CHEMICAL EVOLUTION OF SPIRAL GALAXIES FROM REDSHIFT 4 TO THE PRESENT

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1. Introduction

ISM abundances in nearby spiral galaxies are well known from HII region studies (Zaritsky *et al.* 1994). While early type spirals, Sa, Sb, have rather uniform abundances and a narrow range of present star formation rates (**SFR**) the galaxy-to-galaxy variations both in HII region abundances and in present SFR increase towards late spiral types Sc, Sd (see e.g. Kennicutt & Kent 1983). ISM abundances of spiral galaxies or their progenitors up to the highest redshifts can be studied via the absorption properties imprinted in the spectra of background QSOs. While MgII- and CIV- absorption lines are produced in the low column density gas of the extended haloes around galaxies, the Damped Lyα Absorption (**DLA**) is believed to originate in (proto-)galactic disks. High resolution spectroscopy of a large number of metal lines associated with DLA systems reveal the redshift evolution of ISM abundances from z $\gtrsim$ 4 to z $\sim$ 0.6.
We present a chemo-cosmological evolution model to explore a possible link between high redshift DLA systems and nearby spirals. Inclusion of a spectrophotometric description in parallel to the chemical modelling together with the enormous time baseline corresponding to the redshift range until z $\sim$ 4 allow the galaxy parameters to be seriously constrained.

2. Galaxy Models

Any kind of evolutionary galaxy model requires two fundamental parameters: the star formation history (**SFH**) and the initial mass function (**IMF**). For a given set of input physics – stellar evolutionary tracks, yields, spectra, ... – these two parameters govern both the spectral and the chemical evolution of a model galaxy.

Our unified chemical and spectrophotometric galaxy evolution model describes in detail the spectrophotometric evolution in terms of luminosities $L_U, \ldots, L_K$, colours, gaseous emission lines, stellar absorption indices, and the chemical evolution in terms of ISM abundances of individual elements ^{12}C, ... , ^{56}Fe, including SNI contributions from carbon deflagration white dwarf binaries á la Matteucci (1991). All these quantities are obtained as a function of time, and, for a given cosmological model – characterised by H_0, Ω_0, Λ_0 and a galaxy formation redshift z_{form} – in terms of redshift z.

A specific virtue of this kind of evolutionary model is its analytic power. Luminosities at any wavelength and the enrichment of any element are readily decomposed into contributions from different stellar masses, spectral types, luminosity classes, metallicity subpopulations, nucleosynthetic sites (PNe, SNI, SNII, single stars, binaries, ...), and all this can be followed as a function of time or redshift. It's a simplified 1 − zone model without any dynamics or spatial resolution but it consistently accounts for the finite lifetime of each star, i.e. it does not use an Instantaneous Recycling Approximation.

To cope with the low metallicities of DLAs we have recently extended our code to consistently account for the increasing metallicities of successive generations of stars by using sets of input physics (stellar tracks, yields, spectra, ...) for a range of metallicities from $Z = 0$ to $Z = 2 \cdot Z_\odot$. Sources for the stellar yields for various metallicities are v. d. Hoek & Groenewegen (1997) for stars with masses $m_* \leq 8\ M_\odot$ and Woosley & Weaver (1995) for stars in the range $12 \leq m_* \leq 40\ M_\odot$.

We use different SFHs for the different galaxy types in order to assure detailed agreement of our model galaxy spectra with template spectra for the respective spectral class from Kennicutt (1992). While ellipticals and haloes are well described with a SFR exponentially decreasing in time, spirals are more adequately described by SFRs that are linear functions of the evolving gas content G(t). Characteristic timescales for SF t_*, as defined by the decrease rate of the initial gas content G_0: $\int_0^{t_*} \Psi \cdot dt = 0.63 \cdot G_0$ are $t_* \sim 1$ Gyr (Es & Halos), $t_* \sim 2$ Gyr (Sa), ~ 3 Gyr (Sb), ~ 10 Gyr (Sc), ~ 16 Gyr (Sd).

While spectrophotometric modelling in comparison to observed galaxy spectra and colours allows for reasonable determinations of the SFHs of galaxies of various spectral types it gives only weak constraints on the IMF. Detailed chemical modelling, on the other hand, constrains both the SFHs **and** the IMF through comparison with observations of the redshift evolution of abundances and abundance ratios of elements originating from different nucleosynthetic sites, as e.g. [C/O], [O/Fe], or [Mg/Fe], for an enormous time baseline. The lookback time to redshifts $z \sim 4$ corresponds

to $\gtrsim 90\%$ of the Hubble time.
Fritze - v. Alvensleben *et al.* (1989, 1991) model the redshift evolution of halo abundances and compare with MgII- and CIV- data. HST observations of CIV at low redshift (Bahcall *et al.* 1993) confirm our prediction for carbon.

3. Redshift Evolution of DLA Abundances

Damped Lyα Absorbers usually feature a series of associated low ionisation absorption lines, e.g. of C, N, O, Al, Si, S, Cr, Mn, Fe, Ni, Zn, ...
High resolution spectra allow to derive precise element abundances, which are, by now, available for a large number of DLAs over the redshift range from z ~ 0.6 through z $\gtrsim 4.4$ (Lu *et al.* 1996, Pettini *et al.* 1997). Considerable care is taken to resolve the velocity structure, to only use non- (or weakly) saturated lines and dominant ionisation stages, and to a possible depletion onto dust grains that may vary dramatically from ~ 0 % (for Zn) to $\gtrsim 90$ % (for Cr). We have compiled all available DLA abundances and have carefully referred them all to one "standard" set of oscillator strengths and solar reference values. Observational abundances of DLAs show a weak increase with decreasing redshift – in particular if compared to CIV - halo - systems – and a large scatter at any redshift.

4. Comparison of DLA Abundances with Models for $Z_\odot$

For our modelling approach it would not matter if indeed they highest redshift DLA systems were a bunch of subgalactic fragments rather than one single protodisk. As long as the ensemble of fragments is bound to merge into the counterpart of a present-day galactic disk our model SFH is then meant to describe the SFH of the ensemble.
Using solar metallicity stellar yields, lifetimes and evolutionary tracks as input physics for our modelling, a Scalo IMF, and a "standard cosmology" ($H_0 = 50, \Omega_0 = 1, \Lambda_0 = 0, z_{form} = 5$), we find the following results (Fig. 1):

- Sa – Sd models nicely bracket the DLA abundance data, i.e.,
- for SF timescales t_* typical of spiral galaxies we find an evolution of abundances (and element ratios) which is in good agreement with observations of DLAs over a large portion of the Hubble time,
- the models provide a smooth transition from DLAs to nearby spirals' HII region abundances (Zaritsky *et al.* 1994),
- the range of SF timescales t_* as empirically derived for the near-by Hubble sequence of spiral galaxies from Sa through Sd fully explains the observed scatter of metallicities among DLAs at fixed redshift.

(cf. Fritze - v. Alvensleben & Fricke 1995, Fritze - v. Alvensleben 1995).

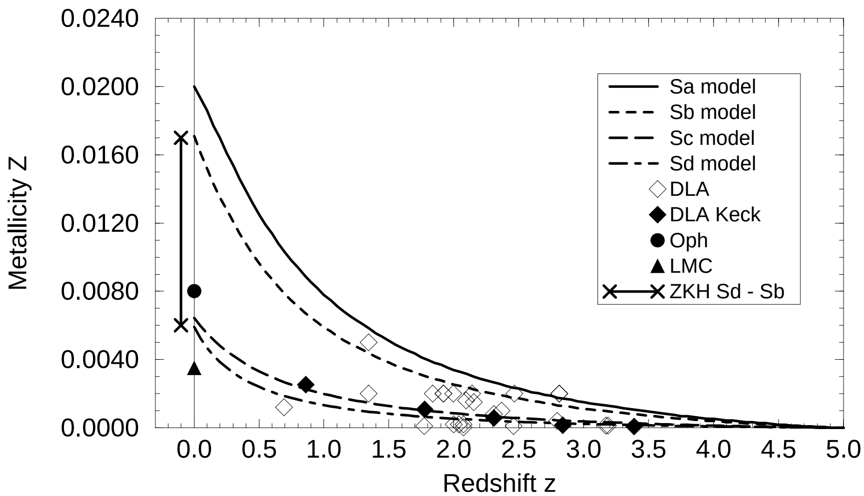

Figure 1. Redshift evolution of the global metallicity: spiral models vs. DLA. ZKH: range of HII region abundances in nearby spirals of types Sb through Sd (Zaritsky *et al.*). $(\mathrm{H}_0, \Omega_0, \mathrm{z}_{\mathrm{form}}) = (50, 1.0, 5)$.

We conclude: Our chemical evolution models confirm the hypothesis that DLA systems could be the progenitors of present day spirals and predict early as well as late type spirals to be among the DLA sample.
In a complementary investigation Lindner *et al.* (1996, 1998) compare the spectrophotometric results from our unified chemical **and** spectrophotometric model to a large sample of optically identified QSO absorbers.

5. Results from our Chemically Consistent Modelling

In view of the low metallicities of DLAs a chemically consistent description is clearly desired. A problem with this approach is that important pieces of input physics, as e.g. stellar yields, explosion energies, lifetimes, mass loss rates, the final fate of a star and its remnant mass for very low metallicities are far from being fully understood. In this sense, the first results we now present from our chemically consistent modelling deserve some caution.

Due to the complicated behaviour of the yields for individual elements as a function of stellar mass and metallicity, changes in the redshift evolution of chemically consistent models with respect to solar metallicity models vary for different elements, and, of course, also with galaxy type (=SFH).

For Zn, the most common metallicity tracer in DLAs, our Sa – Sd models nicely bracket recent and precise DLA abundance data over the redshift range $0.6 \lesssim z \lesssim 3.5$ as seen in Fig. 2.

Abundance ratios change drastically as compared to solar metallicity models. This has far-reaching consequences e.g. for the interpretation of the

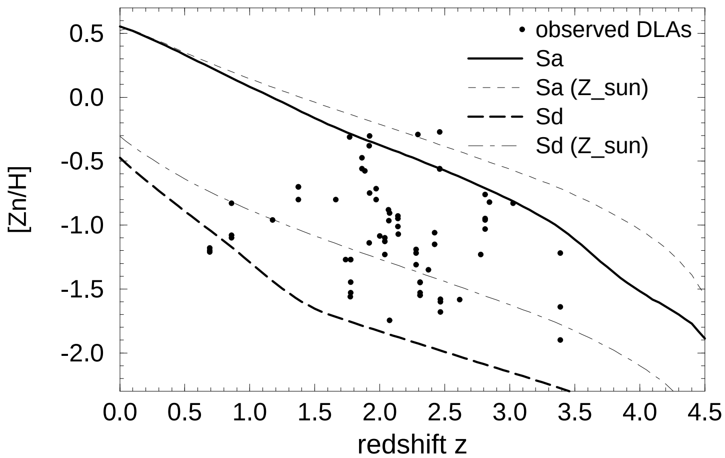

Figure 2. Redshift evolution of [Zn/H] for spiral galaxy models together with DLA data.

stellar [Mg/Fe] in elliptical galaxies (see Fritze - v. Alvensleben 1998).

It is clearly desirable to extend this study to other elements with high resolution data. Our model offers a unique possibility to study the redshift evolution of the Global Cosmic SFR in the Universe including consistently all three observational accesses: gas content, chemical enrichment and spectral properties.

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