Effects of the UV background radiation on galaxy formation

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ABSTRACT
We investigate the effects of the UV background radiation on galaxy formation by using the semi-analytic model including the photoionization process. The semi-analytic model is based on Cole et al. and we use almost the same parameters as their ‘fiducial’ model. We find that the UV background mainly affects the formation of dwarf galaxies when \( J_{-21} \sim 1 \) (\( J \equiv J_{-21} \times 10^{-21} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1} \), \( J \) is the intensity of the UV background). Because of the suppression of star formation, the number density of small objects corresponding to dwarf galaxies decreases compared with the case of no UV radiation when the UV background exists until the present epoch. On the contrary, the UV radiation hardly affects massive galaxies. This is because the massive galaxies are formed by mergers of small galaxies, which are formed at high redshift when the effect of the UV background is negligible. This strongly suggests that it is important to consider the merging histories of the galaxies. On the other hand, when the UV background vanishes at a low redshift (\( z \sim 2 \)), the number density of small objects is hardly changed but the colour becomes bluer, compared with the case of no UV radiation, because stars are newly formed after the UV background vanishes.

Moreover, we show the redshift evolutions of the luminosity functions and the colour distributions of galaxies. Because the effect of the UV background is strong at low redshift, we can discriminate between the types of evolution of the UV background by observing the evolution of the luminosity function and the colour distributions, if the UV intensity is sufficiently strong (\( J_{-21} \gtrsim 1 \)).

Key words: galaxies: evolution – galaxies: formation – galaxies: luminosity function, mass function – large-scale structure of Universe

1 INTRODUCTION

The problem of galaxy formation is one of the most important unresolved problems in astrophysics. Recently, owing to the surprising development of the technology concerned with telescopes (e.g. the Hubble Space Telescope (HST) and the Keck telescope), we can see the birth and evolution of galaxies. Thus we can obtain some significant clues to understanding the galaxy formation processes.

It is known that the intergalactic medium (IGM) is highly ionized through the Gunn–Peterson test (Gunn & Peterson 1965). Ultraviolet (UV) background radiation, which ionizes the IGM, also affects the galaxy formation processes by photoionizing gas clouds. The UV photons penetrate the gas clouds and heat up the gas, then star formation in the gas cloud is suppressed by the UV radiation. Therefore it is important to take into account the effects of the UV radiation when we consider the galaxy formation processes.

The sources of the UV background radiation are considered to be mainly quasi-stellar objects (QSOs). From the observations of Ly\( \alpha \) clouds and QSOs, the intensity of the UV background radiation is indirectly measured by the ‘proximity effect’ (Carswell et al. 1984; Bajtlik, Duncan & Ostriker 1988; Bechtold 1994; Kulkarni & Fall 1993; Williger et al. 1994; Giallongo et al. 1996; Lu et al. 1996). The evolution of the UV intensity at low redshifts (\( z \lesssim 2 \)) is approximately proportional to \((1 + z)^7\), which is 4 from the evolution of the QSO luminosity function (Pei 1995), while at high redshifts (\( z \gtrsim 2 \)) the evolution of the UV background is not yet determined.

It has been pointed out that the UV background affects the galaxy formation (e.g. Dekel & Rees 1987). Babul & Rees
(1992) and Efstathiou (1992) have discussed the suppression of star formation by the UV background in dwarf galaxies by considering the evolution of a single galactic gas cloud. Taking into account the photoionization process, the mass function of cooled objects has been calculated in a hierarchical clustering scenario by Chiba & Nath (1994). Their result is that the number density of massive galaxies decreases compared with the case of no UV background. This behavior is explained as follows. In the hierarchical clustering scenario, large clouds generally collapse later than small clouds. As the mean density of a cloud is assumed to be about 200 times the cosmological background density at the collapsing epoch (see, e.g., Peebles 1993), large clouds have a lower density than small clouds. Then the UV photons penetrate deeply into the large clouds and suppress the star formation, which leads to the decrease in the number density of the massive galaxies. However, mergers of galaxies actually occur in the hierarchical clustering model. If luminous galaxies are formed by the mergers of faint galaxies that could collapse at high redshift with little effects of the UV radiation, the number of such luminous galaxies are probably less affected by the UV background. Therefore, it is important to consider the merging history of galaxies in order to clarify the effects of the UV radiation.

The semi-analytic approach to the galaxy formation, which includes the merging history of dark haloes and galaxies, has been developed recently (e.g. Kauffmann, White & Guiderdoni 1993; Cole et al. 1994; Roukema et al. 1997; Somerville & Primack 1998). It has already been confirmed that the averaged stellar age of each galaxy has only a weak correlation with the luminosity of each galaxy by the semi-analytic model (Kauffmann & Charlot 1998). This result would be inconsistent with the shape of the cold dark matter (CDM) mass spectrum unless the mergers occur. This fact also motivates us to analyse the effects of the UV background on galaxy formation via the semi-analytic approach.

In this paper, we investigate the effects of the UV background radiation with the semi-analytic model, which is an extension of Cole et al. (1994) based on the block model for merging histories of dark haloes (Cole & Kaiser 1988; Nagashima & Gouda 1997) by including the photoionization process. We will show how the luminosity functions and the colour distributions of galaxies are changed by the UV background.

In Section 2, we describe our models. In Section 3, we show the luminosity function and the colour distribution of model galaxies, and their redshift evolution. Section 4 is devoted to conclusions and discussion.

2 MODELS

2.1 Semi-analytic model

We use the semi-analytic model, originally developed by Cole et al. (1994). The model includes the following processes: merging histories of dark haloes, gas cooling and heating, star formation and feedback, mergers of galaxies, and stellar population synthesis. We include the effect of the UV background radiation in their original model. The parameters that we use are the same as the ‘fiducial’ model in Cole et al. (1994), except for the block masses and the stellar population model. The astrophysical parameters in the fiducial model are chosen by matching the bright end of the observed B-band luminosity function. The cosmological parameters are specified as follows: $\Omega_0 = 1, \Lambda_0 = 0, H_0 = 50 \text{ km s}^{-1} \text{Mpc}^{-1}, \sigma_8 = 0.67$ and $\Omega_b = 0.06$. We use two maximum block masses $M_0$ corresponding to $2 \times 10^{10} h^{-1} \text{M}_\odot$ and $\sqrt{2} \times 10^{10} h^{-1} \text{M}_\odot$ in order to avoid the influence of the artificial discreteness of masses of blocks, $M_i = M_0/2^i$. The number of the hierarchy is 24. We use the GISSEL96 as the stellar population model provided by Bruzual & Charlot (in preparation). More details about the original model are found in Cole et al. (1994). The data we will show are averaged over 30 realizations by using each maximum block mass.

2.2 Photoionization and mass fraction of neutral core

The UV radiation permeates a gas cloud to a radius at which the ionization by the UV photons balances with the recombination of ions and electrons. For simplicity, we assume that the gas within the ‘cooling radius’ $r_{\text{cool}}$, at which the cooling time scale without UV radiation equals the lifetime of the halo including the gas, cools and recombines rapidly. The lifetime of the halo is defined as the time between the collapse of the halo and its subsequent incorporation into a larger halo. In Cole et al. (1994), the cooled gas within $r_{\text{cool}}$ is interpreted as the star-forming gas. When the UV background exists, however, the mass of the star-forming gas decreases by the penetration of the UV background. Then we estimate a radius $r_{\text{UV}}$ at which the UV photons are perfectly absorbed. We assume that the intensity of the UV radiation begins to decrease at $r_{\text{cool}}$ and vanishes at $r_{\text{UV}}$ by absorption of the UV photons ($r_{\text{UV}} \leq r_{\text{cool}}$), and that the gas within $r_{\text{UV}}$ is cooled and forms stars. With the ‘inverted’ Strömgren sphere approximation, we obtain this radius $r_{\text{UV}}$ by the following relation,

$$\int_{r_{\text{UV}}}^{r_{\text{cool}}} n_p(r)n_e(r)\alpha(2)(T_{\text{eq}})4\pi r^2 \, dr = \pi(4\pi r_{\text{cool}}^2)1.5 \times 10^5 J_{-21},$$

where $n_p$ and $n_e$ are the proton and electron number densities, respectively, $\alpha(2)(T_{\text{eq}})$ is the recombination coefficient to all excited levels at a temperature $T_{\text{eq}}$, and $J_{-21}$ is the normalized intensity of the UV radiation, $J \equiv J_{-21} \times 10^{-21}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$. As the density distribution of the gas is assumed to be an isothermal distribution ($\propto r^{-2}$), the above equation is solved as follows:

$$r_{\text{UV}} = r_{\text{cool}} \left[ 1 + \left( \frac{r_{\text{cool}}}{R} \right)^3 \frac{A(J_{-21},T_{\text{eq}},M)}{(1+z)^3} \right]^{-1},$$

where

$$A(J_{-21},T_{\text{eq}},M) \equiv \frac{1.35 \times 10^6 \pi J_{-21}}{\alpha(2)(T_{\text{eq}})n_p^2 R(M)},$$

where $R(M)$ is the virial radius of the dark halo with the mass $M$ in the comoving coordinate, and $r_{\text{R}}$ is the mean comoving baryon density within $R(M)$, which is about 200 times the cosmological background baryon density under the assumption of the spherical collapse.

In Fig.1, we plot the ratio $r_{\text{UV}}/r_{\text{cool}}$ from the above function at various redshifts in the case of $J_{-21} = 0.1$. 

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R(M) = r_{cool} and \( M_{\text{baryon}} = 0.06 M \), where \( M_{\text{baryon}} \) is the baryon gas mass. Note that the curve at \( z = 0 \) is in agreement with the horizontal axis because UV photons penetrate into the vicinities of the centres of gas clouds. In our calculations shown in Section 3, \( r_{cool} \) is a function of the lifetime of haloes, which depends on their merging histories. It is assumed that \( T_{eq} = 3 \times 10^4 \) K. As the mean density of clouds at the collapsing epoch, \( n_{\text{b}} \), is equal to \( 200n_\text{th} \), where \( n_{\text{th}} \) is the cosmological background density, clouds are denser at high redshifts and so the UV photons are perfectly absorbed at outer region. Therefore there is little effect of the UV radiation in high redshifts. At all epochs, the smaller gas cloud is, the smaller the ratio \( r_{UV}/r_{cool} \) becomes, because the effect of the photoionization is enhanced in small clouds by \( A(J_{-21}, T_{eq}, M) \propto J_{-21} R(M)^{-1} \propto J_{-21} M^{-1/3} \). Note that \( n_{\text{b}} \) is common to all mass objects that are just collapsed at an epoch. We also show the cases of \( J_{-21} = 0.01 \) and 1 in order to see the effect of changing the intensity. It is found that the ratio \( r_{UV}/r_{cool} \) increases when \( J_{-21} \) decreases. As the second term in the brackets of equation (3) scales as \( J_{-21}(1+z)^{-5} \), increasing \( J_{-21} \) corresponds to decreasing \( z \).

It is reported that this inverted Strömgren sphere approximation is not so good when we solve the radiation transfer dependently on the frequency of the photons (Tajiri & Umemura 1998). They have found that the UV photons permeate the clouds far beyond the radius at the optical depth \( \tau \sim 1 \). In our calculations, we have also used a criterion that has the same dependence on mass and UV intensity as the criterion by Tajiri & Umemura (1998) as a trial. We define the critical density \( n_{\text{crit}} \) as the density corresponding to the radius \( r_{UV} \) at which UV photons are perfectly absorbed, as follows:

\[
n_{\text{crit}} \simeq 10^{-2} \text{cm}^{-3} \left( \frac{M}{10^8 M_\odot} \right)^{-1/5} J_{-21}^{3/5}.
\]

This critical density is almost the same as given by Tajiri & Umemura (1998). We have found that the results are qualitatively the same as those by using the inverted Strömgren sphere approximation. However, they assume the homogeneous density cloud instead of the isothermal sphere exposed to the UV radiation. Then we cannot obtain the exact criterion for the isothermal sphere from their work.

Moreover, \( r_{UV} \) may become much smaller if we consider the condition under which \( H_2 \) molecules can be formed. It is inadequate for forming stars that the gas temperature becomes \( 10^4 \) K (Susa, private communication).

Anyway, it is difficult at present to fix a reasonable criterion for star formation under the photoionization effect of UV radiation. Thus, we will proceed as follows. First, note that assuming smaller \( r_{UV} \) corresponds to increasing intensity of \( J_{-21} \). Then, as a trial, we investigate the effect of the photoionization by changing the value of \( J_{-21} \) instead of changing the criterion of star formation. Hereafter we study the cases \( J_{-21} = 0.1 \) (weak condition) and \( J_{-21} = 10 \) (strong condition).

### 2.3 UV background radiation

There are many uncertainties in the determination of the evolution of the UV background, although it is suggested that the intensity of the UV background rapidly declines at low redshifts (\( z \lesssim 2 \)) as mentioned in the Introduction. In order to take into account possible evolutions of the UV background, we calculate the following cases: (1) no UV background exists, (2) \( J_{-21} = 0.1 \) or 10 for \( 0 \leq z \leq 5 \), (3) \( J_{-21} = 0.1 \) or 10 for \( 2 \leq z \leq 5 \), and (4) \( J \propto (1+z)^\gamma \), where \( \gamma = 4 \) for \( z \lesssim 2 \) and \( \gamma = -1 \) for \( z \gtrsim 2 \), and \( J_{-21} = 0.1 \) or 10 at \( z = 2 \). Case (4) is probably the most realistic of these four cases. We show these models in Fig.2.

### 3 RESULTS
3.1 Luminosity function

3.1.1 Weak condition

In Figs.3(a) and 3(b), we show the B- and K-band luminosity functions of model galaxies, respectively. The solid lines, dotted lines, short-dashed lines and long-dashed lines show cases (1), (2), (3) and (4) for the weak condition. The B-band data are taken from Loveday et al. (1992) and converted from their observed b_J to Johnson B by B = b_J +0.2. The K-band data are those from Mobasher, Sharples & Ellis (1993). Because these data have also been used by Cole et al. (1994), a direct comparison of our results with the results in Cole et al. (1994) becomes easier.

We also show the redshift evolution of the B-band luminosity functions in the galaxies' rest frame in Figs.4. The types of lines are the same as Figs.3. The K-band luminosity functions are not shown, because their properties of the redshift evolution are almost the same as those of the B-band luminosity functions. The output redshifts are (a) z = 0, (b) z = 0.4, (c) z = 1, and (d) z = 2. At z = 2, the lines for case (2) are in agreement with those for case (3) by their definitions.

The differences between luminosity functions for various cases become small at high redshifts. This is considered as follows. At high redshifts, mergers of galaxies occur frequently, so the lifetime $t_{\text{cool}}$ becomes very short. This leads to the small cooling radius $r_{\text{cool}}$, and so this effect results in the same effect as the reduction of the UV intensity, because the effect of the photoionization emerges via the form $(r_{\text{cool}}/R)^3J_{21}$ from equation (4). Therefore, such merging galaxies are slightly affected by the UV background at $z \gtrsim 2$.

We find that the UV background hardly affects the galaxy formation in the weak condition. The number density of faint objects decreases slightly in cases (2) and (4), but these differences from case (1) are within the observational errors.

As shown in Fig.3, the slight differences between the luminosity functions in the different UV evolution models in the weak condition arise only in the faint end, because the UV background affects small galaxies more strongly. These differences become smaller at higher redshifts (Fig.4), and are smaller than the observational errors. Thus we cannot distinguish characteristics of the evolution of the UV background by observing the present luminosity functions when the UV intensity is weak.

3.1.2 Strong condition

In the strong condition, the differences between luminosity functions for various cases are larger than the observational errors (Figs.5 and 6). Here, we see the properties of luminosity functions for various cases of the UV background in the strong condition.

3.1.2.1 Merger effect of galaxies

In order to investigate the effect of galaxy mergers, we compare the luminosity functions for case (1) with those for case (2). In Fig.5, we show the same figures as Fig.3, but for the strong condition. The number of faint objects ($M_B - 5\log(h) \simeq -18$) decreases about a factor of 7.5 in case (2), compared with case (1). On the other hand, the most luminous galaxies are less affected by the UV background, although their number slightly decreases.

In Chiba & Nath (1994), the characteristics of luminosity (mass) functions when the UV background exists are opposite to ours, i.e. the number of dwarf galaxies is not affected by the UV background, while the formation of massive galaxies is much suppressed in their results. This is because in our calculation the luminous galaxies are formed in high density regions and formed by mergers of small galaxies formed at early epochs owing to the high density environments, at which there is only a little effect of the UV background because of the high density of gas clouds (see Fig.1). On the other hand, as most of the dwarf-scale galaxies at high redshifts are merged into luminous galaxies until the present epoch, dwarf galaxies at present are formed at low redshifts compared with the typical epoch estimated from the power spectrum of density fluctuations, so that such dwarf galaxies are much affected by the UV background and their number decreases.

In Fig.6, at all redshifts, the number of faint galaxies is small in case (2); besides, the number of luminous galaxies is also small at the low redshifts. This is because the num-

![Figure 3](image-url)
3.1.2.2 Delayed formation of galaxies. Here we consider case (3). When the UV radiation ceases at \( z = 2 \), the number of galaxies at present does not change compared with the case of no UV radiation. Therefore if the UV background vanishes at \( z = 2 \), we cannot distinguish the types of the evolution of the UV background from the luminosity function at \( z = 0 \) (Fig.5).

After the UV background vanishes at \( z = 2 \) in case (3), the number of galaxies increases rapidly and its luminosity function shows good agreement with case (1) at \( z \lesssim 0.4 \) (Fig.6). This increase occurs similarly over the entire range of magnitudes. This means that the epoch of galaxy formation is delayed as a whole by the UV background (Babul & Rees 1992).

3.1.2.3 Effect of mass dependence of photoionization. Now we consider case (4). In this case, the intensity of the UV background evolves continuously, so that the epoch when clouds become free from the effect of the UV background at low redshifts depends on their mass, and the epoch when massive clouds become free from the UV background is earlier than that of small clouds (see Fig.1).

It is interesting that the number density of faint galaxies in case (4) is in agreement with that in case (1) (Fig.5). In case (4), as the UV intensity decreases after \( z = 2 \), massive clouds become free from the UV background and begin to form stars earlier than small clouds, so that the number of galaxies with \( M_B - 5 \log(h) \lesssim -18 \) increases. Thus the effect of the UV background remains in only small galaxies.

Next, we see the redshift evolution of luminosity functions (Fig.6), in order to investigate the effect of the mass dependence in more detail. Because in this case the UV background exists before \( z = 5 \) and is strong enough to ionize gas clouds at \( z \geq 5 \), the number of faint galaxies at \( z = 2 \) is smaller than that in cases (2) and (3). Note that minimum mass blocks begin to collapse at \( z \sim 10 \) in our model.

At \( z = 2 \), the number of galaxies with intermediate magnitude \( M_B - 5 \log(h) \lesssim -18 \) for case (4) is in agreement with that for case (2). At \( z = 0.4 \), the number of such galaxies for case (4) increases rapidly compared with that for case (2), although the number of faint galaxies \( (M_B - 5 \log(h) \gtrsim -18) \) is nearly constant. This shows that galaxies with magnitude \( M_B - 5 \log(h) \lesssim -18 \) become free from the UV background and begin to form stars at \( z \sim 0.4 \).

Note that when the UV background vanishes completely as for case (3), such differences depending on the mass of galaxies in the photoionization effect do not occur. Therefore, the effect that the epoch when clouds become free from the UV background and begin to form stars depends on their mass, in the case when the UV intensity decreases continuously can be a physical mechanism that lessens the slope at the faint end of the luminosity function, as is favoured by the observations.

From Figs.3-6, the luminosity function in case (4) seems to be closer to the observations than in case (1) for \( 0.1 \lesssim J_{-21} \lesssim 10 \) under the assumption that our criterion of star formation is correct.

3.2 Colour distribution at \( z = 0 \)

In Figs.7(a) and 7(b), we show the \( B-K \) colour distributions of galaxies in the weak condition for dwarf galaxies \(( -19.5 \lesssim M_B \lesssim -17) \) and for luminous galaxies \(( M_B \lesssim -19.5) \), respectively. The types of lines are the same as Fig.3. The dotted histograms are the observational data by Mobasher, Ellis & Sharples (1986), which are normalised by the total number of observed galaxies.

In the weak condition the difference between the lines is small as for the difference between the luminosity functions for our four models shown in Fig.3. In case (2), the colour at the peak of the distribution of faint galaxies becomes slightly redder, because of the suppression of star formation at low redshifts. On the other hand, we cannot find any significant differences in the colour distributions of luminous galaxies.

In Fig.8, we show the same figures as in Fig.7, but for the strong condition. In Fig.8(a), the colour at the peak of the distribution in case (2) becomes redder than that in the case of no UV radiation, because star formation at low redshifts is suppressed by the photoionization. When the UV radiation ceases at \( z = 2 \) in case (3), the colour becomes bluer than that in the case of no UV radiation, because stars are newly formed after the UV radiation vanishes. In case (4), the colour distribution becomes much broader. This is because the epoch at which stars can be formed depends on the mass of objects when the UV intensity continuously.
3.3 Evolution of colour distributions

In Figs. 9 (the weak condition) and 10 (the strong condition), we show the redshift evolution of the colour distribution of galaxies in the galaxies’ rest frame for cases (1) and (4). The solid lines, dotted lines, short-dashed lines and long-dashed lines denote the distributions at $z = 0$, $0.4$, $1$ and $2$, respectively. The colour distribution decreases at low redshifts, as mentioned in the previous subsection (see Fig. 1).

On the other hand, the colour distributions for luminous galaxies are not affected so much by the UV radiation, because of the mergers of galaxies as mentioned in the previous subsection (Fig. 8b). We find, however, that the distributions have two peaks in cases (2) and (4). The reason that one of the peaks is bluer than the peak of the faint galaxies (Fig. 8a) is that massive objects store hot gas which cannot be turned into stars in the progenitors. Such massive objects, which are formed by mergers of the small progenitors can form stars at low redshifts with little effect from the UV radiation. Luminous galaxies, the progenitors of which collapse at high redshift when the effect of the UV background is negligible, make the other peak redder in colour (see Section 3.1.2.1).
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Figure 8. Same as Fig.7, but for the strong condition.

respectively. The thin lines and the thick lines show case (1) no UV, and (4) continuously evolving UV intensity. Figs.9(a) and 10(a) show the distributions for faint galaxies ($-19.5 \leq M_B \leq -17$), and Figs.9(b) and 10(b) for luminous galaxies ($M_B \leq -19.5$).

In Fig.9(a), the difference between cases (1) and (4) becomes slightly larger at lower redshifts. As mentioned in Section 3.1.2.3, at high redshifts $z \gtrsim 2$, mergers of galaxies occur frequently, so that the UV intensity becomes effectively small. Therefore, such merging galaxies are only slightly affected by the UV background. Thus the distributions at high redshifts are those for these merging galaxies. Besides, as colours of galaxies depend not on their luminosity but on their stellar ages, the colours of galaxies at high redshifts are little affected by the UV background, while the number of galaxies decreases when the UV background exists. On the other hand, at low redshifts, the hot gas photoionized by the UV photons at $z \sim 2$ begins to cool and form stars. Therefore, the distributions at low redshifts broaden to blue side, compared with case (1). These properties are more remarkable in the case of the strong condition (Fig.10a). Note that we do not consider the chemical evolution process in this paper, so that the colour reflects the epoch of the major star formation in each galaxy.

In Figs.9(b) and 10(b), we also see the same properties as Figs.9(a) and 10(a). The distributions in cases (1) and (4) for the luminous galaxies are smaller than those for the faint galaxies. The distributions for faint galaxies have longer tails towards the blue side than those for luminous galaxies, because the fractions of young stars in such faint galaxies are larger than those in luminous galaxies. Thus we find that the effect of the UV background on faint-galaxy formation remains until later epochs than that on luminous-galaxy formation (see Section 3.1.2.3). This also arises from the fact that the UV background less affects massive haloes.

4 CONCLUSIONS AND DISCUSSION

We investigate the effects of the UV background radiation on galaxy formation with the semi-analytic model, which is an extension of Cole et al. (1994) by including the photoionization process. We find that the UV background radiation mainly affects low-mass objects corresponding to dwarf galaxies.

If the UV radiation field exists until the present epoch (case 2), the number of dwarf galaxies at present becomes small. In hierarchical clustering scenarios, dwarf-scale galaxies are statistically formed at high redshifts, and such galax-
ies are merged into luminous objects. Therefore, dwarf galaxies at present are formed at low redshifts. Thus, when the effect of the UV background is strong, the star formation in such dwarf galaxies is suppressed by the UV radiation. On the other hand, luminous galaxies are less affected, because such luminous galaxies are formed in high overdensity regions and formed at high redshift owing to the high overdensity environments when the effect of the UV radiation is negligible. This represents that it is very important to consider mergers of galaxies.

When the UV radiation vanishes at \( z = 2 \) (case 3), the number of dwarf galaxies hardly changes, but the colour becomes bluer because baryonic gas in clouds recombines and begins to form stars after the UV radiation field vanishes. These blue galaxies might be related to the 'faint blue galaxies' (e.g. Ellis 1997).

More realistically, in the case that the UV background evolves as \( (1 + z)\gamma \), where \( \gamma = 4 \) for \( z \leq 2 \) and \( \gamma = -1 \) for \( z \geq 2 \) (case 4), the slope of the luminosity functions in the faint end becomes gentler and closer to the observed one, compared with that in the case of no UV background. The reason why the slope changes is considered as follows. When the UV intensity declines after \( z = 2 \), large clouds become free from the effects of the UV background at relatively high redshifts, while small objects are affected until low redshifts. Therefore, the number of galaxies with intermediate magnitudes \( M_B - 5 \log(h) \lesssim -18 \) increases, compared with the case when the UV background exists with a constant intensity until the present epoch. Thus the effect of the UV background remains only in small galaxies. Similarly, the colour distribution becomes very broad because the epoch at which stars can be formed in the decreasing UV radiation field differs according to the mass of the haloes.

We also show the redshift evolutions of the luminosity functions and the colour distributions. If the UV intensity is sufficiently strong (\( J_{21} \gtrsim 1 \)), the difference between the evolutions of the UV background clearly appears in the difference between the evolutions of the luminosity function. Moreover, because the effect of the photoionization depends on the mass of galaxies, we obtain much information about the properties of the UV background from the colour distributions for different classes of absolute magnitudes of galaxies.

Although our knowledge of processes of the galaxy formation and nature of the UV background is far from complete at present, it is certain that, when the observations of evolutions of luminosity function and colour distributions are realized, as well as the observations of the evolution of Lyo clouds, in the near future, they will play a significant role in investigating the evolution of the UV background and its effects on galaxy formation. Thus we believe that it is a powerful tool for investigating the evolution of the UV background to observe the redshift evolutions of the luminosity function and the colour distribution of galaxies.

It should be noted that our conclusion is contrary to the conclusion of Chiba & Nath (1994). They have reported that the number of massive galaxies becomes small in the UV radiation field. This difference results from considering the mergers of galaxies. We emphasize that we must construct a galaxy formation model including the mergers of galaxies, because the epoch of the formation of luminous galaxies is not the same as the epoch of the formation of stars in the luminous galaxies.

At the present moment, we do not know the exact criterion for forming stars with the UV radiation. In order to study the galaxy formations more quantitatively, we need to investigate the criterion for forming stars when the UV background exists in detail, and also the dependence on the merging history model and the other parameters in the model. We will also need to include the chemical evolution process in order to compare our results with the observations in the near future.

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