Star Formation and Chemical Evolution of Lyman-Break Galaxies

Chenggang Shu

1. Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, P. R. China
2. Max-Planck-Institut für Astrophysik Karl-Schwarzschild-Strasse 1, 85748 Garching, Germany
3. National Astronomical Observatories, Chinese Academy of Sciences, P. R. China
4. Joint Lab of Optical Astronomy, Chinese Academy of Sciences, P. R. China

Accepted ....... Received ........

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, in which the amount of cold gas available for star formation must be regulated, is suggested. 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 about 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 halos 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: LBGs - galaxies: formation - galaxies: star formation - galaxies: chemical evolution

1. Introduction

The Lyman-break technique (e.g. Steidel, Pettini & Hamilton 1995) has now been proved very successful in finding large numbers of star forming galaxies at redshift $z \approx 3$ (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 $z \approx 3$ predicted in hierarchical models of structure formation (Mo & Fukugita 1996; Baugh, Cole & Frenk 1998; Mo, Mao & White 1998b; Coles, et al. 1998; Governato, et al. 1998; Jing 1998; Jing & Suto 1998; Katz, et al. 1998; Kauffmann, et al. 1998; 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, Mao & White (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 have a star formation rate of about $65M_{\odot}yr^{-1}$ for $\Omega = 1$ and the star formation time
scale be the order of 1Gyr based on their values of E(B-V) as pointed out by Pet- 
tini et al. (1997b) after adopting the reddening law of Calzetti (1997). Recently, 
Friaca & Terlevich (1999) use 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 with the age less than 0.2Gyr 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 noting 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. As we will demonstrate in Section 2, 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 Section 2) that such 
a 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 Section 3, a brief summary is given 
in Section 4.

As an illustration, we show theoretical results for a CDM model with cosmo-
logical 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 pa-
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 kms$^{-1}$Mpc$^{-1}$, and so $f_B \sim 0.063h^{-2}$. Whenever a numerical value 
of $h$ is needed, we take $h = 0.7$. At the same time, we define parameter $t_*$ 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, Mao & White (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, Mao & White 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

$$\Sigma_0 \approx 380 h M_\odot pc^{-2} \left( \frac{m_d}{0.05} \right) \left( \frac{\lambda}{0.05} \right)^{-2} \left( \frac{V_c}{250 \text{ km s}^{-1}} \right) \left[ \frac{H(z)}{H_0} \right],$$

and

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

where $m_d$ is the fraction of halo mass that settles into the disk, $V_c$ is the circular velocity of the halo, $\lambda$ 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 $\lambda$ is low and $m_d$ 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 $\lambda \propto m_d$ in calculating $\Sigma_0$ and $R_d$.

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

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

where

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

respectively. Here $\Sigma_{\text{SFR}}$ is the SFR per unit area and $\Sigma_{\text{gas}}$ is the gas surface density. Note that this star formation law was derived by averaging the star formation rate of star-forming regions in nearby galaxies.
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):

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

(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 $M = \frac{4\pi}{3}\overline{\rho}_0 R^3$, 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 $\lambda$-distribution which is a log-normal function with mean $\ln \lambda = \ln 0.05$ and dispersion $\sigma_{\ln \lambda} = 0.5$ (see equation [15] in MMWa), we can generate Monte Carlo samples of the halo distributions in the $V_c-\lambda$ 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, $N_{LBG} = 2.4 \times 10^{-3} h^3 \text{Mpc}^{-3}$ 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,

\[ T = 2.24 \times 10^6 K \left( \frac{V_c}{250 \text{km s}^{-1}} \right)^2, \] (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 \( V_c \gtrsim 200 \text{km s}^{-1} \) 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 equations (1)-(4) we can write the SFR as

\[ \dot{M}_* = \frac{2\pi a \Sigma_b H_d^2}{b^2} \approx 2.33 \times 10^2 h^{-0.6} \left( \frac{m_d}{0.05} \right)^{1.4} \left( \frac{\lambda}{0.05} \right)^{-0.8} \left( \frac{V_c}{250 \text{km s}^{-1}} \right)^{3.4} \left[ \frac{H(z)}{H_0} \right]^{-0.6} M_\odot \text{yr}^{-1}, \] (7)

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

\[ \dot{M}_{\text{SFR}} = (1 - R_t) \dot{M}_*, \] (8)

where \( R_t \) is the returned fraction of stellar mass into the ISM; we take \( R_t = 0.3 \) 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

\[ \frac{dE}{dt} = \epsilon_0 \dot{M}_* (700 \text{km s}^{-1})^2, \] (9)

where \( \epsilon_0 \) 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

\[ \dot{M}_{\text{heat}} = 0.8 \frac{dE}{dt}, \] (10)
which is the same form as equation (9) of Kauffmann (1996; see also Somerville 1997). At $z = 3$ and for the cosmology considered here, this rate can be written as

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

Comparing this equation with equations (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 halos. Because LBGs are hosted by massive halos which have large circular velocities $V_c$, the halos are cooling dominated which is confirmed during the detailed calculation below. Following WF we define a mass cooling rate by

$$\dot{M}_{\text{cool}} = 4\pi \rho_{\text{gas}}(r_{\text{cool}}) r_{\text{cool}}^2 \frac{dr_{\text{cool}}}{dt}, \quad (12)$$

where $r_{\text{cool}}$ is the cooling radius and $\rho_{\text{gas}}$ is the density profile of the hot gas in the halo. For simplicity, we assume that $\rho_{\text{gas}}(r) = f_B V_c^2 / (4\pi G r^2)$, and we define $r_{\text{cool}}$ 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, Frenk, & White, 1997) in MMWb. Because the difference of the resulted cooling rates between these two different choices of density profiles is small (Zhao et al, 1999), and 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 $\Lambda \approx 10^{-23} \text{ergs}^{-1} \text{cm}^3$ in the range of $5 \times 10^5 \text{K} \lesssim T \lesssim 2 \times 10^7 \text{K}$ (and assuming gas with primordial composition), the mass cooling rate can then be written as

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

If $\dot{M}_* \text{ smaller than } \dot{M}_{\text{cool}}$, then cold gas will accumulate in the halo centre and lead to higher star formation rate. If, on the other hand, $\dot{M}_* \text{ larger than } \dot{M}_{\text{cool}}$, 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:

\[
\dot{M}_{\text{cool}} \approx \dot{M}_{\text{heat}} + (1 - R_r) \dot{M}_*.
\]

(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 merger 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 be 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 equation (14) on average. As shown in MMWb, to match the observed number density of LBGs, the median value of \( V_c \) is about 300 km s\(^{-1}\) in the present cosmogony. The typical star formation rate is of the order 100M\(_\odot\) yr\(^{-1}\). This is not very different from the observed star formation rates, albeit dust distinction in the observations may be difficult to quantify.

Figure 1 shows the value of \( m_d \) required by the balance condition equation (14) as a function of halo circular velocity, assuming that \( f_B = 0.1 \) and the left hand side exactly equals to the right hand ones in equation (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 \( \lambda \) distribution for the LBG population (MMWb). As one can see, for the majority of LBG hosts, gas cooling indeed regulates the values of \( m_d \) to the range from 0.02 to 0.04. So, we can reasonably choose \( m_d = 0.03 \) 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 equation (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...
Fig. 1. The value of $m_d$ required by the balance condition equation (14) as a function of halo circular velocity $V_c$ at $z = 3$ for $\lambda = 0.035$ and $\lambda = 0.08$, assuming $f_B = 0.1$ (see text).

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 $R_d/b \approx 0.7 R_d$, 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

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

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

$$\frac{d\Sigma_{\text{tot}}}{dt} = (1 - R_e)\Sigma_{\text{SFR}}.$$  \hspace{1cm} (16)

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

Figure 2 shows the star formation rate as a function of halo circular velocity $V_c$ and spin parameter $\lambda$. As expected, the predicted SFR increases with $V_c$ but decreases with $\lambda$. As we can see from the figure, if we define systems with SFR $\gtrsim 40\,M_\odot\,yr^{-1}$ (which matches the SFRs for the observed LBG population) to be LBGs, the majority of their host haloes must have $V_c \gtrsim 200\,\text{km}\,\text{s}^{-1}$ 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 $\lambda$, 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 Figure 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 $Z_i = 0$ in order to make the predictions.
Fig. 3. The metallicity gradients for LBGs for different star formation time $t_*$ assuming that $y = Z_\odot$ and $Z_i = 0$ (see text). Full and dash lines show results for $V_c = 300\text{kms}^{-1}$ and $150\text{kms}^{-1}$, respectively. From top to bottom, $\lambda = 0.03$ and $0.1$; (a) $t_* = 0.5\text{Gyr}$; (b) $t_* = 1\text{Gyr}$

easily compare 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 $\lambda$, and is higher for a longer star formation time. As one can see from equation (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 $\lambda$) when star formation time $t_* \gtrsim 1\text{Gyr}$. The metallicity drops by a factor of $\sim 2$ from its central value at $R \sim 3R_d$. 
Fig. 4. The predicted metallicity distributions for LBG populations assuming that $y = Z_\odot$ and $Z_i = 0$ in order to make the predictions easily compare with observations (see text). Results are shown for two star formation timescales $t_* = 0.5$ Gyr (dash) and $t_* = 1$ Gyr (solid), respectively (cf. equation (15)).

3.2. LBG Population

Since the distribution of haloes with respect to $V_c$ and $\lambda$ are known, we can generate Monte-Carlo samples of the halo distribution in the $V_c$-$\lambda$ 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 Sec. 2.

We define the typical metallicity of a galaxy as the one at its effective radius. Figure 4 shows the distribution of this metallicity for two choices of the star formation time, $t_* = 0.5$ Gyr and 1 Gyr. Just as the same reason as Figure 3.
Chenggang Shu: Star Formation and Chemical Evolution of LBGs

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

In last section, we have assumed that \( y = Z_\odot \) and \( Z_i = 0 \) in order to make the predictions easily compare with observations. The median values of \( (Z - Z_i)/y \) are 0.60 and 0.84 for \( t_* = 0.5 \) 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 Figure 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 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. \( t_* \gtrsim 0.5 \) 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 Figure 5. The distribution is similar to that of MMWB. The predicted range is \( 1.0 \lesssim R_{\text{eff}} \lesssim 5.0 \, h^{-1}\text{kpc} \) with a median value of \( 2.5 \, h^{-1}\text{kpc} \). Note that the effective radii in the cooling-regulated model are independent of the star formation time.
Fig. 6. The predicted SFR distribution for LBGs in the cooling-regulated scenario.

The predicted SFR distribution also resembles the prediction of MMWb except for a slight difference with MMWb, which is shown in Figure 6. The median values are $180\,M_\odot\,yr^{-1}$ for the model and spans from 100 to $500\,M_\odot\,yr^{-1}$. 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 are 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 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)

\[
j_{\nu} = 5.4 \times 10^{-39} n_e^2 T^{-1/2} e^{-h\nu/kT} \text{erg cm}^{-3} \text{s}^{-1} \text{ster}^{-1} \text{Hz}^{-1},
\]

(17)

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

\[
J = 1.42 \times 10^{-27} T^{1/2} n_e^2 \text{erg cm}^{-3} \text{s}^{-1}.
\]

(18)

We write the total luminosity \( L_b \) in thermal bremsstrahlung as

\[
L_b = \beta \dot{M}_{\text{cool}} V_c^2,
\]

(19)

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

\[
L_{\text{sx}}(V_c) \approx 4.1 \times 10^{40} f_{\text{soft}} \left( \frac{V_c}{250 \text{km/s}} \right)^4 \left( \frac{f_B}{0.1} \right)^{3/2} \text{erg s}^{-1},
\]

(20)

where

\[
f_{\text{soft}} = \frac{1}{kT} \int_{2(1+z)}^{2(1+z)} e^{-E/kT} dE
\]

(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

\[
\rho_{\text{sx}} = \int \int dV_c dV_{\text{com}} \frac{n(z) L_{\text{sx}}}{4\pi d_L^2} \approx 5.7 \times 10^{-8} \left( \frac{f_B}{0.1} \right)^{3/2} \text{erg s}^{-1} \text{cm}^{-2},
\]

(22)

where \( n(z) \) is the comoving number density of LBG haloes as a function of redshift \( z \), \( dV_{\text{com}} \) 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 1998a,b). This contribution should be compared with the value derived from the ROSAT observations (Hasinger et al. 1998) in the 0.5-2 keV band

\[
\rho_{\text{sx}} \approx 2.4 \times 10^{-7} \text{erg s}^{-1} \text{cm}^{-2}.
\]

(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

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

(24)

which is much smaller than the UV background from AGNs, $i_{4\text{Ryd}} \sim 10^{-22}$ 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 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 Sec. 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 $N_{\text{LBG}} = 2.4 \times 10^{-3}h^3\text{Mpc}^{-3}$ for the assumed cosmology (Adelberger et al. 1998). Defining that $\Omega_Z$ is the metal density relative to the critical density, we get that $\Omega_Z$ of LBGs are $0.19\Omega_B \times y$ and $0.29\Omega_B \times y$ 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 halos 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 $0.08\Omega_B \times Z_\odot$ (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 ($>10^{20.3} \text{ cm}^{-2}$), and are believed to be either high-redshift thick disk galaxies (Prochaska & Wolfe 1998) or merging protogalactic clumps (Haehnelt, Steinmetz & Rauch 1998). In either case, to match the observed abundance of DLSs, most DLSs should have circular velocity between $50 \text{ km s}^{-1}$ to $200 \text{ km s}^{-1}$, much smaller than the median circular velocity of LBGs ($\sim 300 \text{ km s}^{-1}$). Based on the PS formalism (equation (5)) and disk galaxy formation scenario suggested by MMWa (equations (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 Figure 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 $Z_i = 0$ to let the predictions more easily compare 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. Notice, however, that the metallicity of these DLSs could still be higher than most DLSs at the same redshift, which typically have metallicity of $0.1Z_\odot$ (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 about the order of $1Z_\odot$ 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 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.

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 to be 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 halos 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 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 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.

Acknowledgments

This project is partly supported by the Chinese National Natural Foundation. I thank Dr. S. Mao, Dr. H. J. Mo and Prof. S. D. M. White for detailed discussions, and the useful help of anonymous referee.

References

Adelberger,K.L., Steidel,C., & Giavalisco,M., et al., 1998, ApJ, 505, 18
Bardeen, J.M., Bond, J.R., & Kaiser, N., et al., 1986, ApJ, 304, 15
Baugh,C.M., Cole,S., & Frenk,C.S., 1998, preprint[astro-ph/9808209]
Baugh,C.M., Benson, & Cole,S., et al., 1999, MNRAS, 305, L21
Binney,J. & Tremaine,S., 1987, Galactic dynamics. Princeton Univ. Press, Princeton, NJ, P580
Burles,S., & Tytler,D., 1998, ApJ, 507, 732
Calzetti,D., 1997, AJ, 113, 162
Calzetti,R., Lucchin,F., & Matarrese,S., 1996, MNRAS, 300, 182
Cole,M. & Lacey,C., 1996, preprint[astro-ph/9510147 v3]
Friaca,A.C.S. & Terlevich,R.J., 1999, MNRAS, 305, 90
Giavalisco,M., Steidel,C., & Adelberger,K.L., 1998, ApJ, 503, 543
Giavalisco,M., Steidel,C., & Macchetto,F.D., 1996, ApJ, 470, 189
Governato,F., Baugh,C.M., & Frenk,C.S., et al., 1998, Nature, 392, 359
Haehnelt M., Steinmetz M., Rauch M., 1998, ApJ, 495, 647
Hasinger,G., Burg,R., & Giacconi,R., et al., 1993, A&A, 275, 1
Jing,Y.P., 1998, ApJ, 503, L9
Jing,Y.P. & Suto,Y., 1998, 494, L5
Kauffmann,G., 1996, MNRAS, 281, 475
Kauffmann,G., Colberg,J.M., Diaferio,A., & White, S.D.M., 1999, MNRAS, 303, 188
Katz,N., Hernquist,L., & Weinberg,D.H., et al., 1998, preprint[astro-ph/9806257]
Kennicutt,R., 1998, ApJ, 498, 541
Kolatt, et al., 1999, preprint [astro-ph/9906104]
Lacey,C. & Cole,S., 1994, MNRAS, 271, 676
Lowenthal,J.D., Koo,D.C., & Guzman,R., et al, 1997, ApJ, 481, 673
Madau,P., Pozzetti,L., & Dickinson,M., 1998, ApJ, 499, 106
Madau,P., Ferguson,H.C., & Dickinson,M., et al., 1996, MNRAS, 283, 1388
Maeder,A., 1992, A&A, 264, 105
Mihos,J.C. & Hernquist,L., 1996, ApJ, 464, 641
Miralda-Escude,J. & Ostriker.J.P., 1990, ApJ, 350, 1
Mo, H.J. & Fugugita,M., 1996, ApJ, 467, L9
Mo, H.J., Mao, S., & White, S.D.M., 1998a, MNRAS, 295, 319(MMWa)
Mo, H.J., Mao, S., & White, S.D.M., 1998b, 1999, MNRAS, 304, 175 (MMWb)
Moller,P. & Warren,S.J., 1998, MNRAS, 299, 661
Moscardini,L., Coles,P., & Lucchin,F., et al., 1998, MNRAS, 299, 95
Narvarro, J. F., Frenk, C. S., & White, S. D. M., 1997, ApJ, 490,493
Ouchi,M. & Yamada T., 1999, ApJ, 517, L19
Peacock, J.A., Jimenez, R., & Dunlop, J.S., et al., 1998, preprint (astro-ph/9801184).

Peebles, P.J.E., 1993, Principles of Physical Cosmology, Princeton Univ. Press, Princeton, NJ, P577.

Pettini, M., 1999, preprint (astro-ph/9902173).

Pettini, M., Smith, L.J., King, D.L., & Hunstead, R.W., 1997a, ApJ, 486, 665.

Pettini, M., Steidel, C., Dickinson, M., Kellogg, M., Giavalisco, M., & Adelberger, K.L., 1997b, preprint (astro-ph/9707200).

Pettini, M., Kellogg, M., & Steidel, C., et al., 1998, ApJ, 508, 539.

Press, W.H. & Schechter, P., 1974, ApJ, 187, 425 (PS).

Prochaska, J.X. & Wolfe, A.M., 1998, ApJ, 507, 113.

Sawicki, M., Yee H.K.C., 1998, AJ, 115, 1329.

Somerville, R.S., 1997, PhD Thesis.

Somerville, R.S., Primack, J.R., & Faber, S.M., 1999, MNRAS, 307, 15.

Steidel, C., Pettini, M., & Hamilton, D., 1995, AJ, 110, 2519.

Steidel, C., Giavalisco, M., & Pettini, M., et al., 1996, ApJ, 462, L17.

Steidel, C., Adelberger, K.L., & Dickison, M., et al., 1998, ApJ, 492, 428.

Steidel, C., Adelberger, K.L., & Giavalisco, M., et al., 1999a, ApJ, 519, 1.

Steidel, C., Adelberger, K.L., & Dickison, M., et al., 1999b, preprint, (astro-ph/9812167).

Tinsley, B.M., 1980, Fundam. Cosmic Phys., 5, 287.

Toomre, A., 1964, ApJ, 139, 1217.

Wechsler, R.H., Gross, M.A.K., & Primack, J.R., et al., 1998, ApJ, 509, 19.

White, S.D.M. & Frenk, C.S., 1991, ApJ, 379, 25 (WF).

White, S.D.M. & Rees, M.J., 1978, MNRAS, 183, 341.

Zhao, D., Shu, C., Song, G., & Zhao, J., 1999, submitted to ApJ.