Star formation and chemical evolution of damped Lyman α systems

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Accepted 2000 November 8. Received 2000 October 10; in original form 2000 May 5

ABSTRACT

In this paper, we investigate the star formation and chemical evolution of damped Lyman-α systems (DLAs) based on the disc galaxy formation model which is developed by Mo, Mao & White. We propose that the DLAs are the central galaxies of less massive dark haloes present at redshifts \( z \sim 3 \), and they should inhabit haloes of moderately low circular velocity. The empirical Schmidt law of star formation rates, and closed box model of chemical evolution that an approximation known as instantaneous recycling is assumed, are adopted. In our models, when the predicted distribution of metallicity for DLAs is calculated, two cases are considered. One is that, using the closed box model, empirical Schmidt law and star formation time, the distribution of metallicity can be directly calculated. The other is that, when the simple gravitational instability of a thin isothermal gas disc as first discussed by Toomre is considered, the star formation occurs only in the region where the surface density of gas satisfies the critical value, not everywhere of a gas disc. In this case, we first obtain the region where the star formation can occur by assuming that the disc has a flat rotation curve and rotational velocity is equal to the circular velocity of the surrounding dark matter halo, and then calculate the metallicity distribution as case one. We assume that star formation in each DLA lasts for a period of 1 Gyr from redshifts \( z = 3 \). There is only one output parameter in our models, i.e. the stellar yield, which relates to the time of star formation history and is obtained by normalizing the predicted distribution of metallicity to the mean value of \( 1/13 \ Z_\odot \) as presented by Pettini et al. The predicted metallicity distribution is consistent with the current (rather limited) observational data. A random distribution of galactic discs is taken into account.

Key words: galaxies: formation - galaxies: evolution - galaxies: stellar content.

1 INTRODUCTION

Damped Lyman-α systems (DLAs) are high column density (the HI column density is higher than \( 10^{20.3} \) \( /cm^2 \)) absorbers detected in the optical spectra of quasars up to relatively high redshift (up to \( z \sim 5 \)), and can be used to probe the cosmic chemical evolution, i.e. the gaseous evolution of gas, metallicity and star formation rates in the Universe. DLAs are now generally believed to be the progenitors of present-day galactic discs (Wolfe et al. 1986; Wolfe 1988). This view is supported by the arguments based on mass estimates, which are from the column densities and absorber sizes at redshifts \( z \sim 2 - 3 \), as well as by the kinematic features consistent with models of fast-rotating (at velocities of order \( 200 \) km s\textsuperscript{-1}), thick discs (Prochaska & Wolfe 1997a,b, 1998; Wolfe & Prochaska 1998). At the same time, on the basis of \([\alpha/Fe]\) and \([N/O]\) abundance ratios and their large scatter, an origin of DLAs in dwarf and low surface brightness galaxies is also presented (Matteucci, Molaro & Vladilo 1997; Vladilo 1998; Jimenez, Bowen & Matteucci 1999). Because DLAs contain most of the cool, neutral gas in the universe at high redshift, they play an important role in studies of the galaxy formation, gas process, star formation and metal enrichment as well as the large scale structure. The pioneering work in this field was done by Meyer, Welty & York (1989) and Pettini, Boksenberg & Hunstead (1990). In the past few years, Pettini et al. (1994, 1997a) have devoted great efforts in observation of DLAs’ column densities and metal abundances. They found that, with the increase
of observed data, DLAs are generally metal poor with a mean value only of 1/13 \( Z_{\odot} \) and are very young galaxies in the early stage of chemical enrichment, and the metallicity distribution of DLAs shows a large spread of nearly two magnitudes. They also pointed out that the abundance of Cr is relatively poorer than that of Zn due to the depletion of dust.

Lu et al. (1996) used the powerful Keck 10 m telescope to study the metal abundances of many heavy elements, and presented a very detailed analysis of DLAs including comparing their distribution of metallicities, electron density and kinematics with those of our Milky Way galaxy, etc. Boisè et al. (1998) presented HST spectra for a sample of six DLAs with intermediate redshift \((z_{\alpha} \leq 1)\), and concluded that the available observations may be biased against dust-rich absorbers and dust extinction causes a preferential selection of QSOs with intervening gas relatively poor in metals, dust and molecules. They also strongly suspect that surveys of DLAs down to fainter QSOs would reveal more systems with large HI column densities and high metallicities. Møller & Warren (1998) used HST images to estimate the cross-section-weighted mean radius of DLA absorbers at high redshift \((z > 2)\), that is they are smaller than 23.6 \( h^{-1} \) kpc and 12.7 \( h^{-1} \) kpc for \( q_0 = 0.0 \) and 0.5, respectively. They also found that for \( q_0 = 0.5 \) the space density of DLAs at high redshift is more than five times that of the spiral galaxies locally, but the problem will be ruled out if \( q_0 \) decreases. The observations of H\( \alpha \) emission done by Bunker et al. (1999) and near-IR and IR done by Bechtold et al. (1998) also supported the conclusions of Møller & Warren (1998) above.

Until now, most of the researches in DLAs are for observational constraints. There has, however, been relatively little work on its simple prescription. It is worthy of emphasizing that the observation of HST (Møller & Warren 1998) strongly suggests DLAs and LBGs may commonly associated with each other. Based on their successful disc galaxy formation model, Mo, Mao & White (1999) have investigated the global properties of LBGs, such as the sizes, luminosities, kinematics and star formation rates. They presented that the number of density and clustering properties of LBGs are consistent with them being the central galaxies of the most massive dark haloes present at \( z \sim 3 \).

In this paper, under an assumption that the DLAs are the central galaxies of less massive dark haloes present at \( z \sim 3 \), and they should inhabit haloes of moderately low circular velocity, we study how star formation and chemical enrichment may have proceeded in them by using the simplest models possible with the smallest number of parameters.

The outlines of this paper are as follows. In Section 2, we give a simple description of our models; The predicted distributions of metallicity and neutral hydrogen column density for DLAs are presented in Section 3, and some correlations will also be shown in this section; The summary and discussion are presented in Section 4.

2 MODELLING DAMPED LYMAN-\( \alpha \) SYSTEMS

We model the assembly of DLAs in the context of the standard hierarchical picture (White & Rees 1978; White & Frenk 1991). Structure growth in this model is specified by the parameters of the background cosmology and by the power spectrum of initial density fluctuations. As an illustration, we show theoretical results for a CDM model with cosmological density parameter \( \Omega_0 = 0.3 \), cosmological constant \( \Omega_{\Lambda} = 0.7 \). The power spectrum is assumed to be that given in Bardeen et al. (1986), with shape parameter \( \Gamma = 0.2 \) and with normalization \( \sigma_8 = 1.0 \). We denote the mass fraction in baryons by \( f_B = \Omega_B/\Omega_0 \), where \( \Omega_B \) is the cosmic baryonic density parameter. According to the cosmic nucleosynthesis, the currently favoured value of \( \Omega_B \) is \( \Omega_B \sim 0.019h^{-2} \) (Burles & Tytler 1998), where \( h \) is the present Hubble constant in units of 100 \( km s^{-1} Mpc^{-1} \), and so \( f_B \sim 0.063h^{-2} \). Whenever a numerical value of \( h \) is needed, we take \( h = 0.7 \).

2.1 Galaxy formation

There are some traditional methods to investigate the galaxy formation and evolution. One can, for instance, assume the redshift of galaxy formation and star formation history, based on the stellar IMF and cosmological model, to trace the observations (Tinsley 1980; Pozzetti, Bruzual & Zamorani 1996; Jimenez, Padoan & Matteucci 1998). White and his collaborators (White & Frenk 1991; Kauffmann & White 1993; Kauffmann, White & Guiderdoni 1993; Kauffmann et al. 1999) construct hierarchical models of galaxy formation and evolution, and are successful in many observations such as the statistical properties of local and distant galaxies, etc. Madau, Pozzetti & Dickinson (1998) developed a method which focuses on the integrated light of galaxy populations as a whole to match the properties of the star formation history for the field galaxies.

In the present paper, we use the Mo, Mao & White (1998) (hereafter, MMW) galaxy formation model in assuming that central galaxies form when collapse of the protogalactic gas is halted either by its angular momentum or by fragmentation as it becomes self-gravitating. This model is in hierarchical cosmogonies, in which a disc is a thin and centrifugally supported structure with an exponential surface density profile. LBGs can be well understood in MMW with large circular velocity \( V_c \) and small spin parameter \( \lambda \) which correspond to compact objects with massive haloes (Mo et al. 1999). In this paper, we assume that DLAs are the central galaxies of less massive dark haloes present at redshifts \( z \sim 3 \), and they should inhabit haloes of moderately low circular velocity.

According to MMW, if the mass profile of the disc is taken to be exponential

\[ \Sigma(r) = \Sigma_0 \exp(-r/R_d), \]

then \( \Sigma_0 \) and \( R_d \) that are the central surface density and the scale length of the exponential disc, respectively, and the rotation curve of the galaxy, are determined uniquely. Specifically,

\[ R_d \approx 8.8h^{-1} \text{kpc} \left( \frac{\lambda}{0.05} \right) \left( \frac{V_c}{250 \text{ km s}^{-1}} \right) \left( \frac{H(z)}{H_0} \right)^{-1} \]

\[ (2) \]
and
\[ \Sigma_0 \approx 380 h M_\odot \text{pc}^{-2} \left( \frac{m_d}{0.05} \right) \left( \frac{\lambda}{0.05} \right)^{-2} \left( \frac{V_c}{250 \text{km s}^{-1}} \right)^2 \left( \frac{H(z)}{H_0} \right), \] (3)
where \( m_d \) is the fraction of disk to halo mass, \( V_c \) the circular velocity of the halo, \( \lambda \) the dimensionless spin parameter, \( H(z) \) the Hubble constant at redshift \( z \), \( H_0 \) the present-day Hubble constant (See detailed in MMW). Because the Hubble constant \( H(z) \) increases with redshift, it is expected from equations (2) and (3) that the galaxy disc should be less massive and smaller but have a higher surface density at higher redshift. One can find if \( V_c \), \( \lambda \) and cosmogony are given, \( R_d \), which dominates the disk profile, will not change.

For a given cosmogony, the mass function of dark matter haloes at redshift \( z \) can be estimated from the Press-Schechter formalism (Press & Schechter 1974):
\[ dN_h(M_h, z) = -\sqrt{\frac{2}{\pi}} \frac{\delta_c(z)}{\Sigma(M_h)} \frac{d \ln \Delta(M_h)}{d \ln M_h} \times \exp\left[ -\frac{\delta_s^2(z)}{2\Delta^2(M_h)} \right] \frac{dM_h}{M_h} \],
\[ \delta_c(z) = \delta_c(0) (1 + z) g(0)/g(z) \]
where \( \delta_c(0) \approx 1.686 \), \( \Delta(M_h) \) is the rms linear mass fluctuation at \( z = 0 \) in a sphere which on the average contains mass \( M_h \) by \( M_h = (4\pi/3)\bar{\rho}_0 R_s^3 \), \( \bar{\rho}_0 \) is the mean mass density of the universe at \( z = 0 \). The relation between the mass \( M_h \) and circular velocity \( V_c \) of a halo is in equation (2) of MMW, and a more detailed description of the PS formalism and the related issues can be found in the Appendix of MMW.

Based on the PS formalism and the \( \lambda \) distribution, with the latter being a log-normal function with mean \( \ln \lambda = 0.05 \) and dispersion \( \sigma_{\ln \lambda} = 0.5 \) (MMW), we can generate Monte Carlo samples of the halo distribution in the \( M_h - \lambda \) plane at redshifts \( z = 3 \). We can then use the galaxy formation model of Section 2.1 to transform the halo population into a DLA population. Finally, suppose that each halo at \( z \sim 3 \) has a central galaxy with a star formation rate (SFR) that is a monotonic function of halo mass, and only a negligible fraction of haloes hosts a second galaxy bright enough to be seen. The observed DLAs then correspond to haloes at \( z \sim 3 \). Here a lower-limit for \( V_c \) of 50 km/s of haloes is chosen, and a random distribution of galactic discs is taken into account.

It should be pointed out that the interaction between discs and bulges is not considered in the present study. This interaction will become more and more important for very compact objects which correspond to \( \lambda < 0.025 \) (MMW). Here, we treat galaxies with \( \lambda < 0.025 \) as \( \lambda = 0.025 \). It can be easily estimated from Warren et al. (1992), Cole & Lacey (1996) and Steinmetz & Bartelmann (1995) that, there are only 10 percent galaxies with \( \lambda < 0.025 \). This will not influence our main results.

2.2 Star formation rates

For star formation rates (SFR), we take the empirical Schmidt law (Kennicutt 1998)
\[ \Sigma_{\text{SFR}} = a \left( \frac{\Sigma_g(r)}{M_\odot \text{pc}^{-2}} \right)^b M_\odot \text{yr}^{-1} \text{pc}^{-2}, \]
where
* \( a = 2.5 \times 10^{-10}, b = 1.4 \), respectively. Here \( \Sigma_{\text{SFR}} \) is the SFR per unit area, and \( \Sigma_g(r) \) the gas surface density. This star formation law was derived by averaging the cool gas density over large areas on spiral discs and over starburst regions.

2.3 Closed box model

For a closed box model, the metallicity \( Z \) of gas is (Binney & Merrifield 1997; Tinsley 1980)
\[ Z - Z_\odot = -y \ln(\Sigma_g(r)/\Sigma_g(0)) = y \ln \mu^{-1}, \]
where \( Z_\odot \) is the initial metallicity of cool gas that is taken to be 0.01\( Z_\odot \) in the present paper, \( y \) the stellar yield that is obtained by normalizing the predicted distribution of metallicity to the mean value of 1/13 \( Z_\odot \) as presented by Pettini et al. (1997a) in this study (see next section). \( \Sigma_{\text{gas}}(r) \) the initial gas surface density and \( \mu \) the gas fraction, and
\[ \frac{d \Sigma_{\text{gas}}(r)}{dt} = -(1 - R_s) \Sigma_{\text{SFR}}, \]
where \( R_s \) is the returned fraction of stellar mass into the ISM, and we take \( R_s = 0.3 \) for a Salpeter IMF (see Madau et al. 1998). We assume that at initial time \( (t = 0), \Sigma_{\text{SFR}} = 0 \) and \( \Sigma_{\text{gas}}(r) = \Sigma_{0}(r) \exp(-r/R_s) \), with the latter being given by equation (1). After a period of \( T \), the surface density of the survived cool gas can be obtained by equations (5) and (8), that is
\[ \Sigma_g(r) = \Sigma_{0}(r)(1 + T/\tau)^{-\frac{1}{\tau}}, \]
and the current SFR is
\[ \Sigma_{\text{SFR}} = a \Sigma_{0}(r)(1 + T/\tau)^{-\frac{b}{\tau}}, \]
where
\[ \tau = \frac{\Sigma_{1-b}}{a(b - 1)(1 - R_s)}. \]

As we know, in the simple closed-box model of chemical evolution, all metals produced by stars are retained within the galaxy. The metallicity of the galaxy is simply determined by the stellar yield \( y \), defined as the mass of metals produced per solar mass of long-lived stars that are formed (Tinsley 1980). It is worthy to note that, the instantaneous recycling approximation is not valid as regards the contributions to metal enrichment of either type Ia supernovae or of stars of a few solar masses (Binney & Merrifield, 1997). Pagel (1997) has refined to take into account the time delay between star formation and the ejection into the ISM of heavy elements.

In this paper, we use \( \log(X/Y)_\odot \) for the logarithm of metallicity, and all the histograms are normalized to unity.

* We use the normal notation where \[ \log(X/Y) = \log(X/Y) - \log(X/Y)_\odot. \]
2.4 Criterion for star formation

According to Toomre (1964), in the case of a gaseous disc, instability for star formation is expected if the surface density of gas exceeds the following critical value

$$\Sigma_c(r) = \frac{\alpha \kappa \sigma_r}{3.36G^2},$$

(12)

where \( \alpha \) is taken to be 2 (van der Kruit & de Grijs, 1999); and

$$\kappa = 1.41 \frac{V}{r}(1 + \frac{r}{V} \frac{dV}{dr})^{1/2};$$

(13)

and \( \sigma_r \) is a gas velocity dispersion, we take it to be 6 km s\(^{-1}\) (Kauffmann 1996), which is consistent with the observational results at any redshift till now (see Larson 1998).

When this criterion is considered, the star formation occurs only in the region where the surface density of gas satisfies the critical value, not everywhere of the gas disc.

3 RESULTS

In this section, we present the predicted normalized distributions of metallicity and HI column density for the DLA population. As explained by Pettini, King & Smith (1997b), [Zn/H] is a straightforward measure of the degree of metal enrichment analogous to the stellar [Fe/H]. So, we use the mean value of [Zn/H] as presented by Pettini et al. (1994, 1997a) to normalize the predicted distribution of metallicity for DLAs in order to obtain the stellar yield. A random distribution of discs is taken into account.

3.1 Distribution of metallicity without considering the Toomre’s criterion

At first, we do not consider the criterion for star formation which is developed by Toomre (1964). Based on the Monte Carlo samples at \( z = 3 \), we can calculate the metallicity \( Z \) of DLA population by the formulas from (5) to (11) by assuming that, at initial time \( (t_0 = 0) \), \( \Sigma_{\text{SFR}} = 0 \) and \( \Sigma_{\text{H}}(r) = \Sigma_\odot \exp(-r/R_\odot) \); and the star formation time \( T \) is 1 Gyr. \( \Sigma_\odot \) and \( R_\odot \) are decided by equations (2) and (3). The stellar yield is obtained by normalizing the predicted distribution of metallicity to the mean value of 1/13 \( Z_\odot \) as presented by Pettini (1997a). It is 0.22 \( Z_\odot \). The results are plotted in Fig. 1. For comparison, the metallicities of 18 DLAs at redshifts \( z \sim 3 \) (2.3 < \( z < 3.4 \)) that were obtained by Meyer, Welty & York (1989) and Pettini et al. (1994, 1997a) are also presented. This figure shows that, the observational data that have a spread of nearly two orders of magnitude agree with our model, but the predicted metallicity distribution cannot spread as widely as the observations. The observational data are still quite sparse, and larger and more complete samples are needed. In order to test whether our model fits the abundances of DLAs, we provide the Kolmogorov-Smirnov Test. The results are that the maximum value of the absolute difference is 0.33, and the significance level probability is 69.94 percent.

\[^{\dagger}\] The solar system abundance of Zn is from the compilation by Anders & Grevesse (1989), i.e. \( \log(Zn/H)_\odot = -7.35 \).

3.2 Distribution of metallicity with considering the Toomre’s criterion

When we take into account the Toomre instability criterion of star formation, the star formation occurs only in the region where the surface density of gas must be larger than \( \Sigma_c(r) \). So, we first obtain the regions where the star formation can occur based on the formulas (1), (12) and (13), assuming that the disc has a flat rotation curve and rotational velocity is equal to the circular velocity of the surrounding dark matter halo. If the observation is not in these regions, the predicted distribution of metallicity for DLAs is obtained by the formulas from (5) to (11).

3.3 Distribution of HI column density

HI column density is the major characteristics of DLAs, because it is the first physical parameter that we can obtain from observations of QSO absorption lines. If we assume that the survived gas from the star formation in a disc is dominated by the neutral hydrogen, the model column density of neutral hydrogen can be obtained by the formulas from

[Figure 1. The distribution of metallicities for DLAs. The solid histogram gives the model prediction and the dashed histogram shows the observational data in Meyer et al. (1989) and Pettini et al. (1994, 1997a).]
Figure 2. The distribution of metallicities for DLAs. The solid histogram gives the model prediction and the dashed histogram shows the observational data in Meyer et al. (1989) and Pettini et al. (1994, 1997a).

Figure 3. The distribution of HI column densities for DLAs. The solid histogram gives the model prediction and the dashed histogram shows the observational data in Meyer et al. (1989) and Pettini et al. (1994, 1997a).

Figure 4. The distribution of HI column densities for DLAs. The solid histogram gives the model prediction and the dashed histogram shows the observational data in Meyer et al. (1989) and Pettini et al. (1994, 1997a).

3.4 Relation between metallicity and HI column density

In order to present the predicted relation between metallicity and HI column density for DLAs, we randomly select 100 samples from the DLA population by their cross-sections because the observations of DLAs are based on the QSO absorption lines.

In Figs. 5 and 6, we plot the predicted distribution of [Zn/H] as a function of HI column density for DLAs without and with considering the Toomre’s criterion, respectively. For comparison, the observational data of 18 DLAs at redshifts $z \sim 3$ ($2.3 < z < 3.4$) that were obtained by Meyer, Welty & York (1989) and Pettini et al. (1994, 1997a) are also plotted. The predicted correlations (especially, without considering the Toomre’s criterion) are that, the higher the column density, richer the metallicity. In fact, Boissé et al. (1998) have already emphasized that, in an unbiased sample, the large N(HI) values should correspond to the innermost parts of galaxies where the metallicity is presumably higher. The observational data show a different trend, i.e. the metal-
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4 SUMMARY AND DISCUSSION

In the present paper, we establish two simple scenarios to investigate the nature of DLAs at redshifts $z \sim 3$ based on the disc galaxy formation model developed by Mo, Mao & White (1998). One is without considering the Toomre’s criterion, another is with considering the Toomre’s criterion. The star formation rate is chosen to be in the form of the empirical Schmidt law (Kennicutt 1998). The approximation of instantaneous recycling is assumed. The predicted distribution of metallicity for DLAs spreads larger than one order of magnitude, which is consistent with the observations by Meyer, Welty & York (1989) and Pettini et al. (1994, 1997a).

Although the star formation time of 1 Gyr, which we adopted, is arbitrary, its order is consistent with that of observations (Bechtold et al. 1998). It is no problem for us to choose it as a typical time of star formation to investigate the global properties of DLAs.

In our models, the star formation time scale in the disc is implicitly assumed to be the same everywhere. This will lead to the slow consumption of gas in the central parts of the disc. In fact, as we know well, the star formation in the central region is very rapid, and the central region should correspond to higher metallicities and lower HI column densities. Furthermore, we treat all the survived gases as HI. There actually exist H$_2$, ionized gases and other elements. This is also leads to a overestimation of HI column density, especially in the central region of the disc. In addition, the DLAs that correspond to have small $V_c$, should form earlier and the merging could take place more frequently. So, the DLAs are to a certain extent more complicated.

There is only one output parameter in our models, i.e. the stellar yield, which relates to the star formation time scale and is obtained from the normalization of the predicted distribution of metallicity to the mean value of $1/13 \, Z_\odot$ as presented by Pettini et al. (1997a). The metallicity of the initial cool gas is assumed to be of 0.01 $Z_\odot$. According to Pagel (1987), the stellar yield is 0.3 $Z_\odot$ for the disc clusters and 0.4 $Z_\odot$ for the solar neighborhood. The stellar yields in our models are also quite similar to that of LMC of some 0.2 $Z_\odot$ (Binney & Tremaine 1987).

Finally, we must point out, although our models are very simple without many physical processes being considered, such as the interaction between discs and bulges, merging effects, gas reheating and supernovae feedback, etc., it can predict some properties of DLAs.

ACKNOWLEDGMENTS

We are indebted to the anonymous referee for many critical comments and helpful suggestions that have greatly improved our paper. We are also grateful to H. J. Mo for much help in finishing this paper. This project is partly supported by Chinese National Natural Foundation and the “Sonderforschungsbereich 375-95 für Astro-Teilchenphysik” der Deutschen Forschungsgemeinschaft.
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