Chemical Abundances in Star-forming Galaxies and Damped Lyman Alpha Systems

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Abstract.
We investigate the chemical abundances of local star-forming galaxies which cause Damped Lyman Alpha lines. A metallicity versus redshift diagram is 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 ionized 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 that gas-rich galaxies had lower chemical abundances when they were younger.

Keywords. Galaxies: abundances, ISM, quasars: absorption lines

1. Introduction
The chemical evolution of the Universe is due to two channels. Big-bang nucleosynthesis generated several light chemical elements during “the first three minutes”. In the following 13 Gyr, the metals have been synthesized 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 $2 \times 10^{20} \text{cm}^{-2}$, are expected to be of the order of a few 10 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-ionized gas, and refer to the α-capture element oxygen (e.g., Garnett 2004). Figure 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...
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 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 
an 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 \([\text{O}/\text{H}]_{\text{II}}\) for HII regions and 
SFGs from the SDSS. These are ex- 
tended 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 
\([\text{O, S, Si}/\text{H}]_{\text{I}}\) from the compilation 
of Prochaska et al. (2003). The 
short-dashed lines show the maxi- 
mum 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 II provides a list of local SFGs exhibiting DLA lines in their own, UV spectra. Chem- 
ical abundances are referenced to the solar values of Holwege (2001). For oxygen this is 12 + 
log O/H = 8.736 ± 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 ionized 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, on Fig. 2.

† We use a cosmology with \(H_0 = 70\ \text{km s}^{-1}\text{Mpc}^{-1}\), \(\Omega_m = 0.3\), 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 Tab. 1, which display DLAs in their own spectra. For each SFG which is also a DLA, the bright symbols mark the ionized 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 – Overplotted here are the abundances of SFGs from Tab. 2, and the corresponding unambiguous abundances (or abundance limits) determined on the sightline to the QSO.

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

| Galaxy     | z      | log(N$_{HI}$) | Type | M_B   | L  | SFR  | [O/H]$_{II}$ | [O/H]$_{I}$ |
|------------|--------|---------------|------|-------|----|------|--------------|-------------|
| NGC 625    | 0.001321 | 20.5          | DIRR | $-16.3$ | 0.03 | 0.05 | $-0.6_{-1.4}^{+2}$ | $-1.4_{-1.1}^{+1}$ |
| NGC 1705   | 0.00210  | 20.20         | BCD  | $-15.8$ | 0.02 | 0.03 | $-0.5_{-1.4}^{+5}$ | $-0.7_{-1.1}^{+5}$ |
| I Zw 18    | 0.00250  | 21.34         | BCD  | $-14.3$ | 0.004 | 0.09 | $-1.56_{-1.46}^{+2.17}$ | $-2.1_{-1.46}^{+2.17}$ |
| Mrk 59     | 0.003631 | 20.8          | BCD  | $-17.5$ | 0.08 | 1.5  | $-0.75_{-1.7}^{+1}$ | $-1.7_{-1.7}^{+1}$ |
| I Zw 36    | 0.0094   | 21.30         | BCD  | $< -13.9$ | $>0.03$ | $<0.03$ | $-0.9_{-1.7}^{+5}$ | $-1.7_{-1.7}^{+5}$ |
| SBS 0335-052 | 0.013486 | 21.85        | BCD  | $-17.1$ | 0.04 | 1.3  | $-1.44_{-1.8}^{+10}$ | $-1.8_{-1.8}^{+10}$ |
| MS 1512-cB58 | 2.7276  | 20.85         | LBG  | $-22.0$ | 5.3  | $>100$ | $-0.5_{-0.4}^{+2}$ | $-0.4_{-0.4}^{+2}$ |

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)

The advantage of examining DLAs produced within SFGs by their own starburst clusters, is that the neutral and the ionized gas are probed on the exact same sightline. A disadvantage of this technique, is that the background sources are extended. The sightline also, traverses some ionized 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;
Table 2. SFGs causing Lyman alpha lines in background QSO spectra

| QSO         | Galaxy | a     | log(N_{HI}) | Type | L       | SFR  | (O/Hi) | (O/Hi) | α, other than O |
|-------------|--------|-------|-------------|------|---------|------|--------|--------|----------------|
| HS 1543+5921| 0.5    | SBS 1543+593 | 0.0096 | 20.3 | $S_m$ | -16.8 | 0.04   | 0.006  | -0.599        | -0.5^a S, Si |
| Q1543+489   | 107    | Galaxy 5  | 0.0382 | 18.4 | S      | -17.9 | 0.12   | 0.37   | -0.067        | > -0.45 S, Mg |
| PHL 909     | 140    | SDSS J005719 | 0.0622 | 17.7 | Sc     | -19.7 | 0.6    | 1.5    | -0.227        | ...          |
| PKS 0439-433| 7      | Object 1  | 0.1012 | 19.7 | Sb     | -20.2 | 1.0    | 0.4    | -0.035        | > -1.0 Mg, Si |
| PHL 909     | 19     | SDSS J005710 | 0.1237 | 18.5 | S      | -18.5 | 0.2    | 1.7    | -0.4^a        | > -1.2       |
| PHL 1226    | 17.6   | Galaxy G  | 0.1012 | 19.7 | S      | -20.0 | 0.8    | 0.5    | -0.045        | > -2.0       |
| Q1209+107   | 38     | Galaxy 19/4 | 0.0930 | 19.5 | S      | -18.5 | 0.2    | 1.7    | -0.4^a        | > -1.2       |
| B2 0827+243 | 36     | G1      | 0.525   | 20.3 | S      | -19.8 | 0.68   | 0.08   | > 0.066       | > -2.8 S, Si |

Note: The α values were derived assuming the optically thin case and applying the approximation formula from Schulte-Ladbeck et al. (2005).

Table 2 summarizes the result for a few additional SFG/QSO pairs, for which we were able to list α-element abundances in the ionized 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 [α/H] 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 by 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.

and indeed, some GRBs exhibit Lyman α emission lines in their DLA troughs. At this time, abundance analyses of the ionized 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 DLAs in the galaxy SBS 1543+593 in emission and absorption. The background QSO HS 1543+5921 has an impact parameter of 2.4", and intercepts the dwarf galaxy’s disk close to its center. SBS 1543+593 offers an excellent opportunity to directly compare element abundances inferred from cool interstellar gas (DLAs) and ionized gas (SFGs). None of the previously imaged DLA galaxies resolves to show individual HII regions. In none of them, does the sightline to the QSO intercept the disk of the galaxy close to its center, eliminating concerns over disk metallicity gradients.

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

On Fig. 3 we show [S/H]_{II} for the neutral-gas abundance, and [O/H]_{II} for the ionized-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, the 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 practice, 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).
4. Conclusions

- Emission and absorption diagnostics of one SFG/QSO pair giving rise to a DLA, are shown to give the same $\alpha$-element abundances for the ionized 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

The paper makes use of publicly available SDSS data. The SDSS website is [http://www.sdss.org/](http://www.sdss.org/). Chris Miller is thanked for providing the catalog of line fluxes from which the SDSS HII-region and SFG metallicities were derived. This paper was funded in part by NASA HST archival project 10282. We thank the School of Arts & Sciences for support.

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