Chemical abundances in star-forming galaxies and damped Lyman alpha systems

Regina E. Schulte-Ladbeck, Brigitte König and Brian Cherinka

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA

Abstract. We investigate the chemical abundances of local star-forming galaxies which cause damped Lyman alpha lines. A metallicity versus redshift diagram was constructed, on which the chemical abundances of low-redshift star-forming galaxy populations are compared with those of high-redshift damped Lyman alpha systems. We discuss two types of experiments on individual star-forming galaxies. In the first, the damped Lyman alpha line is created against an internal ultraviolet light source generated by a star-forming cluster or a supernova explosion. In the second, the damped Lyman alpha line is seen against a background quasar. The metallicities measured from ionised gas in the star-forming regions, and neutral gas in the damped Lyman alpha systems, are compared with one another on a case-by-case basis. We highlight the occurrence of the star-forming galaxy/quasar pair SBS 1543+593/HS 1543+5921, where the emission- and absorption-line derived abundances give the same result. We argue that we therefore can in principle interpret damped Lyman alpha system metallicities as an extension of star-forming galaxy metallicities to higher redshifts, supporting the idea that gas-rich galaxies had lower chemical abundances when they were younger.

1. Introduction

The chemical evolution of the Universe occurs via two channels. Big-bang nucleosynthesis generated several light chemical elements during "the first three minutes". In the following 13 Gyr, metals were synthesised by stars in galaxies, a process which continues until the present epoch. The ratios of certain metals, for example, those of the α-to-iron-group elements, can be used to constrain the evolution of galaxies.

Gas-phase chemical abundances in the high-redshift Universe have been obtained by the study of QSO absorption lines, and traditionally refer to iron-peak elements (e.g. Prochaska *et al.* 2003). It is generally thought that absorbers with high neutral hydrogen column densities, such as damped Lyman alpha (DLA) systems and sub-DLAs, originate in gas-rich galaxies. Typical impact parameters needed to reach the DLA-defining column density N of $2 \times 10^{20} \mathrm{cm}^{-2}$ are expected to be of the order of a few 10 s of kpc, based on the HI sizes of local gas-rich galaxies (Rosenberg & Schneider 2003). However, the connection between DLAs and galaxies is far from clear. For instance, the very low metallicity of high-redshift DLAs has been interpreted to indicate that DLA galaxies are preferentially dwarf galaxies, in which case they would not be representative of the local field galaxy population (e.g. Kulkarni *et al.* 2005).

Only at low redshifts can the galaxies responsible for causing DLAs be observed directly. We discuss here a few cases for which detailed studies are in progress. Chemical properties of galaxies at low redshifts are based on measurements of emission lines from photo-ionised gas, and refer to the α-capture element oxygen (e.g. Garnett 2004). Fig. 1 illustrates the local α-element abundances derived from emission-lines, and the high-redshift abundances derived for DLAs from absorption lines, showing only those for which α- rather than Fe-peak element abundances are available. We also indicate

the maximum and minimum oxygen abundances seen in the local Universe, and note that a) there are no local galaxies known with abundances as low as those of the lowest-metallicity DLAs; and b) there are no DLAs known which reach super-Solar abundances known locally to occur in the most luminous SFGs. The chemical abundances of Lyman Break Galaxies (LBGs) and of DLAs are beginning to show some overlap at a redshift of about 2, where emission-line abundances of LBGs have recently become available (e.g. Teplitz *et al.* 2000; Shapley *et al.* 2004). LBGs are luminous star-forming galaxies (SFG), which are presumed to be offset from the local luminosity-metallicity relation because of their youth†.

In order to compare the properties of SFGs with those of high-redshift DLAs, we need to answer the question whether emission- and absorption-line techniques yield concordant values for chemical abundances. The experiment requires the use of a SFG, a background light source, and a high neutral H column density on its path. For some time, the neutral gas in SFGs has been probed against internal star clusters. More recently, the studies have been expanded to bona fide DLA galaxies using SFG-QSO pairs.
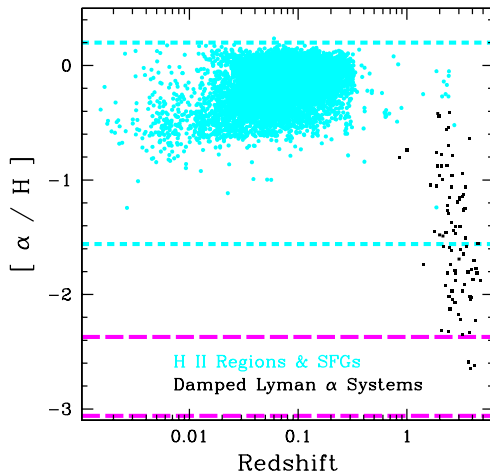

Figure 1. Metallicity as a function of redshift. The bright circles are values of $[O/H]_{II}$ for HII regions and SFGs from the SDSS. These are extended to redshifts above 0.3 by using data from Shapley *et al.* (2004), Steidel *et al.* (2004), Koo *et al.* (1994), Kobulnicky & Zaritsky (1999), Lemoine-Busserolle *et al.* (2003), Liang *et al.* (2004), Rigopoulou *et al.* (2000), Maier *et al.* (2004), Contini *et al.* (2002), Cardiel *et al.* (2003), and Teplitz *et al.* (2000). The black squares are values of $[O, S, Si/H]_I$ from the compilation of Prochaska *et al.* (2003). The short-dashed lines show the maximum and minimum values of oxygen abundances in local HII regions and SFGs based on the direct or T_e method (Izotov & Thuan 1999; Castellanos, Díaz & Terlevich 2002). The long-dashed lines are the theoretical expectations of oxygen enrichment from the first supernovae (Salvaterra & Ferrara 2003), assuming a non-rotating (lower line) and a rotating (upper line) Population III progenitor.

2. SFGs causing DLAs in their own spectra

Table 1 provides a list of local SFGs exhibiting DLA lines in their own UV spectra. Chemical abundances are referenced to the Solar values of Holweger (2001). For oxygen this is $12 + \log O/H = 8.736 \pm 0.078$. The neutral gas-phase abundances are for oxygen, with the exception of MS 1512-cB58, where they refer to the average of several α elements. Oxygen abundances in the ionised gas phase are given as well. We illustrate how the abundances of these SFGs compare to other low-redshift SFGs and to high-redshift DLAs in Fig. 2.

† We use a cosmology with $H_0 = 70 \, \mathrm{km \, s^{-1} Mpc^{-1}}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$. All literature data were converted to this cosmology when needed.
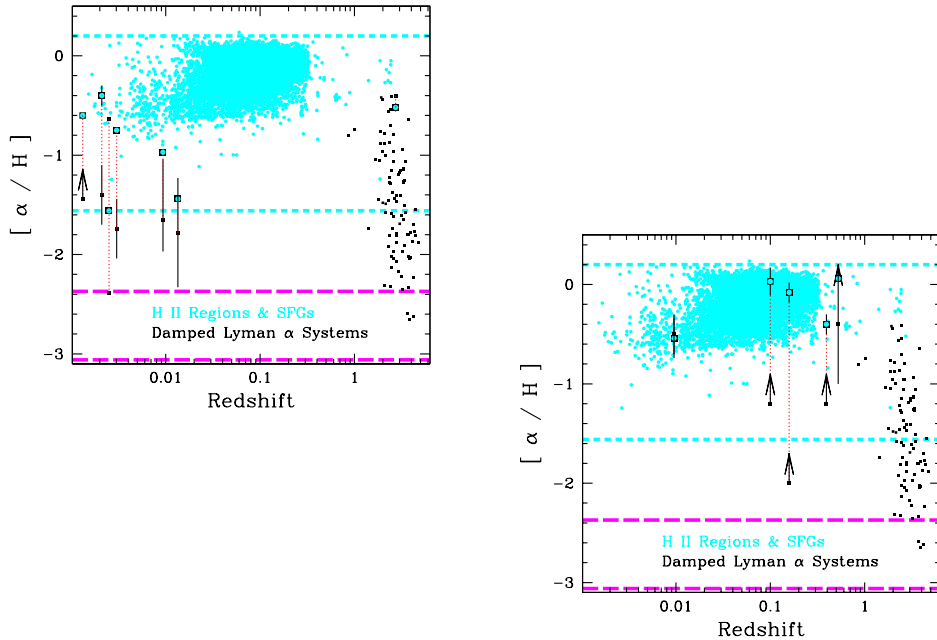
Figure 2. Left – Metallicity as a function of redshift as in Fig. 1. Over-plotted are the abundances of SFGs from Table 1, which display DLAs in their own spectra. For each SFG which is also a DLA, the bright symbols mark the ionised gas abundance, and they are connected by dotted lines, to dark squares which indicate the neutral gas abundance. For I Zw 18, the extrema of neutral gas metallicities allowed by the analyses of two teams are shown.

Figure 3. Right – Over-plotted here are the abundances of SFGs from Table 2, and the corresponding unambiguous abundances (or abundance limits) determined on the sight-line to the QSO.

The advantage of examining DLAs produced within SFGs by their own starburst clusters, is that the neutral and the ionised gas are probed on the exact same sight-line. A disadvantage of this technique is that the background sources are extended. The sight-line also traverses some ionised gas.

So far, six out of seven SFGs studied with this technique are dwarf galaxies with small star-formation rates (SFR). In general in these galaxies $[O/H]_{II}$ – $[O/H]_I > 0$ (although the case of I Zw 18 is controversial). The seventh galaxy studied is the luminous, gravitationally-lensed, high-redshift LBG MS 1512-cB58. Here, $[O/H]_{II}$ and $[O/H]_I$ are in close agreement.

The discovery of DLA lines in the spectra of gamma ray burst (GRB) source afterglows has recently opened up a new window on neutral gas metallicities at high redshift (e.g. Vreeswijk *et al.* 2004). GRBs are thought to originate from supernova explosions in star-forming regions, and indeed some GRBs exhibit Lyman α emission lines in their DLA troughs. At this time, abundance analyses of the ionised gas in GRB-DLAs are not available, thus none of these objects are listed in Table 1.

3. SFGs causing DLAs in the spectra of background QSOs

Schulte-Ladbeck *et al.* (2005) recently studied the α-element abundances of the DLA galaxy SBS 1543+593 in emission and absorption. The background QSO HS 1543+5921

Table 1. SFGs causing Lyman alpha lines in their own spectra

Galaxy	z	$\log(N_{HI})$	Type	M_B	L [L^*]	SFR [$M_\odot \text{yr}^{-1}$]	$[O/H]_{II}$	$[O/H]_I$
NGC 625	0.001321	20.5	DIRR	−16.3	0.03	0.05	-0.6^{12}	$> -1.4^{11}$
NGC 1705	0.00210	20.20	BCD	−15.8	0.02	0.03	-0.4^5	-1.4^4
I Zw 18	0.00250	21.34	BCD	−14.3	0.09	0.09	-1.56^1	$-1.4^6, -2.1^7$
Mrk 59	0.003631	20.8	BCD	−17.5	0.08	1.5	-0.75^1	-1.7^8
I Zw 36	0.0094	21.30	BCD	< -13.9	> 0.003	> 0.03	-0.97^1	-1.7^9
SBS0335-052	0.013486	21.85	BCD	−17.1	0.04	1.3	-1.44^1	-1.8^{10}
MS1512-cB58	2.7276	20.85	LBG	−22.0	5.3	> 100	-0.52^2	-0.4^3

[1] Izotov & Tuan (1999), [2] Teplitz *et al.* (2000), [3] Pettini *et al.* (2002) , [4] Heckman *et al.* (2001),
[5] Storchi-Bergmann *et al.* (1994), [6] Aloisi *et al.* (2003), [7] Lecavelier des Etangs *et al.* (2004),
[8] Izotov & Thuan (2002), [9] Lebouteiller *et al.* (2004), [10] Thuan *et al.* (2005),
[11] Cannon *et al.* (2005), [12] Skillman *et al.* (2003)

Table 2. SFGs causing Lyman alpha lines in background QSO spectra

QSO	b [kpc]	Galaxy	z	$\log(N_{HI})$	Type	M_B	L [L^*]	SFR [$M_\odot \text{yr}^{-1}$]	$[O/H]_{II}$	$[O/H]_I$	α, other than O
HS 1543+5921	0.5	SBS 1543+593	0.0096	20.3	Sm	−16.8	0.04	0.006	-0.59^a	-0.5^*	S, Si
Q1543+489	107	Galaxy 5	0.0382	18.4	S	−17.9	0.12	0.37	-0.06^f	$> -0.8?$	S, Mg
PHL 909	140	SDSS J005719+	0.0822	$\leqslant 17.7$	Sc	−19.7	0.6	1.5	-0.22^g	...	
PKS 0439-433	7	Object 1	0.1012	19.7	Sab	−20.2	1.0	0.4	0.03^b	> -1.2	Mg, Si
PHL 909	19	SDSS J005710	0.1237	18.58	Sa	−18.5	0.2	1.1	-0.15^g	$> -1.2?$	
PHL 1226	17.6	G4	0.1602	19.7	S	−20.0	0.8	0.5	-0.08^d	> -2.0	
Q1209+107	38	Galaxy 19/8	0.3930	19.54	Int	−18.5	0.2	1.7	$-0.4^{c,e}$	> -1.2	
B2 0827+243	36	G1	0.525	20.3	S	−19.8	0.69	0.08	$> 0.06^b$	> -2.8	S, Si

[a] Schulte-Ladbeck *et al.* (2005), [b] Chen *et al.* (2005), [c] Cristiani (1987), [d] Christensen *et al.* (2005)
[e] Yanny (1990), [f] Bowen *et al.* (1997), [g] this work
The $[O/H]_I$ values were derived assuming the optically thin case and applying the approximation formula from
Petitjean (1998). [*] [S/H], [+] also SDSS J154519

has an impact parameter of 2.4″, and intercepts the dwarf galaxy's disk close to its centre. SBS 1543+593 offers an excellent opportunity to directly compare element abundances inferred from cool interstellar gas (DLAs) and ionised gas (SFGs). None of the previously imaged DLA galaxies are resolved enough to show individual HII regions. In none of them does the sight-line to the QSO intercept the disk of the galaxy close to its centre, eliminating concerns over disk metallicity gradients.

The brightest HII region in SBS 1543+593 yields $[O/H]_{II} = -0.54 \pm 0.20$ and $[S/H]_{II} = -0.27 \pm 0.30$ (where the Solar S abundance (7.20 ± 0.06) is referenced to Grevesse & Sauval 1998). HST/FOS data reveal $[O/H]_I > -2.14$, and HST/STIS data give $[S/H]_I = -0.50 \pm 0.33$. Within the errors these four values are the same. Also, $\log (N/O)_{II} = -1.40^{+0.20}_{-0.30}$ is within the range of $-2.0 \lesssim \log (N/S)_I \lesssim -0.8$, suggesting agreement.

In Fig. 3 we show $[S/H]_I$ for the neutral-gas abundance, and $[O/H]_{II}$ for the ionised-gas abundance. Here is one DLA for which we can demonstrate that in principle, emission- and absorption-line techniques give the same results when chemical elements with similar nucleosynthetic origins are compared at similar locations within a DLA galaxy. This result validates in principle comparisons between the two types of objects, SFGs and DLAs, on the metallicity versus redshift diagram. SBS 1543+593 thus supports the case that metal enrichment has taken place in the gas-rich star-forming galaxy population between redshifts of 5 and 0. In practise, galaxy metallicity gradients will be important for a detailed comparison between SFG and DLA metallicities (see e.g. Christensen *et al.* 2005; Chen *et al.* 2005).

Table 2 summarises the result for a few additional SFG/QSO pairs, for which we were able to list α-element abundances in the ionised phase, and derive abundance limits in

the neutral phase. We find that in two sub-DLAs (G4/PHL 1226 and Object1/PKS 0439-433), the QSO intercepts the disk just at its outer radius. Here $[\alpha/\mathrm{H}]_\mathrm{I}$ is consistent with expectations of the local disk metallicity gradient of Ferguson *et al.* (1998). As the impact parameter grows, this extrapolation must eventually become invalid. We note that the present sample traces α elements to a distance of about 100 kpc from SFGs.

Chen *et al.* (2005) have argued that low-redshift DLAs can be explained via a combination of gas cross section selection and metallicity gradients. Galaxy metallicity gradients have only been investigated locally. We do not have any insight into how they may evolve with redshift. One point in particular is worth pondering. It is now becoming evident that the optical sizes of galaxies grow smaller with increasing redshift (Bouwens *et al.* 2004). This might suggest an as yet little explored bias in the observed metallicity-redshift dependence of DLAs.

4. Conclusions

• Emission and absorption diagnostics of one SFG/QSO pair giving rise to a DLA are shown to give the same α-element abundances for the ionised gas in the SFG and the neutral gas in the DLA.

• Emission- and absorption-derived abundance offsets in SFG/QSO pairs in which the impact parameter is less than or equal to the optical radius of the galaxy so far appear consistent with the expectation of a disk metallicity gradient.

• High-redshift SFGs and DLAs exhibit lower abundances than their low-redshift counterparts, indicating that gas-rich galaxies had lower abundances when they were younger.

Acknowledgements

References

Aloisi, A., Savaglio, S., Heckman, T. M., Hoopes, C. G., Leitherer, C., Sembach, K. R., 2003, ApJ, 595, 760

Bouwens, R. J., Illingworth, G. D., Blakeslee, J. P., Broadhurst, T. J., Franx, M., 2004, ApJ, 611, L1

Bowen, D. V., Osmer, S. J., Blades, J. C., Tytler, D., 1997, MNRAS, 284, 599

Cannon, J. M., Skillman, E. D., Sembach, K. R., Bomans, D. J., 2005, ApJ, 618, 247

Cardiel, N., Elbaz, D., Schiavon, R. P., Willmer, C. N. A., Koo, D. C., Phillips, A. C., Gallego, J., 2003, ApJ, 584, 76

Castellanos, M., Díaz, A. I., Terlevich, E., 2002, MNRAS, 329, 315

Chen, H.-W., Kennicutt Jr, R. C., Rauch M., 2005, astro-ph/0411006

Christensen, L., Schulte-Ladbeck, R. E., Sánchez, S. F., Becker, T., Jahnke, K., Kelz, A., Roth, M. M., Wisotzki, L., 2005, A&A, 429, 477

Cristiani, S., 1987, A&A, 175, L1

Contini, T., Treyer, M. A., Sullivan, M., Ellis, R. S., 2002, MNRAS, 330, 75

Ferguson, A. M. N., Gallagher, J. S., Wyse, R. F. G., 1998, AJ, 116, 673

Garnett, D. R., 2004, Cosmochemistry. The melting pot of the elements, 171

Grevesse, N., Sauval, A. J., 1998, Space Science Reviews, 85, 161

Heckman, T. M., Sembach, K. R., Meurer, G. R., Strickland, D. K., Martin, C. L., Calzetti, D., Leitherer, C., 2001, ApJ, 554, 1021

Holweger, H., 2001, AIP Conf. Proc. 598: Joint SOHO/ACE workshop "Solar and Galactic Composition", 598, 23

Izotov, Y. I., Thuan, T. X., 1999, ApJ, 511, 639

Izotov, Y. I., Thuan, T. X., 2002, ApJ, 567, 875

Kobulnicky, H. A., Zaritsky, D., 1999, ApJ, 511, 118

Koo, D. C., Bershady, M. A., Wirth, G. D., Stanford, S. A., Majewski, S. R., 1994, ApJ, 427, L9

Kulkarni, V. P., Fall, S. M., Lauroesch, J. T., York, D. G., Welty, D. E., Khare, P., Truran, J. W., 2005, ApJ, 618, 68

Lebouteiller, V., Kunth, D., Lequeux, J., Lecavelier des Etangs, A., Désert, J.-M., Hébrard, G., Vidal-Madjar, A., 2004, A&A, 415, 55

Lecavelier des Etangs, A., Désert, J.-M., Kunth, D., Vidal-Madjar, A., Callejo, G., Ferlet, R., Hébrard, G., Lebouteiller, V., 2004, A&A, 413, 131

Lemoine-Busserolle, M., Contini, T., Pelló, R., Le Borgne, J.-F., Kneib, J.-P., Lidman, C., 2003, A&A, 397, 839

Liang, Y. C., Hammer, F., Flores, H., Elbaz, D., Marcillac, D., Cesarsky, C. J., 2004, A&A, 423, 867

Maier, C., Meisenheimer, K., Hippelein, H., 2004, A&A, 418, 475

Petitjean, P., 1998, astro-ph/9810418

Pettini, M., Rix, S. A., Steidel, C. C., Adelberger, K. L., Hunt, M. P., Shapley, A. E., 2002, ApJ, 569, 742

Prochaska, J. X., Gawiser, E., Wolfe, A. M., Castro, S., Djorgovski, S. G., 2003, ApJ, 595, L9

Rigopoulou, D., *et al.*, 2000, ApJ, 537, L85

Rosenberg, J. L., Schneider, S. E., 2003, ApJ, 585,

Salvaterra, R., Ferrara, A., 2003, MNRAS, 340, L17

Schulte-Ladbeck, R. E., König, B., Miller, C. J., Hopkins, A. M., Drozdovsky, I. O., Turnshek, D. A., Hopp, U., submitted to ApJL 256

Schulte-Ladbeck, R. E., Rao, S. M., Drozdovsky, I. O., Turnshek, D. A., Nestor, D. B., Pettini, M., 2004, ApJ, 600, 613

Shapley, A. E., Erb, D. K., Pettini, M., Steidel, C. C., Adelberger, K. L., 2004, ApJ, 612, 108

Skillman, E. D., Côté, S., Miller, B. W., 2003, AJ, 125, 610

Steidel, C. C., Shapley, A. E., Pettini, M., Adelberger, K. L., Erb, D. K., Reddy, N. A., Hunt, M. P., 2004, ApJ, 604, 534

Storchi-Bergmann, T., Calzetti, D., Kinney, A. L., 1994, ApJ, 429, 572

Teplitz, H. I., *et al.*, 2000, ApJ, 533, L65

Thuan, T. X., Lecavelier des Etangs, A., Izotov, Y. I., 2005, ApJ, 621, 269

Vreeswijk, P. M., *et al.*, 2004, A&A, 419, 927

Yanny, B., 1990, ApJ, 351, 396