 2003). After all, the ejecta of SNe are heavily enriched and inject large parts of the energy that is assumed to ultimately drive the outflow. If the mixing with other DLA-gas is not extremely efficient before the outflow occurs, it can then be expected that the wind material has potentially much higher metallicity than the DLA, thereby selectively removing metals.

A related possibility concerns the metallicities of the cold and diffuse phases of the DLA. In the present study, we assumed that metals are always efficiently

https://doi.org/10.1017/S0074180900196706 Published online by Cambridge University Press

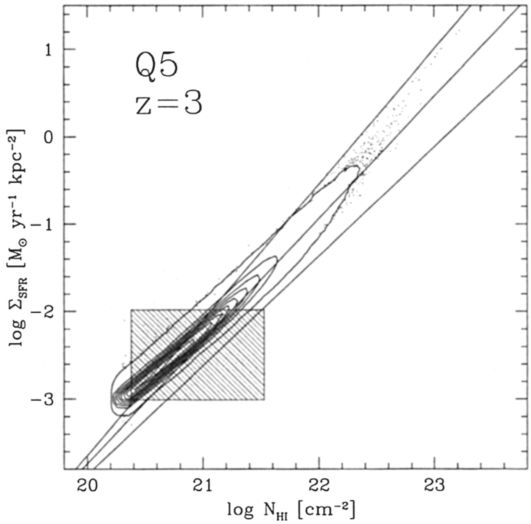

Figure 3. Projected SFR density vs. neutral hydrogen column density at $z = 3$ for the 'Q5'-run. Each point in the figure represents one line-of-sight. Contours are equally spaced on a logarithmic scale. The shaded area indicates the region of observed data points by Wolfe et al. (2003b), and the 3 solid lines show the Kennicutt (1998) law with the top and bottom lines indicating the range of uncertainty which includes a reasonable estimate of systematic errors.

and rapidly mixed between the gas of the cold clouds and the ambient medium, such that there is a homogeneous metal distribution in the DLA (operationally, we used only a single metallicity variable for each gas particle, reflecting this assumption). However, this assumption may not be fully correct. If the metals were preferentially kept in the hot phase of the ISM after they are released by SNe, then they would not be observed in the cold gas that is responsible for the DLAs. Since we did not track the metal distribution in cold and hot phases separately in the current simulations, we may then have overestimated the amount of metals in DLAs by counting those in the hot phase as well as those in the cold phase. Note that a more detailed tracking of metals in the simulation, separately for hot and cold phases of the gas, could in principle be done easily on a technical level. The difficulty, however, lies in obtaining a reasonable description of the physics that governs the exchange of metals between the different phases of the ISM, something that is presently not attainable from either observation or theory.

The viability of the feedback model in the simulations can also be tested by comparing with observations of the Lyman-α forest, which is generated by systems of much lower column density than the DLAs studied in this work. Curiously, an analysis using the current simulation series (Springel et al. in preparation), as well as a study by Theuns et al. (2002), suggest that the spectral features of the Ly-α forest are not significantly affected by the feedback from galactic outflows, despite the fact that the wind strength is taken to be on the 'strong side' in these studies, and despite the fact that a non-negligible fraction of the IGM volume is heated by the winds. Note that in our simulations

https://doi.org/10.1017/S0074180900196706 Published online by Cambridge University Press

with a strong wind model, the H_I mass density in the entire simulation box is somewhat lower than that suggested by observational estimates (Nagamine et al. 2004a), therefore it appears problematic to increase the wind strength even beyond the present value.

The high metallicity of DLAs may also be related to the steep luminosity function of galaxies in our SPH simulations (Nagamine et al. 2004c). An analysis using a population synthesis model shows that the luminosity function still has a very steep slope at the faint end even at low redshift, similar to that of the dark matter halo mass function. (It is not obvious whether the steep faint end in the simulation at $z > 1$ is a problem, because it is not well constrained observationally at $z > 1$ yet.) This means that the formation of low-mass galaxies in our simulation was not sufficiently suppressed, or equivalently, that star formation was too efficient in low-mass haloes. Stronger winds may help to alleviate this problem, but it appears unlikely that our present feedback model can solve it satisfactorily simply by adopting a higher efficiency parameter for feedback. It is more plausible that additional physical processes need to be considered in a more faithful way. One simple possibility for this is related to the UV background field, which is turned on by hand at $z = 6$ in our present simulations, to mimic reionization of the Universe at a time when the first Gunn-Peterson troughs in spectra to distant quasars are observed (Becker et al. 2001). However, it is possible (in fact suggested by the WMAP satellite) that the Universe was reionized at much higher redshift. The associated photoheating may then much more efficiently have impaired the formation of low-mass galaxies than in our present simulations. We plan to explore this possibility in future work by adopting different treatments of the UV background radiation field.

In conclusion, we have shown that the DLAs found in our simulation series have many plausible properties. In particular, they are in good agreement with recent observations of the total neutral hydrogen mass density, the N_{HI} distribution function, the abundance of DLAs, and the distribution of SFR in DLAs. However, our simulated DLAs show typically considerably higher metallicity than what is presently observed for the bulk of these systems. This likely indicates that metal transport and mixing processes have not been efficient enough in our simulations. It will be interesting to study more sophisticated metal enrichment models in future simulations in order to further improve our understanding of the nature of DLAs in hierarchical CDM models.

References

Becker, R. H., et al. 2001, AJ, 122, 2850
Boissé, P., Le Brun, V., Bergeron, J., & Deharveng, J. M. 1998, A&A, 333, 841
Bromm, V., Yoshida, N., & Hernquist, L. 2003, ApJ, 596, 135
Ellison, S. L., et al. 2001, A&A, 379, 393
Kennicutt, R. C. Jr. 1998, ARA&A, 36, 189
Mac Low, M. M., & Ferrara, A. 1999, ApJ, 513, 142
Nagamine, K., Springel, V., & Hernquist, L. 2004a, MNRAS, 348, 421
Nagamine, K., Springel, V., & Hernquist, L. 2004b, MNRAS, 348, 435
Nagamine, K., Springel, V., Hernquist, L., & Machacek, M. 2004c, MNRAS, 350, 385

https://doi.org/10.1017/S0074180900196706 Published online by Cambridge University Press

Pagel, L. 2002, in ASP Conf. Ser. Vol. 253, Chemical Enrichment of Intracluster and Intergalactic Medium, ed. R. Fusco-Femiano & F. Matteucci (San Francisco: ASP), 489

Pettini, M. 2004, in Cosmochemistry: The Melting Pot of the Elements, ed. C. Esteban, R. J. Garcia López, A. Herrero, & F. Sánchez (New York: Cambridge University Press), Ch 7 (astro-ph/0303272)

Pettini, M., Ellison, S. L., Steidel, C. C., & Bowen, D. V. 1999, ApJ, 510, 576

Prochaska, J. X., & Wolfe, A. M. 2000, ApJ, 533, L5

Prochaska, J. X., & Wolfe, A. M. 2002, ApJ, 566, 68

Schaye, J. 2001, ApJ, 562, L95

Springel, V., & Hernquist, L. 2002, MNRAS, 333, 649

Springel, V., & Hernquist, L. 2003a, MNRAS, 339, 289

Springel, V., & Hernquist, L. 2003b, MNRAS, 339, 312

Storrie-Lombardi, L. J., & Wolfe, A. M. 2000, ApJ, 543, 552

Theuns, T., et al. 2002, ApJ, 578, L5

Wolfe, A. M., Prochaska, J. X., & Gawiser, E. 2003a, ApJ, 593, 215

Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2003b, ApJ, 593, 235