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Star formation and chemical evolution of Lyman-break galaxies

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Abstract. The number density and clustering properties of Lyman-break galaxies (LBGs) observed at redshift $z \sim 3$ are best explained by assuming that they are associated with the most massive haloes at $z \sim 3$ predicted in hierarchical models of structure formation. In this paper we study, under the same assumption, how star formation and chemical enrichment may have proceeded in the LBG population. A consistent model is suggested, in which the amount of cold gas available for star formation must be regulated. It is found that gas cooling in dark haloes provides a natural regulation process. In this model, the star formation rate in an LBG host halo is roughly constant over about 1 Gyr. The predicted star formation rates and effective radii are consistent with observations. The metallicity of the gas associated with an LBG is roughly equal to the chemical yield, or of the order of $1Z_\odot$ for a Salpeter IMF. The contribution to the total metals of LBGs is roughly consistent with that obtained from the observed cosmic star formation history. The model predicts a marked radial metallicity gradient in a galaxy, with the gas in the outer region having much lower metallicity. As a result, the metallicities for the damped Lyman-alpha absorption systems expected from the LBG population are low. Since LBG haloes are filled with hot gas in this model, their contributions to the soft X-ray background and to the UV ionization background are calculated and discussed.

Key words: galaxies: active – galaxies: formation – galaxies: evolution – galaxies: stellar content

1. Introduction

The Lyman-break technique (e.g. Steidel et al. 1995) has now been proved very successful in finding large numbers of star forming galaxies at redshift $z \sim 3$ (e.g. Steidel et al. 1996, 1999b). The observed number density and clustering properties of Lyman-break galaxies (hereafter LBGs, Steidel et al. 1998; Giavalisco et al. 1998; Adelberger et al. 1998) are best explained by assuming that they are associated with the most massive haloes at $z \sim 3$ predicted in hierarchical models of structure formation (Mo & Fukugita 1996; Baugh et al. 1998; Mo et al. 1998b; Coles et al. 1998; Governato et al. 1998; Jing 1998; Jing & Suto 1998; Katz et al. 1998; Kauffmann et al. 1999; Moscardini et al. 1998; Peacock et al. 1998; Wechsler et al. 1998). This assumption provides a framework for predicting a variety of other observations for the LBG population. Steidel et al. (1999b and references therein) gave a good summary of recent studies on this population including the luminosity functions, luminosity densities, color distribution, star formation rates, clustering properties, and the differential evolution.

Assuming that LBGs form when gas in dark haloes settles into rotationally supported discs or, in the case where the angular momentum of the gas is small, settles at the self-gravitating radius, Mo et al. (1998b) predict sizes, kinematics and star formation rates and halo masses for LBGs, and find that the model predictions are consistent with the current (rather limited) observational data; Steidel et al. (1999a) suggest that the total integrated UV luminosity densities of LBGs are quite similar between redshift 3 and 4 although the slope of their luminosity function might have a large change in the faint-end.

Furthermore, Steidel et al. (1999b) suggest that a “typical” LBG has a star formation rate of about $65h_{50}^{-2}\mathrm{M}_\odot\mathrm{yr}^{-1}$ for $\Omega_0 = 1$ and that the star formation time scale is of the order of 1Gyr based on their values of E(B-V) as pointed out by Pettini et al. (1997b) after adopting the reddening law of Calzetti (1997). Recently Friaca & Terlevichet al. (1999) used their chemodynamical model to propose that an early stage (the first Gyr) of intense star formation in the evolution of massive spheroids could be identified as LBGs.

However, Sawicki & Yee (1998) argued that LBGs could be very young stellar populations less than 0.2Gyr old, based on the broadband optical and IR spectral energy distributions. This is also supported by the work of Ouchi & Yamada (1999) based on the expected sub-mm emission and dust properties. It is worthy of note that the assumptions about the intrinsic LBG spectral shape and the reddening curve play important roles in these results.

In this paper, we study how star formation and chemical enrichment may have proceeded in the LBG population. It will be demonstrated in Sect. 2, that the observed star formation rate at $z \sim 3$ requires a self-regulating process to keep the gas supply for a sufficiently long time. We will show (in Sect. 2) that such a

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process can be achieved by the balance between the energy feedback from star formation and gas cooling. Model predictions for the LBG population and further discussions about the results are presented in Sect. 3, a brief summary is given in Sect. 4.

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 $f_{\rm B} = \Omega_{\rm B}/\Omega_0$, where $\Omega_{\rm B}$ is the cosmic baryonic density parameter. According to the cosmic nucleosynthesis, the currently favoured value of $\Omega_{\rm B}$ is $\Omega_{\rm B} \sim 0.019h^{-2}$ (Burles & Tytler 1998), where h is the present Hubble constant in units of 100 $\rm kms^{-1}Mpc^{-1}$, and so $f_{\rm B} \sim 0.063h^{-2}$. Whenever a numerical value of h is needed, we take $h = 0.7$. At the same time, we define parameter $t_\star$ as the time scale for star formation in the LBG population throughout the paper.

2. Models

2.1. Galaxy formation

In this paper, we use the galaxy formation scenario described in Mo et al. (1998a, hereafter MMWa) to model the LBG population. In this scenario, central galaxies are assumed to form in dark matter haloes when collapse of protogalactic gas is halted either by its angular momentum, or by fragmentation as it becomes self-gravitating (see Mo et al. 1998b, hereafter MMWb, for details). As described in MMWb, the observed properties of LBGs can be well reproduced if they are assumed to be the central galaxies formed in the most massive haloes with relatively small spins at $z \sim 3$. As in MMWb, we assume that gas in a dark halo initially settles into a disk with exponential surface density profile.

When the collapsing gas is arrested by its spin, the central gas surface density and the scale length of an exponential disk are

$$\Sigma_0 \approx 380h{\rm M_\odot pc^{-2}} \left(\frac{m_{\rm d}}{0.05}\right)\left(\frac{\lambda}{0.05}\right)^{-2} \left(\frac{V_c}{250{\rm kms^{-1}}}\right)\left[\frac{H(z)}{H_0}\right], \tag{1}$$

and

$$R_{\rm d} \approx 8.8h^{-1}{\rm kpc}\left(\frac{\lambda}{0.05}\right)\left(\frac{V_c}{250{\rm kms^{-1}}}\right)\left[\frac{H(z)}{H_0}\right]^{-1}, \tag{2}$$

where $m_{\rm d}$ is the fraction of halo mass that settles into the disk, V_c is the circular velocity of the halo, λ is the dimensionless spin parameter, $H(z)$ is the Hubble constant at redshift z and H_0 is its present value (see MMWa for details). Since $H(z)$ increases with z, for a given V_c disks are less massive and smaller but have a higher surface density at higher redshift. When λ is low and $m_{\rm d}$ is high, the collapsing gas will become self-gravitating and fragment to form stars before it settles into a rotationally supported disk. In this case, we will take an effective spin $\lambda \propto m_{\rm d}$ in calculating Σ_0 and $R_{\rm d}$.

We take the empirical law (Kennicutt 1998) of star formation rate (SFR) to model the star formation in high-redshift disks which is

$$\Sigma_{\rm SFR} = a\left(\frac{\Sigma_{\rm gas}}{\rm M_\odot pc^{-2}}\right)^b {\rm M_\odot yr^{-1}pc^{-2}}, \tag{3}$$

where

$$a = 2.5 \times 10^{-10},\ b = 1.4 \tag{4}$$

respectively. Here $\Sigma_{\rm SFR}$ is the SFR per unit area and $\Sigma_{\rm gas}$ is the gas surface density. Note that this star formation law was derived by averaging the star formation rate and cold gas density over large areas on spiral disks and over starburst regions (Kennicutt 1998). We will apply this law differentially on a disk and also take into account the Toomre instability criterion of star formation (Toomre 1964; see also Binney & Tremaine 1987).

For a given cosmogonic model, the mass function for dark matter haloes at redshift z can be estimated from the Press-Schechter formalism (Press & Schechter 1974):

$$dN = -\sqrt{\frac{2}{\pi}}\frac{\rho_0}{M}\frac{\delta_c(z)}{\Delta(R)}\frac{d\ln\Delta(R)}{d\ln M}\exp\left[-\frac{\delta_c^2(z)}{2\Delta^2(R)}\right]\frac{dM}{M}, \tag{5}$$

where $\delta_c(z) = \delta_c(0)(1+z)g(0)/g(z)$ with $g(z)$ being the linear growth factor at z and $\delta_c(0) \approx 1.686$, $\Delta(R)$ is the linear rms mass fluctuation in top-hat windows of radius R which is related to the halo mass M by $M = (4\pi/3)\overline{\rho}_0 R^3$, with $\overline{\rho}_0$ being the mean mass density of the universe at $z = 0$. The halo mass M is related to halo circular velocity V_c by $M = V_c^3/[10GH(z)]$. A detailed description of the PS formalism and the related cosmogonic issues can be found in the Appendix of MMWa.

From the Press-Schechter formalism and the λ-distribution which is a log-normal function with mean $\overline{\ln\lambda} = \ln 0.05$ and dispersion $\sigma_{\ln\lambda} = 0.5$ (see Eq. [15] in MMWa), we can generate Monte Carlo samples of the halo distributions in the V_c-λ plane at a given redshift and, using the star formation law outlined above, assign a star formation rate to each halo. As in MMWb, we select LBGs as the galaxies with the highest star formation rate, so that the comoving number density for LBGs is equal to the observed value, $N_{\rm LBG} = 2.4 \times 10^{-3}h^3{\rm Mpc^{-3}}$ for the assumed cosmology at $z = 3$, as given in Adelberger et al. (1998). Here it is worth noting that the model selection of LBGs we adopted is without the dust extinction being considered. This implies that the contribution of the dust is assumed to be uniform. But in fact, it could be very different from galaxies to galaxies. So, our selection of LBGs may not have one-to-one correspondence with the observed LBGs (Baugh et al. 1999), but the selection should be correct on average.

2.2. Cooling-regulated star formation

What regulates the amount of star-forming gas in a dark halo? In the standard hierarchical scenario of galaxy formation (e.g. White & Rees 1978; White & Frenk 1991, hereafter WF), gas in a dark matter halo is assumed to be shock heated to the virial temperature,

$$T = 2.24 \times 10^6 \mathrm{K} \left(\frac{V_c}{250 \mathrm{km\,s^{-1}}} \right)^2, \quad (6)$$

as the halo collapses and virializes. The hot gas then cools and settles into the halo centre to form stars. As suggested in WF, the amount of cold gas available for star formation in a dark halo is either limited by gas infall or by gas cooling, depending on the mass of the halo. For the massive haloes ($V_c \gtrsim 200 \mathrm{km\,s^{-1}}$) we are interested here, gas cooling rate is smaller than gas-infall rate, and the supply of star-forming gas is limited by gas cooling (see WF for details). It is therefore likely that gas cooling is the main process that constantly regulates the SFR in LBGs.

To have a quantitative assessment, let us compare different rates involved in the problem. Using Eqs. (1)-(4) we can write the SFR as

$$\begin{aligned} \dot{M}_\star &= \frac{2\pi a \Sigma_0^b R_\mathrm{d}^2}{b^2} \\ &\approx 2.33 \times 10^2 h^{-0.6} \left(\frac{m_\mathrm{d}}{0.05} \right)^{1.4} \left(\frac{\lambda}{0.05} \right)^{-0.8} \\ &\quad \left(\frac{V_c}{250 \mathrm{km\,s^{-1}}} \right)^{3.4} \left[\frac{H(z)}{H_0} \right]^{-0.6} \mathrm{M_\odot\,yr^{-1}}, \end{aligned} \quad (7)$$

where m_d is the current gas content of the disk. The rate at which gas is consumed by star formation is therefore

$$\dot{M}_\mathrm{SFR} = (1 - R_\mathrm{r}) \dot{M}_\star, \quad (8)$$

where R_r is the returned fraction of stellar mass into the ISM; we take $R_\mathrm{r} = 0.3$ for a Salpeter IMF (e.g. Madau et al. 1998). According to WF, the heating rate due to supernova explosions under the approximation of instantaneous recycling can be written as

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \epsilon_0 \dot{M}_\star (700 \mathrm{km\,s^{-1}})^2, \quad (9)$$

where ϵ_0 is an efficiency parameter which is still very uncertain. We take it to be 0.02 as in WF. The rate at which gas is heated up (to the virial temperature) is therefore

$$\dot{M}_\mathrm{heat} = \frac{0.8}{V_c^2} \frac{\mathrm{d}E}{\mathrm{d}t} \quad (10)$$

which is the same form as Eq. (9) of Kauffmann (1996; see also Somerville 1997). At $z = 3$ and for the cosmology considered here, this rate can be written as

$$\begin{aligned} \dot{M}_\mathrm{heat} &\approx 29.2 h^{-0.6} \left(\frac{m_d}{0.05} \right)^{1.4} \left(\frac{\lambda}{0.05} \right)^{-0.8} \\ &\quad \left(\frac{V_c}{250 \mathrm{km\,s^{-1}}} \right)^{1.4} \left[\frac{H(z)}{H_0} \right]^{-0.6} \mathrm{M_\odot\,yr^{-1}}. \end{aligned} \quad (11)$$

Comparing this equation with Eqs. (7) and (8), we can find that the rate for gas consumption due to star formation is much larger than the rate of gas heating for LBG haloes. Because LBGs are hosted by massive haloes which have large circular velocities V_c, the haloes are cooling dominated which is confirmed during the detailed calculation below. Following WF we define a mass cooling rate by

$$\dot{M}_\mathrm{cool} = 4\pi \rho_\mathrm{gas}(r_\mathrm{cool}) r_\mathrm{cool}^2 \frac{\mathrm{d}r_\mathrm{cool}}{\mathrm{d}t}, \quad (12)$$

where r_cool is the cooling radius and ρ_gas is the density profile of the hot gas in the halo. For simplicity, we assume that $\rho_\mathrm{gas}(r) = f_\mathrm{B} V_c^2/(4\pi G r^2)$, and we define r_cool to be the radius at which the cooling time is equal to the age of the universe, which is similar to the time interval between major mergers of haloes (Lacey & Cole 1994). The density distribution of the halo mass here is assumed to be isothermal. However, it is the NFW profile (Navarro et al. 1997) in MMWb. Because the difference of the resulting cooling rates between these two different choices of density profiles is small (Zhao et al. 1999), and since the major goal here is to show whether or not the cooling-regulated star formation can be valid, the adoption of isothermal profile will not influence the final result very much.

Under this definition, gas within the cooling radius can cool effectively before the halo merges into a larger system where it may be heated up to the new virial temperature if it is not converted into stars. Using the cooling function given by Binney & Tremaine (1987) where cooling function $\Lambda \approx 10^{-23} \mathrm{ergs^{-1}cm^3}$ in the range of $5 \times 10^5 \mathrm{K} \lesssim T \lesssim 2 \times 10^7 \mathrm{K}$ (and assuming gas with primordial composition), the mass cooling rate can then be written as

$$\dot{M}_\mathrm{cool} \approx 49.8 h^{1/2} \left(\frac{V_c}{250 \mathrm{km\,s^{-1}}} \right)^2 \left(\frac{f_\mathrm{B}}{0.1} \right)^{3/2} \mathrm{M_\odot yr^{-1}}. \quad (13)$$

If $\dot{M}_\star$ is smaller than $\dot{M}_\mathrm{cool}$, then cold gas will accumulate in the halo centre and lead to higher star formation rate. If, on the other hand, $\dot{M}_\star > \dot{M}_\mathrm{cool}$, the amount of cold gas will be reduced by star formation and supernova heating, leading to a lower star formation rate. We therefore assume that there is a rough balance among these three rates:

$$\dot{M}_\mathrm{cool} \approx \dot{M}_\mathrm{heat} + (1 - R_\mathrm{r})\, \dot{M}_\star. \quad (14)$$

It should be noted that the cooling-regulated star formation process is only a reasonable hypothesis, and the real situation must be much more complicated. For example, during a major merging of galactic haloes, the amount of gas that can cool must be much larger than that given by the cooling argument, and the star formation may occur in a short burst (e.g. Mihos & Hernquist 1996). However, such bursts are not expected to dominate the observed LBG population, because of their brief lifetimes. Thus, star formation rates in the majority of LBGs are expected to be regulated by Eq. (14) on average. As shown in MMWb, to match the observed number density of LBGs, the median value of V_c is about $300 \mathrm{\,km\,s^{-1}}$ in the present cosmogony. The typical star formation rate is of the order of $100 \mathrm{M_\odot\,yr^{-1}}$. This is not very different from the observed star formation rates, albeit dust distinction in the observations may be difficult to quantify.

Fig. 1 shows the value of m_d required by the balance condition Eq. (14) as a function of halo circular velocity, assuming that $f_\mathrm{B} = 0.1$ and the left hand side exactly equals the right

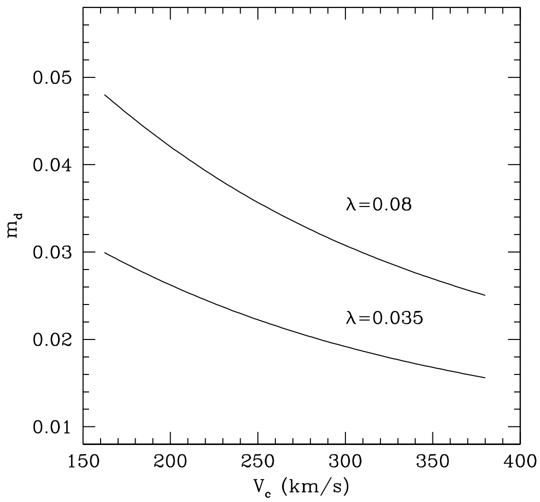

Fig. 1. The value of $m_{\rm d}$ required by the balance condition Eq. (14) as a function of halo circular velocity V_c at $z = 3$ for $\lambda = 0.035$ and $\lambda = 0.08$, assuming $f_{\rm B} = 0.1$ (see text).

hand one in Eq. (14). Results are shown for two choices of spin parameters, $\lambda = 0.035$ and 0.08, corresponding to the 50 and 90 percent points of the λ distribution for the LBG population (MMWb). As one can see, for the majority of LBG hosts, gas cooling indeed regulates the values of $m_{\rm d}$ to the range from 0.02 to 0.04. So, we can reasonably choose $m_{\rm d} = 0.03$ for the LBG population as MMWb did. Since the cooling time is approximately the age of the universe at $z \sim 3$, cooling regulation ensures that star formation at the predicted rate can last over a large portion of a Hubble time.

3. Model predictions for the LBG population

Since the cooling regulation discussed above gives specific predictions of how star formation may have proceeded in LBGs, here we use this model to predict the properties of the LBG population. The condition in Eq. (14) implies that the star formation rate in a disk is equal to the rate of gas infall (due to a balance between cooling and heating). Thus the evolution of the gas in the disk of an LBG host halo is described by the standard chemical evolution model with infall rate equal to star formation rate, i.e., the new infalling gas to the disk distributed radially in an exponential form with the scale length of $R_{\rm d}/b \approx 0.7 R_{\rm d}$, and the reheated gas removed decreases with the increasing radius due to the decreasing SFR. Under the instantaneous recycling approximation (Tinsley 1980), the gas metallicity Z is given by

$$Z = y(1 - e^{-\nu}) + Z_i, \; \nu = \frac{\Sigma_{\rm tot}}{\Sigma_{\rm gas}} - 1, \quad (15)$$

where Z_i is the initial metallicity of the infalling gas, y is the stellar chemical yield, $\Sigma_{\rm gas}$ is the gas surface density (which is kept constant by gas infall) and $\Sigma_{\rm tot}$ is the total mass surface density, which increases as star formation proceeds:

$$\frac{{\rm d}\Sigma_{\rm tot}}{{\rm d}t} = (1 - R_{\rm r})\Sigma_{\rm SFR}. \quad (16)$$

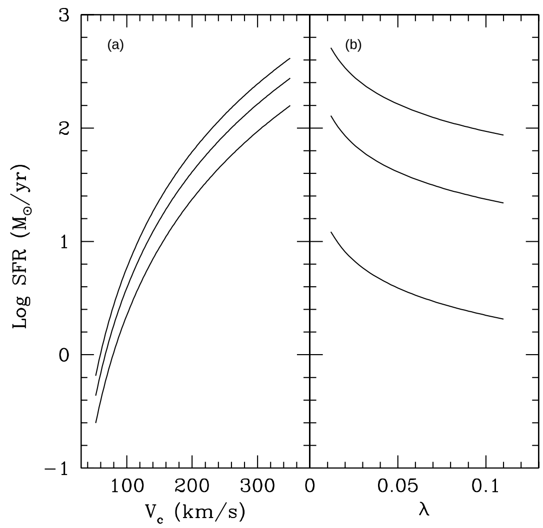

Fig. 2a and b. Predicted SFR as a function of V_c and λ in the cooling-regulated model. **a** SFR vs V_c, for λ =0.03, 0.05 and 0.1 (from top to bottom). **b** SFR vs λ, for V_c =300, 200 and 100km/s (from top to bottom).

Here the enrichment of the halo hot gases is not taken into account because the amount of metals heated up to the haloes by SNs is relatively smaller than that of primordial gases.

3.1. Individual objects

Fig. 2 shows the star formation rate as a function of halo circular velocity V_c and spin parameter λ. As expected, the predicted SFR increases with V_c but decreases with λ. As we can see from the figure, if we define systems with ${\rm SFR} \gtrsim 40 {\rm M_\odot\,yr^{-1}}$ (which matches the SFRs for the observed LBG population) to be LBGs, the majority of their host haloes must have $V_c \gtrsim 200\,{\rm km\,s^{-1}}$ which are cooling dominated. This result is the same as that obtained by MMWb based on the observed number density and clustering of LBGs. Thus, the star formation rate based on cooling argument is also consistent with the observed number density and clustering. Because SFR is higher in a system with smaller λ, the LBG population are biased towards haloes with small spins, but given its relatively narrow distribution, this bias is not very strong.

The predicted metallicity gradients on individual disks are shown in Fig. 3 for two different choices of star formation time scale $t_\star$ of 0.5Gyr and 1Gyr respectively, where we assume that $y = Z_\odot$ and $Z_{\rm i} = 0$ in order to make the predictions easily comparable with observations. The metallicity gradients are negative in all cases. When radius is measured in disk scale length, the predicted metallicity depends weakly on V_c but strongly on λ, and is higher for a longer star formation time. As one can see from Eq. (15), the largest metallicity in the model is $Z = Z_i + y$. This metallicity can be achieved in the inner part of compact disks (with small λ) when star formation time $t_\star \gtrsim 1$ Gyr. The metallicity drops by a factor of ~ 2 from its central value at $R \sim 3R_{\rm d}$.

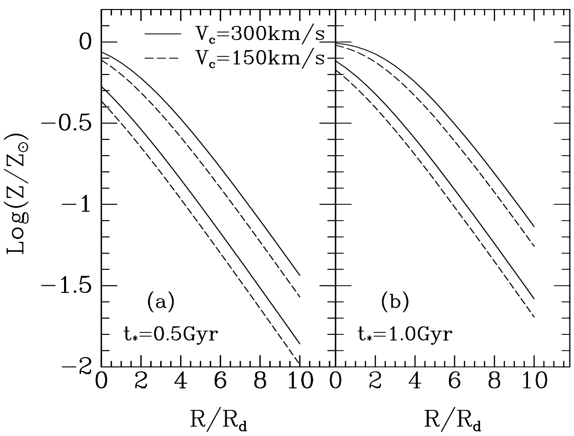

Fig. 3a and b. The metallicity gradients for LBGs for different star formation time $t_\star$ assuming that $y = Z_\odot$ and $Z_\mathrm{i} = 0$ (see text). Full and dash lines show results for $V_c = 300\mathrm{kms}^{-1}$ and $150\mathrm{kms}^{-1}$, respectively. From top to bottom, $\lambda = 0.03$ and 0.1; **a** $t_\star$ =0.5Gyr; **b** $t_\star$ =1Gyr

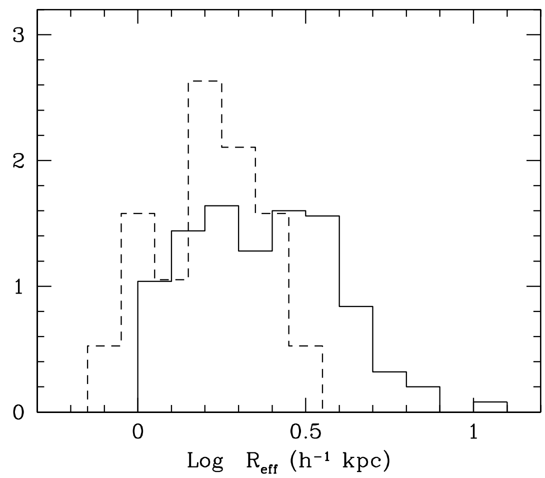

Fig. 5. The predicted effective-radius distribution for LBGs in the cooling-regulated scenario (solid), compared to the observed distribution (dash).

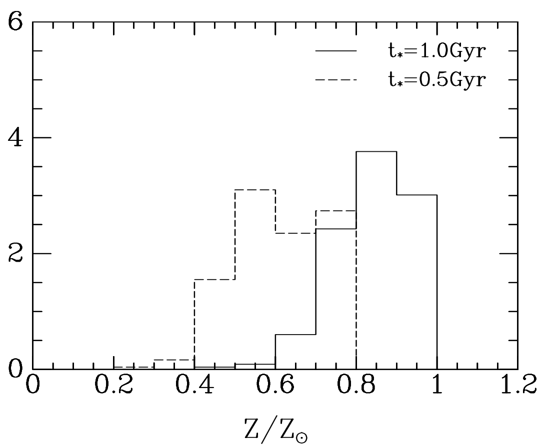

Fig. 4. The predicted metallicity distributions for LBG populations assuming that $y = Z_\odot$ and $Z_\mathrm{i} = 0$ in order to make the predictions easily comparable with observations (see text). Results are shown for two star formation timescales $t_\star = 0.5$ Gyr (dash) and $t_\star = 1$ Gyr (solid), respectively (cf. Eq. (15)).

3.2. LBG population

Since the distribution of haloes with respect to V_c and λ are known, we can generate Monte-Carlo samples of the halo distribution in the V_c-λ plane at any given redshift. We can then use the galaxy formation model (MMWb) discussed above to transform the halo population into an LBG population based on LBGs with highest SFRs which is the same as that outlined in Sect. 2.

We define the typical metallicity of a galaxy as the one at its effective radius. Fig. 4 shows the distribution of this metallicity for two choices of the star formation time, $t_\star = 0.5$ Gyr and 1 Gyr. Just as the same reason as Fig. 3 in last section, we have assumed that $y = Z_\odot$ and $Z_\mathrm{i} = 0$ in order to make the predictions easily comparable with observations. The median values of $(Z - Z_i)/y$ are 0.60 and 0.84 for $t_\star = 0.5$ Gyr and 1 Gyr, respectively. The sharp truncation at $(Z - Z_i)/y = 1$ is due to the fact that this quantity has a maximum value of 1 in the present chemical evolution model. It can be inferred from Fig. 3 that the range in $(Z - Z_i)/y$ decreases with increasing star formation time. Thus, if gas infall lasts for a long enough time, the distribution in $(Z - Z_i)/y$ will be very narrow near 1 and all LBGs will have metallicity $Z = Z_i + y$. According to the works of Tinsley (1980) and Maeder (1992), the stellar yield y is of the order of $Z_\odot$ for the Salpeter IMF. If we adopt a stellar yield $y \sim 0.5Z_\odot$ and $Z_i = 0.01Z_\odot$, and if LBGs are not short bursts (e.g. $t_\star \gtrsim 0.5$ Gyr) then their metallicity will be $Z \gtrsim 0.2Z_\odot$ which is similar to that proposed by Pettini (1999).

The predicted distribution of effective radii for the LBG population is shown in Fig. 5. The distribution is similar to that of MMWb. The predicted range is $1.0 \lesssim R_\mathrm{eff} \lesssim 5.0\,h^{-1}\mathrm{kpc}$ with a median value of 2.5 h^{-1}kpc. Note that the effective radii in the cooling-regulated model are independent of the star formation time $t_\star$ and m_d. The model prediction is in agreement with the observational results given by Pettini et al. (1998), Lowenthal et al. (1997) and Giavalisco et al. (1996) which are mentioned above.

The predicted SFR distribution of LBGs also resembles the prediction of MMWb except for a slight difference with MMWb, which is shown in Fig. 6. The median values are $180\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ for the model and spans from 100 to $500\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. To compare with observations, we have to take into account the effect of dust. If we apply an average factor of 3 in dust extinction, then the predictions closely match the values derived from infrared observations by Pettini et al. (1998) although there might exist rare LBGs with very high SFR.

3.3. Contribution to the soft X-ray and UV background

Since the virial temperature of LBG haloes is quite high, in the range of $10^6 - 10^7$K, significant soft X-ray and hard UV photons may be emitted as the halo hot gas cools. It is therefore

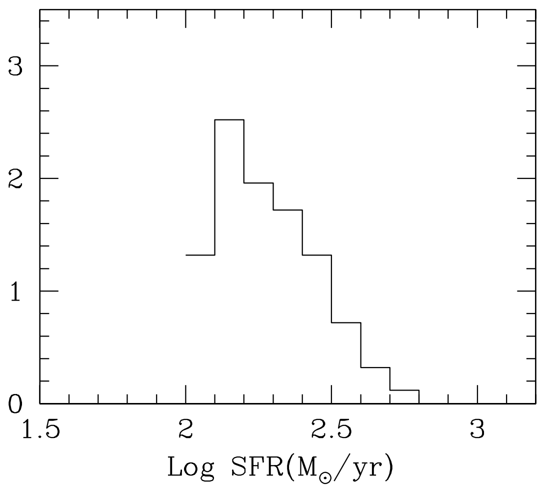

Fig. 6. The predicted SFR distribution for LBGs in the cooling-regulated scenario.

interesting to examine whether the LBG population can make substantial contribution to the soft X-ray and UV backgrounds.

The dominant cooling mechanism for hot gas with temperature $\gtrsim 10^6$ K is the thermal bremsstrahlung. The bremsstrahlung emissivity is given by (e.g., Peebles 1993)

$$j_\nu = 5.4 \times 10^{-39} n_e^2 T^{-1/2} e^{-h\nu/kT} \\ \mathrm{erg\,cm^{-3}\,s^{-1}\,ster^{-1}\,Hz^{-1}}, \quad (17)$$

where n_e (in cm^{-3}) is the electron density and T (in K) is the temperature given by Eq. (6). The total power emitted per unit volume is

$$J = 1.42 \times 10^{-27}\, T^{1/2}\, n_e^2\ \mathrm{erg\ cm^{-3}\ s^{-1}}. \quad (18)$$

We write the total luminosity L_b in thermal bremsstrahlung as

$$L_\mathrm{b} = \beta \dot{M}_\mathrm{cool} V_c^2, \quad (19)$$

and we take $\beta = 2.5$ here as WF so that L_b is equal to the initial thermal energy in the cooling gas. Note that the value of β is quite uncertain because it depends on the density and temperature profiles of the hot gas. Substituting Eq. (13) into the above equation, we obtain the total soft X-ray luminosity for an LBG

$$L_\mathrm{sx}(V_c) \approx 4.1 \times 10^{40} f_\mathrm{soft} \left(\frac{V_c}{250\mathrm{km/s}}\right)^4 \left(\frac{f_\mathrm{B}}{0.1}\right)^{3/2} \mathrm{erg\ s^{-1}}, \quad (20)$$

where

$$f_\mathrm{soft} = \frac{1}{kT} \int_{0.5(1+z)}^{2(1+z)} e^{-E/kT} dE \quad (21)$$

is the fraction of total energy that falls into the ROSAT soft X-ray (0.5-2 keV) band. The contribution of the LBG population to the soft X-ray background is then

$$\rho_\mathrm{sx} = \int\int dV_c dV_\mathrm{com} \frac{n(z) L_\mathrm{sx}}{4\pi d_L^2} \\ \approx 5.7 \times 10^{-8} \left(\frac{f_\mathrm{B}}{0.1}\right)^{3/2} \mathrm{erg\ s^{-1} cm^{-2}}, \quad (22)$$

where $n(z)$ is the comoving number density of LBG haloes as a function of redshift z, dV_com is the differential comoving volume from z to $z + dz$ and d_L is the luminosity distance. The integrate for V_c is to sum up all selected LBGs with V_c based on their highest SFRs. We have integrated over redshift range from 3 to 4 where the number density of LBGs is nearly a constant (Steidel 1999a,b). This contribution should be compared with the value derived from the ROSAT observations (Hasinger et al. 1993) in the 0.5-2 keV band

$$\rho_\mathrm{sx} \approx 2.4 \times 10^{-7} \mathrm{erg\,s^{-1}cm^{-2}}. \quad (23)$$

As we can see, the soft X-ray contribution from LBGs could be a substantial fraction (about 20%) of the total soft X-ray background.

Similarly we can calculate the contribution of LBGs to the UV background at $z = 3$. We evaluate the UV background at 4 Ryd (1Ryd=13.6 eV) using nearly identical procedures, we find that

$$i_\mathrm{4Ryd} \approx 2.4 \times 10^{-24} \left(\frac{f_\mathrm{B}}{0.1}\right)^{3/2} \mathrm{ergs^{-1}cm^{-2}Hz^{-1}ster^{-1}}, \quad (24)$$

which is much smaller than the UV background from AGNs, $i_\mathrm{4Ryd} \sim 10^{-22} \mathrm{ergs^{-1}cm^{-2}Hz^{-1}ster^{-1}}$ (e.g. Miralda-Escude & Ostriker 1990).

3.4. Contribution to the total metals

Based on the recent observational results of the cosmic star formation history, Pettini (1999) obtained a predicted total mass of metals produced at $z = 2.5$. After combining results of all contributors observed, he argued that there seems to exist a very serious "missing metal" problem, i.e., the predicted result is much higher than the observed ones. So, it is interesting to evaluate the total metals produced by LBGs in our model.

According to the method we select LBGs to be the galaxies with highest SFR and our chemical evolution model mentioned in Sect. 3.2, we can calculate the total metal density produced by the LBG population at $z = 3$ based on their observed comoving number density which is $N_\mathrm{LBG} = 2.4 \times 10^{-3} h^3 \mathrm{Mpc}^{-3}$ for the assumed cosmology (Adelberger et al. 1998). Defining that Ω_Z is the metal density relative to the critical density, we get that Ω_Z of LBGs are $0.19\Omega_\mathrm{B} \times y$ and $0.29\Omega_\mathrm{B} \times y$ for star formation time of 0.5Gyr and 1Gyr respectively, where y is the stellar yield which is the same as above. Because the virial temperature of LBG haloes are very high, a significant fraction of the metal should be in hot phase. Comparing our results with that estimated by Pettini (1999) which is $0.08\Omega_\mathrm{B} \times Z_\odot$ (the cosmogony has been taken into account), we find that there is no "missing metal" problem in our model.

3.5. LBGs and damped Lyman-alpha systems

Damped Lyman-alpha systems (DLSs) are another population of objects that can be observed at similar redshift to LBGs. The DLSs are selected according to their high neutral HI column density ($> 10^{20.3}\ \mathrm{cm}^{-2}$), and are believed to be either

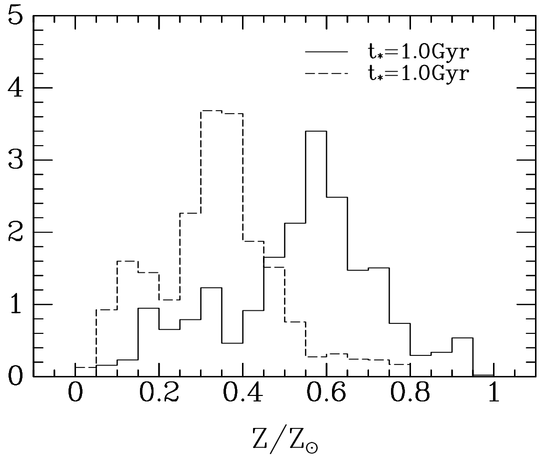

Fig. 7. The predicted metallicity distribution for the DLSs expected from the LBG population (see text). Results are shown for two star formation timescales $t_\star = 0.5$ Gyr (dash) and $t_\star = 1$ Gyr (solid), respectively.

high-redshift thick disk galaxies (Prochaska & Wolfe 1998) or merging protogalactic clumps (Haehnelt et al. 1998). In either case, to match the observed abundance of DLSs, most DLSs should have circular velocity between $50\,\mathrm{km\,s^{-1}}$ to $200\,\mathrm{km\,s^{-1}}$, much smaller than the median circular velocity of LBGs ($\sim 300\,\mathrm{km\,s^{-1}}$). Based on the PS formalism (Eq. (5)) and disk galaxy formation scenario suggested by MMWa (Eqs. (1) and (2)), we can estimate with the random inclination being taken into account, that the fraction of absorbing cross-sections contributed by LBGs amounts to only about 5% of the total absorption cross-section assumed LBGs with highest SFRs. This means that only a very small fraction of DLSs can be identified as LBGs.

The physical connection between LBGs and DLSs is still unclear, although the recent observation of Moller & Warren (1998) using HST indicates that some DLSs could be associated with LBGs. In Fig. 7, we show the predicted metallicity distribution for the subset of DLSs which can be observed as LBGs. Again, we have assumed that $y = Z_\odot$ and $Z_\mathrm{i} = 0$ to make the predictions more easily comparable to observations. As can be seen, the DLSs generally have lower metallicity than LBGs, because they are biased towards the outer region of the host galaxies, where the star formation activity is reduced. Note, however, that the metallicity of these DLSs could still be higher than most DLSs at the same redshift, which typically have a metallicity of $0.1 Z_\odot$ (Pettini et al. 1997a).

4. Summary

In this paper, we have examined the star formation and chemical enrichment in Lyman break galaxies, assuming them to be the central galaxies of massive haloes at $z \sim 3$ and using simple chemical evolution models. We found that gas cooling in dark haloes provides a natural process which regulates the amount of star forming gas. The predicted star formation rates and effective radii are consistent with observations. The metallicity of the gas associated with an LBG is roughly equal to the chemical yield, or the order of $1 Z_\odot$ for a Salpeter IMF. Because of the relatively long star-formation time, the colours of these galaxies should be redder than that of short starbursts. It is not clear whether this prediction is consistent with current (rather) limited observations, because the interpretation of the observational data depends strongly on the adopted dust reddening. Stringent constraint can be obtained when full spectral information of the LBG population is carefully analyzed.

The model predicts a marked radial metallicity gradient in an LBG, with the gas in the outer region having lower metallicity. As a result, the metallicities for the damped Lyman-alpha absorption systems expected from the LBG population are lower than those for the LBGs themselves, although high metallicity is expected for a small number of sightlines going through the central regions of an LBG. At the same time, our modeled contribution to the total metal is roughly consistent with that obtained from the observed cosmic star formation history, i.e., there might not exist so-called “missing metal” problem although there could be more than half of the metals in the hot phase. Finally, a prediction of our model is that LBG haloes are filled with hot gas. As a result, these galaxies may have a non-negligible contribution to the soft X-ray background. The contribution of LBGs to the ionizing UV background is found to be small.

There are two basic assumptions in our work. One is that the LBG population is one-to-one associated with the most massive haloes which are generated from the PS formalism, as done by MMWb; another is that the timescale of star formation for LBG population is assumed to be of the order of 1Gyr, which is suggested by Steidel et al. (1999a,b, 1995). However, Baugh et al. (1999) recently argue that the prediction of the clustering properties of LBGs based on this first simple assumption will be a discrepancy with the results of more detailed semi-analytic models. Still, the second will lead to difficulty in reproducing the redshift evolution of bright galaxies (Kolatt et al. 1999). More detailed modelling done by Somerville (1997) suggest the collisional starbursts could be expected to be an important effect in understanding the LBGs. So, further observations are required to investigate the intrinsic properties of LBGs.

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