THE CHEMICAL EVOLUTION OF THE UNIVERSE

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ABSTRACT
We are encouraged by the improving abundance measurements for quasar damped absorption line systems to start a new study of galaxy chemical evolution from high to low redshifts. Our goal is a simple, robust model based on a synthesis of our best understanding of the relevant physics, such as cosmology, large-scale structure formation, galaxy collapse, star formation and chemical evolution. Our initial model assumes continuous quiescent star formation, and no galaxy mergers. We use this galaxy chemical evolution model to study the properties high column density gas out to high redshifts, as revealed by damped Lyα absorption (DLA). We find that there is a significant population of dwarf galaxy DLA systems at moderate redshift (z ∼ 2.5), which would not have been accessible to previous imaging surveys around DLA quasars. Our model also provides a reasonable prediction of the global star formation history of the Universe as measured from the UV luminosity density. The next theoretical step is clearly to allow galaxy mergers and hence, model the effects of major bursts of (probably dust-enshrouded) star formation. We are also using time-delayed element production to probe stellar populations in DLA galaxies.

Key words: Stars: formation – Galaxies: evolution

1. INTRODUCTION
Some of the most detailed observations which we can make of external galaxies are spectroscopic, yielding reliable measurements of gas phase metallicities. Of particular interest are the systems with high neutral hydrogen column densities which are found via Lyα absorption lines in the spectra of high redshift quasars: the damped Lyα absorbers (DLAs). These DLAs may be signatures of normal galaxies at redshifts 0.1 < z < 4.5, which we can only detect because of the chance alignment with a background quasar along our line-of-sight. Because of the high overall gas column density (20 < log (NHI [cm⁻²]) < 21.8), it is possible to detect numerous metal line species and hence infer a range of metal abundances. The database of DLA abundance data in the literature is growing steadily (see Mathlin et al. 2000 and references therein). Meanwhile, major technological advances are underway, with numerous eight-metre class optical telescopes and adaptive optics systems being commissioned which will greatly improve our observations of distant galaxies. The time is ripe for a new synthesis of our knowledge of the formation and evolution of galaxies, in order to produce robust theoretical predictions which can be confronted by these exciting new observations. This contribution outlines such a project, which is described in much more detail in the forthcoming paper Mathlin et al. 2000.

(Nota: All calculations assume an Einstein-de Sitter cosmology (Ω = 1) with a present-day Hubble parameter H₀ = 100h km⁻¹ s⁻¹ Mpc⁻¹ determined by h = 0.7, unless otherwise stated.)

2. A SIMPLE, ROBUST MODEL
We do not yet have a complete physical understanding of many of the mechanisms and processes by which galaxies evolve in their element abundance makeup. A particularly important area is the physics of the formation, evolution and death of stars, and the consequences of stellar processing for evolution of the gas in galaxy potential wells. Our cosmological models of the Universe, and of the formation of large scale structure, and galaxies, are also uncertain. However, a number of very simple, yet surprisingly robust ‘preliminary’ models or parameterisations do exist. Therefore, to build a chemical evolution model of high redshift galaxies, we have selected the closest to a consensus model which exists in each astrophysical area. We use an Einstein-de Sitter cosmology (Section 2.1.1), a Schmidt Law for star formation (Section 2.1.2), assume constant, universal stellar yields, and we use the Simple Model of chemical evolution (Section 2.1.3). We also make a number of simplifying assumptions at this initial stage, which are being investigated and relaxed where appropriate as the model is tested and developed. We assume a universal baryon fraction by mass f_b = 0.1, that the internal structure of galaxies can be neglected, that there are no gas flows (e.g. inflows or outflows, such as accretion, supernovae or mergers), that all elemental species are ‘prompt’ (no time delays or secondary element nucleosynthesis), and in later stages, that the Holmberg size-luminosity relation for galaxies is valid (Section 3.2.1). Each of these assumptions is discussed in detail in Mathlin et al. 2000. This is an extremely simple model, which should how-
ever be robust and easy to interpret, because the input assumptions are clear, and well understood.

2.1. The basics of the model

We start by constructing the simplest physically reasonable model of a galaxy, which is a homogeneous spherically-symmetric cloud of matter, described by a total mass $M$, and an initial radius $R_0$. The initial mass of baryons $M_b = f_b M = 0.1 M$. We study model galaxy clouds with total gravitational masses in the range $10^8 < M/M_b < 10^{12}$, and the baryonic component is assumed to be primordial gas, which can form stars and contribute to the column density.

2.1.1. Cosmology

We initially adopt the simplest cosmological model which is commonly considered, the Einstein-de Sitter universe. This is the ‘critical’ Universe, which is exactly closed by the matter density so that $\Omega = 1$. In line with the best observational evidence, we adopt Hubble parameter $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. We assume that structure forms in a ‘bottom-up’ fashion.

2.1.2. Galaxy formation

Each model galaxy cloud will ‘form’ when it breaks away from the Hubble expansion, and starts collapsing to form a gravitationally bound system, at a redshift which is determined by its fractional overdensity (relative to the average density of the Universe at that epoch). Small length scales will ‘turn around’ first (see Peebles 1993 for extensive discussion). We halt the collapse of each galaxy at $r = 0.1 R_0$, and allow each galaxy to continue to evolve at constant size. We do not allow galaxies to interact or merge, which is an important assumption which has significant consequences for the chemical evolution of each galaxy (Section 2.1.4), and for the global star formation history of the model Universe (see Section 3.3). There is as yet no known galaxy initial mass function, but where necessary, we will simulate one using the the Holmberg Relation between galaxy size and luminosity (Section 3.2.1).

2.1.3. Star formation

We allow the baryonic gas in the model galaxy clouds to form stars according to a very simple Schmidt law, dependent only upon total gas volume density. Kennicutt has demonstrated that such a prescription is a remarkably good representation of star formation rates under a wide range of physical conditions in present day galaxies. We adopt the form

$$\Gamma = \kappa \rho_{\text{gas}}^n$$

where $\Gamma$ is the star formation rate density, and we set the constant $n = 1.5$ (guided by Kennicutt 1998). We also set the constant $\kappa = 1.45 M_\odot^{-0.5} \text{pc}^{1.5} \text{Gyr}^{-1}$ (consistent with Churches 1999), and resist the temptation to fine-tune this parameter, since we have no astrophysically robust prescription for such variations. We have used present day galaxy gas fraction measurements to guide us in our choice of $\kappa$, which results in reasonable values across the whole range of initial galaxy cloud masses we consider.

We do not impose a specific stellar Initial Mass Function (IMF). However, we assume a constant, universal yield of metals in our chemical evolution prescription (Section 2.1.4), which is consistent with a constant, universal IMF.

As part of our galaxy evolution models, we automatically keep track of the total mass locked up in long-lived stars and stellar remnants, and we also calculate the instantaneous mass passing through the current generation of short-lived stars. This immediately allows us to make a crude estimate of the relative blue and red luminosities of each model galaxy cloud at each redshift. A more sophisticated analysis will use stellar synthesis codes.

2.1.4. Chemical evolution

We use the Simple Model of chemical evolution (Edmunds 1990; Pagel 1997). We assume that, in each generation of stars, a fraction $\alpha$ of the gas which was consumed becomes locked up in long-lived stars and stellar remnants, and is hence removed from the gas phase and is not available to subsequent generations of star formation. We assume each galaxy cloud is a ‘closed box’, so that there are no inflows nor outflows of any gas. This is consistent with our assumption that there are no galaxy interactions nor mergers. We use the instantaneous recycling and complete mixing approximations, so that the heavy elements created by each stellar generation are immediately and uniformly redistributed through the gas cloud.

2.1.5. Model Galaxy Cloud Evolution

Taking all these ingredients, we can allow model galaxy clouds to form and evolve, and track the changes in metallicity and column density as cosmic time elapses (see Edmunds 1990; Pagel 1997). Therefore, we can now calculate the key observable physical parameters of DLAs, the absorption redshift $z_{\text{abs}}$, the neutral hydrogen column density $N_{\text{HI}}$ and the metallicity $[Z/H]$. There is an implicit fourth observable parameter, the optical depth $\tau$ of the DLA system along our line-of-sight, which must be sufficiently low to enable us to detect the background quasar (see Section 3.1.2).

3. Comparison with Observations

There are about 100 DLAs in the literature for which absorption redshift, HI column density and (in most cases) some measure of metal abundances are catalogued. In par-
ticular, thanks to the concerted efforts of Pettini and collaborators, there are approximately 40 DLAs with measurements or limits on the gas phase zinc abundance \([\text{Zn}/\text{H}]\). In principle, we would like to use iron and oxygen as our primary abundance indicators. However, few observations of \([\text{O}/\text{H}]\) have yet been recorded for DLAs. As far as \([\text{Fe}/\text{H}]\) is concerned, there are extensive DLA measurements, but it is likely that iron is significantly depleted into the solid dust phase, and therefore, the observed gas phase \([\text{Fe}/\text{H}]\) is very likely an underestimate of the true metallicity (Pettini et al. 1994). It is thought that, as an iron group element, zinc tracks iron during stellar nucleosynthesis. It is also known that zinc is significantly less depleted than iron, and therefore should more accurately probe the gas phase abundance. This is why there has been a campaign to obtain \([\text{Zn}/\text{H}]\) measurements for DLAs, and why we are utilising these data for comparison with our theoretical chemical evolution predictions. An important caveat is that the precise stellar origin of zinc remains unclear, and it may have significant prompt and delayed contributions (Pagel 1997).

We can therefore directly compare the column density and metal evolution of some of our model galaxy clouds with the DLA data, as shown graphically in Fig. 1. In panel a), the model galaxy cloud tracks start when the protogalaxy detaches from the Hubble expansion, and are shown as dashed lines when we estimate that the cloud will become optically thick (presumably obscuring the background quasar, and hence becoming undetectable). Each track is for a cloud of different mass (increasing to higher column density) forming at a different redshift. In panel b), we have used the observed zinc abundance as a probe of the overall metallicity, and each track represents a different formation redshift (mass is degenerate in this parameter space, because the chemical evolution depends only upon density through the Schmidt star formation law).

It is clear that the most simple model produces galaxy cloud evolution which comfortably explores most of the observed regions of (redshift, column density, metallicity) parameter space for DLAs. There are just a few systems with zinc metallicities which are higher than can be explained by any of our model galaxy cloud evolution tracks, mostly in the region \(2 < z < 3\).

3.1. Galaxy gradients in dusty disks

The next stage in the development of our theoretical model is to drop the assumption that galaxy internal structure is negligible. We choose to do this by allowing our model galaxy clouds to possess gas, metallicity and dust gradients as have been observed for nearby disk galaxies.

\[ [\text{Z}/\text{H}] = \log \left( \frac{n_\text{Z}}{n_\text{H}} \right) - \log \left( \frac{n_\text{Z}}{n_\text{H}} \right)_\odot \]

where \(n_\text{Z}\) is the number of atoms of Z, and \(\odot\) indicates Solar values.

3.1.1. Exponential radial gradients

We assume purely radial variations, and parameterise the abundance gradient as \(\log Z(r) = a - br\) where Z is the fraction of metals by mass, \(a\) is the central metal fraction, and the slope \(b \sim 0.2\) dex/scalelength. We calibrate this relationship against our Galaxy by noting that \([\text{Z}/\text{H}]_\odot \sim 0.017\) at the Solar circle \(r_\odot \sim 8\) kpc. We adopt a universal galaxy stellar scalelength of \(h_\ast \sim 7\) kpc, typical of giant disk galaxies, and assume that the gas scalelength is the same as the stellar scalelength, \(h_{HI} = h_\ast\).

![Figure 1. A comparison between the properties of observed damped Lyα systems and the evolution of individual model galaxy clouds. All the data available in the literature are shown as data points, and the model evolution tracks are overplotted (using a dashed line if the cloud is optically thick in dust (see Section 3.1.3)). (a) HI column density \(N_{HI} \text{ cm}^{-2}\) (b) Metallicity measured from zinc ([Zn/H])](attachment:figure1.png)
3.1.2. Estimating dust opacity

If a DLA is to be detected, there must be a suitable background quasar in the catalogues, which are often compiled at blue wavelengths. The quasar must also be bright enough to allow high resolution, high signal-to-noise spectroscopy. The optical depth of the foreground DLA galaxy must therefore not be sufficient to redden and obscure the background quasar beyond the quasar survey and spectroscopic magnitude limits.

We can easily estimate the maximum dust optical depth of our model galaxy clouds as a function of redshift and galaxy radius, using the column density, gas fraction by mass, and radial gas gradient (see Eales & Edmunds 1998). We assume that the dust properties are similar to Galactic dust at all redshifts, and we assume that a fixed fraction ($\eta \sim 0.5$) of metals will condense into the solid phase. The maximum dust opacity then just a function of the gas column density and the gas fraction, and so the opacity gradient will track the gas gradient.

This calculation implies that the maximum dust opacity through the disk in the centre of our Galaxy is $\tau_{\text{dust}} \sim 6$, which is a believable firm upper limit, despite uncertainties in the central HI column density in galaxies. We also predict $\tau_{\text{dust}} < 1.3$ at the Solar circle, which is consistent with observations.

3.1.3. The properties of DLA galaxies

We now have a family of homogeneous model galaxy cloud evolutionary tracks, and a prescription for the radial variation in gas, metal and dust properties within each galaxy. We therefore have a large set of possible DLA properties, which are defined by putting a random line-of-sight through any model galaxy cloud, and reading off the properties at the radius of intersection. By relaxing the assumption of cloud homogeneity, the predicted DLA parameters encompass the region below the fiducial tracks in Fig. 2, reaching $N_{\text{HI}} = 20$, and $\Delta ([\text{Zn/H}]) = 0.6$ respectively.

In principle, these theoretical sets of parameters might not correspond to anything which is actually observed. The predictions might also be degenerate, with numerous model galaxy clouds reproducing one column density and metallicity pair at a given redshift. But in fact, for almost every known DLA, we have been able to find a unique model galaxy cloud which has the appropriate column density and metallicity at the observed redshift, within the observational error bars. An example is shown in Fig. 2, for a DLA observed in the spectrum of the quasar Q1354 + 258.

We have therefore reached an important milestone in our study. We can now take the observed properties of a damped Ly$\alpha$ absorption system, and use our model to make some definite predictions about the properties of the underlying galaxy. In particular, for Q1354 + 258, we predict relatively massive galaxy, with a baryonic mass $M_b \sim 10^{10} M_\odot$ (and so, a total gravitational mass $M \sim 10^{11} M_\odot$) which formed at a redshift $z_{\text{turn}} \sim 4.5$. As noted in Section 2.1.3, we can also roughly calculate the luminosity of the young and old stellar populations. For Q1354 + 258, we predict $B \sim 26$ and $K \sim 20$. We also predict that the nucleus of the DLA galaxy lies about 5 kpc from our line-of-sight to the quasar.

We now know where to look on the sky, and in blue and red apparent magnitude space, to try and directly detect the DLA galaxy itself. These are very interesting predictions from an observational point-of-view. Furthermore, some interesting patterns start to emerge as we extend the modelling to all the individual DLAs for which $[\text{Zn/H}]$ measurements exist. Approximately half of all the underlying DLA galaxies are far less massive than that implicated in the Q1354 + 258 system. We therefore predict that approximately half of DLAs in the redshift range
$1 < z < 3$ are due to absorption occurring in dwarf galaxies, in stark contrast to the ‘standard model’ of DLA galaxies as the progenitors of present day giant disk galaxies. This in turn implies that although the majority of DLA galaxies are going to be exceedingly faint at optical wavelengths, a significant fraction should be detectable in the near-IR, above $K \sim 20.5$. Our model allows us to clearly predict which DLA galaxies are mostly likely to be accessible to currently observational technology. We are therefore in a position to use our model to construct a well-motivated experimental observational programme, to make high spatial resolution near-IR imaging observations of carefully selected DLA quasars. We hope to be able to report the results of such a programme soon.

### 3.2. The distribution of DLAs in parameter space

What is the probability that a random line of sight will pass through a damped Ly$\alpha$ galaxy with a given column density at a given redshift? We can make a rough calculation, since we know the cross-sectional area and column density of our model galaxy clouds, given that we have a cosmological model and a galaxy initial mass function. Since the galaxy IMF is not yet known, some other prediction of a galaxy mass-formation relation, or equivalently, a galaxy mass-radius relation, must be found.

#### 3.2.1. The Holmberg Relation

There does exist a well-known linear correlation between galaxy absolute magnitude and the logarithm of galaxy radius, as originally described by Holmberg (1975). We have converted this into a galaxy mass-radius relationship by assuming a constant, universal mass-to-light ratio. This means that all galaxies of a given mass have the same present-day radius, and hence, the same turn-around radius $R_0$, the same turn-around density, and the same turn-around or formation redshift. We can now construct a statistically meaningful Universe where the galaxies of the lowest mass turn around at the highest redshift. We constrain our Universe to reproduce the Schechter form of the observed present-day overall galaxy luminosity function (Binney & Merrifield 1998). Therefore, as cosmic time advances, we ‘march down’ the Schechter function, forming fewer and fewer galaxies of larger and larger mass as we approach $z = 0$.

A serious caveat is that there are strong indications that the Holmberg relationship may be an artifact of a combination of observational selection effects. There are reasons to believe that compact, luminous galaxies are missed in surveys because they are mistaken for stars, and that diffuse, faint galaxies (the famous Low Surface Brightness galaxies) are also missed against the sky background. An important development of our theoretical framework will be to discard the Holmberg Relation and find a better prescription for the galaxy birth function.

#### 3.2.2. Random lines of sight

We have chosen to make one calculation of the probable DLA properties along a random line of sight in our standard Einstein-de Sitter cosmology. We have also repeated the exercise for a low density Universe ($\Omega = 0.3$). The results are shown in Fig. 3 as a grey scale of the logarithm of the probability that a random line of sight will intersect at that point in column density-redshift parameter space. (Note that we cannot calculate the probability across the entire graph - the regions which are white are undefined because we do not have model galaxy clouds which track through those parameter regions.)
It is clear from panel a) that we have extreme difficulty in explaining the existence of high column density systems at high redshift in an Einstein-de Sitter Universe with our current model. In the low density Universe (panel b), we seem to broadly be able to understand the spread of the observed DLA population. It is tempting to use this as evidence for or against particular cosmological models. However, it is vital to recall that in general, it is impossible to separate cosmological evolutionary effects from the characteristics of an evolving population of astronomical objects. This can only be done on the basis of a firm independent understanding of the physics and evolution of the astronomical objects in question. This trap for the unwary has resulted in overly confident cosmological pronouncements in the past.

There are also important subtle observational selection effects operating in the selection of DLA galaxies. Technological and physical limitations mean that spectroscopic measurements are best for systems around \( z \sim 1 \) (space-based UV data *e.g.* HST) and \( 2 < z < 3 \) (ground-based optical data). Meanwhile, although damping wings start to appear in the Ly\( \alpha \) line at column densities \( \log N_{HI} \sim 19 \), the effect is very difficult to reliably detect below \( \log N_{HI} \sim 20 \). Also, as alluded to above (Section 3.1.2), concerns about the foreground DLA obscuring any background quasar become significant at the higher column densities. Therefore, we can only hope for a relatively uniform *observational* selection function in two small ‘boxes’ in column density-redshift space.

There are thousands of quasars in the catalogues, of which fewer than 1% are currently known to have DLA systems in their spectra. It is difficult to calculate reliable statistics for the complete population of known quasars. The shape of our predicted probability distribution around \( z \sim 2.5 \) appears to be broadly correct, rolling off towards higher column densities, and fairly flat towards the observational cutoff at \( \log N_{HI} = 20 \). However, we appear to be predicting that 10% of quasars should have a moderate redshift DLA system (\( z \sim 2.5 \)), which clearly contradicts the observations.

### 3.3. The Star Formation History of the Universe

There has been much recent excitement about ‘measurements’ of the evolution of the star formation rate by mass per co-moving volume with cosmic time. Once we have specified the birth function of galaxies, and the star formation law in our model, we too can calculate this quantity. We have specified the birth function of galaxies, and the star formation law in our model, we too can calculate this quantity. The results are shown in Fig. 4. We have not attempted to make a fit to the observational values for the star formation rate evolution. The rough predictions shown are a consequence of the parameters which we have chosen for the Holmberg galaxy size-luminosity relation and the Schmidt star formation law, subject to the general constraints that present-day galaxies should exist, spanning the range of mass from dwarf to giant, and should still contain some hydrogen gas (rather than turning into ‘ball bearings’ with only metals).

The comparisons between our rough model predictions and the star formation rate evolution predicted from measurements of the UV luminosity density evolution of the Universe are very thought-provoking. Remember that we have not allowed our galaxies to merge, and therefore, there is no interaction or merger-induced starburst activity included in our models. Merger-induced bursts of star formation are closely linked with highly dust-embedded, infrared-luminous galaxies (Clements et al. 1996), which have extremely low UV luminosities. Much controversy has surrounded the contribution of such dust-embedded star formation to the overall budget for the conversion of gas to stars, which must largely be missing from UV based calculations such as those of Steidel et al. 1999. Since this star formation mode is not yet included in our models, our rough predictions should be quite directly comparable to the UV star formation rate measurements. It is clear from Fig. 4 that our model galaxy clouds are forming stars at approximately the same rate as can be observed in the UV in the real Universe, and during approximately the same period in cosmic time. Just as clearly, our rough prediction for the current UV luminosity from star formation is significantly too high. We could fine-tune this by tuning \( \kappa \) in the Schmidt law, but this would over-predict the star formation rate at higher redshifts. We could tweak the Holmberg relation to compensate for that effect, but this will not be very instructive (see Section 3.2.1).
4. Conclusions and Further Work

The extremely simple galaxy chemical evolution model which we have described in this contribution has been remarkably successful and informative when applied to the study of galaxies detected as damped Lyα absorption systems in the spectra of quasars. We have gained sufficient insight to make definite predictions about the nature of the DLA galaxies. Our models suggest that, contrary to some expectations, perhaps half the DLA systems at moderate redshifts \((z \sim 2.5)\) arise in dwarf galaxies. These dwarf DLA galaxies will be faint systems at low impact parameters \((5 - 10 \, \text{kpc})\) to our line-of-sight to the quasar. This prediction makes sense of the relative lack of success of previous imaging searches for moderate-redshift DLA galaxies (e.g. [Aragón-Salamanca, Ellis & O’Brien 1996]). In our current theoretical framework, we would expect that at high redshifts \((z > 3)\), the population of galaxies selected as DLA absorption systems would be dominated by dwarf galaxies, since giant galaxies are yet to form. At low redshifts \((z < 1)\), the giant galaxies would dominate the DLA population.

However, at this stage, we have pushed this first model to its very limits, and now need to start exploring the consequences of relaxing some of the more stringent assumptions. In particular, the next theoretical iteration is already underway, to allow mergers between model galaxy clouds, to find a robust prescription for the galaxy IMF, and to consider the chemical evolution of delayed element products of stellar nucleosynthesis. These extra theoretical elements will enable us to include the effects of merger-induced (probably dust-enshrouded) star formation in our chemical evolution models, to make much firmer statistical predictions about the DLA galaxy population, and to study potential dust, ionisation and stellar population variations in DLA galaxy evolution. The results will be presented in [Baker et al. 2000].

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