E V O L U T I O N O F L Y M A N B R E A K G A L A X I E S B E Y O N D \( z = 4 \)

RENYUE CEN
Princeton University Observatory, Princeton University, Princeton, NJ 08544; cen@astro.princeton.edu
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ABSTRACT

The formation rate of luminous galaxies seems to be roughly constant from \( z \approx 2 \) to \( z \approx 4 \) from the recent observations of Lyman break galaxies (LBGs). The abundance of luminous quasars, on the other hand, appears to drop off by a factor of more than 20 from \( z \approx 2 \) to \( z \approx 5 \). The difference in evolution between the two classes of objects in the overlapping, observed redshift range (\( z = 2-4 \)) can be explained naturally if we assume that quasar activity is triggered by mergers of luminous LBGs and one quasar lifetime is \( \approx 10^7-10^8 \) yr. If this merger scenario holds at higher redshift, for the evolutions of these two classes of objects to be consistent at \( z > 4 \), the formation rate of luminous LBGs is expected to drop off at least as rapidly as \( \exp \left( -5 \right) \) at \( z > 4 \).

Subject headings: cosmology: theory — large-scale structure of universe — quasars: general

1. INTRODUCTION

Observations of galaxies in the rest-frame UV band (Lilly et al. 1996; Madau et al. 1996; Connolly et al. 1997; Sawicki, Lin, & Yee 1997; Treyer et al. 1998; Pascarelle, Lanzetta, & Fernandez-Soto 1998) indicate that the galaxy formation rate rises steeply from \( z = 0 \) to \( z \approx 1 \), with a nearly constant rate thereafter up to \( z \approx 4 \) (Steidel et al. 1999). While at low redshift (\( z < 2 \)) the evolution of luminous quasar abundance resembles that of luminous galaxies (e.g., Sanders & Mirabel 1996; Boyle & Terlevich 1998), at high redshift (\( z > 2 \)) the two classes of objects do not seem to parallel one another, with the luminous quasar formation rate (e.g., Warren, Hewett, & Osmer 1994; Schmidt, Schneider, & Gunn 1995) dropping off more steeply than that of luminous galaxies.

In this Letter, a phenomenological approach is taken to relate the observed formation rate of luminous Lyman break galaxies (LBGs) to the observed abundance evolution of luminous quasars at \( z > 2 \). It is shown that, if (1) quasar activity is triggered by LBG mergers and (2) each quasar period lasts \( \sim 10^7-10^8 \) yr, then the apparent difference between the evolutions (in both shape and amplitude) of bright LBGs and bright quasars from \( z = 2 \) to \( 4 \) can be explained quantitatively. The first assumption above finds its support from both the observational evidence that a significant fraction of quasar hosts have disturbed morphologies or ongoing galaxy-galaxy interactions (e.g., Boyce et al. 1996; Bahcall et al. 1997; Boyce, Disney, & Bleaken 1999) and theoretical consideration that merger of two (spiral) galaxies seems to provide a natural mechanism to fuel the central black hole (e.g., Barnes & Hernquist 1991). The second assumption is also theoretically well motivated (Rees 1984, 1990) and now strongly implied or required by the mounting observational evidence that most nearby massive galaxies seem to harbor inactive black holes at their centers (e.g., Richstone et al. 1998).

The primary purpose of this work is to use this merger model to infer the LBG formation rate at high redshift, \( z > 4 \). Given the precipitous drop-off of luminous quasar (\( M_B < -26.0 \)) abundances from \( z = 2 \) to \( 5 \), the formation rate of luminous (\( M_{AB} \geq -23 \) to \( -22 \)) LBGs at high redshift (\( z > 4 \)) is predicted to drop off as least as fast as \( \exp \left( -5 \right) \) if the merger scenario holds. A cosmological model with \( \Omega_0 = 0.5 \) and Hubble constant \( H_0 = 50 \) km s\(^{-1}\) Mpc\(^{-1}\) is assumed for the analysis presented here.

It is noted that this simple merger model would probably fail at \( z < 2 \) without having taken into account the evolution of the gaseous fuel supply to the central black holes in galaxies (Kaufmann & Haehnelt 1999; Haiman & Menou 2000).

2. GALAXY Merger Rate AND QUASAR ABUNDANCE

Denoting \( f(z) \) as the galaxy formation rate (galaxy formation per unit time per unit comoving volume) as a function of redshift, then the (cumulative) number density of formed galaxies (number of galaxies per unit comoving volume) is (ignoring the small fraction of galaxies that merge)

\[
g(z) = \int^z_0 f(z') \frac{dt}{dz'} dz'.
\]

For simplicity \( \Omega_0 = 1 \) will be assumed, which should be a good approximation at high redshift (\( z > 2 \)) for the range of cosmological models of current interest (\( \Omega_0 > 0.2 \)). The merger rate for a galaxy with an internal one-dimensional velocity dispersion \( \sigma(z) \) in a cluster/group with galaxy number density \( d(z) \) (assuming all galaxies under consideration are identical) and one-dimensional velocity dispersion \( \sigma(z) \) has been computed by Makino & Hut (1997, eq. [33]) to be

\[
P(z) = \frac{18}{\sqrt{\pi}} \frac{1}{x(z)^{1/2}} d(z) r(z)^2 \sigma(z) R(x),
\]

where \( R(x) \) is a dimensionless function of \( x(z) \equiv \sigma / \sigma_c \), which depends on the galaxy model, and \( r(z) \) is the virial radius of a galaxy. Makino & Hut (1997) demonstrate that \( R(x) \) is a constant (\( \sim 11-14 \)) to good accuracy for \( x > 2 \) for several different galaxy models.

Clearly, not all galaxies participate in merging at any given time; most galaxies have merger timescales much longer than the Hubble time. Rather, only galaxies in dense environments such as groups or clusters of galaxies have significant probability of merging with others. To make the problem more tractable, it is assumed that a fraction \( \beta(z) \) of all galaxies \( [g(z)] \) under consideration at any given time is in dense environments (i.e., typical groups/clusters at \( z \)) where most mergers occur, and the remainder of galaxies (i.e., field galaxies) have zero
probability of merger. Then, the total merger rate is

$$M(z) = \beta(z)g(z)P(z),$$  \hspace{1cm} (3)

and the quasar abundance at any given redshift $z$ is

$$Q(z) = M(z)t_q(z),$$  \hspace{1cm} (4)

where $t_q(z)$ is the assumed quasar lifetime (assuming that $t_q$ is much less than the Hubble time, which turns out to be necessary for the model to be viable).

There are two significantly uncertain remaining parameters, $d(z)$ and $\sigma(z)$, which need to be specified. It is noted that quasar activities at high redshift seem to occur mostly in regions with galaxy number density typical of present-day clusters/groups of galaxies. This information is provided by observations of quasar companions that have a typical separation from a quasar of a few hundred comoving kiloparsecs (e.g., Djorgovski 1999). At redshift $z = 1-2$ there is evidence from larger observational data sets that quasars reside in cluster-like environments (Hall & Green 1998). It thus appears that $d(z)$ may be a weak function of redshift and is assumed to be constant here (more discussion on this later). The velocity dispersion of characteristic systems (groups/clusters in this case) $\sigma(z)$ should be a decreasing function of redshift in any hierarchical cosmological model. Here we take advantage of the insight of Kaiser (1986) and use the solution for simple power-law models:

$$\sigma(z) = \sigma(0)(1 + z)^{(3/2)(n-1/2)n+3},$$  \hspace{1cm} (5)

where $n$ is the power index of the primordial density fluctuation spectrum at the relevant scales for clusters/groups. For cold dark matter–like models or from observations of local large-scale structure, $n$ is expected to be $\sim 1$.

The purpose of estimating LBG formation rate at $z > 4$ is met by finding $f(z)$ at $z > 4$ that matches the observed quasar abundance in the range $z > 2$. For the present analysis, a simple functional form of LBG formation rate is adopted:

$$f(z) = \begin{cases} 
A & \text{for } 2 < z < 4 \\
A \exp[-(z-4)^{6/5}] & \text{for } z > 4,
\end{cases}$$  \hspace{1cm} (6)

consistent with the latest LBG observations at high redshift up to $z = 4$ (Steidel et al. 1999), where $A$ is a normalization constant. At $z > 4$, where observations are unavailable, a simple form is proposed so as to provide an adequate fit to the observed quasar abundance at $z > 4$ (see Fig. 1 below). Using equations (1)–(3) and (5)–(6), we find $Q(z)$ (eq. [4]), shown as the heavy solid curve in Figure 1. Here, for the shown $Q(z)$ we use $n = -1.0$, $\sigma(0) = 10^3 \text{ km s}^{-1}$, $\sigma = 100 \text{ km s}^{-1}$, $\beta = 0.025$ (being constant, which is consistent with the adoption of $n = -1$ power-law model), $d = 40.0 \text{ h}^3 \text{ Mpc}^{-3}$, $r_c = 200 \text{ h}^{-1} \text{ kpc}$, $R(z)$ = 12, and $t_q = 3 \times 10^7 \text{ yr}$. Also shown as symbols are observational data of bright quasars ($M_B < -26.0$): open circles are from Warren et al. (1994), and solid dots are from Schmidt et al. (1995). The open square from Kennefick et al. (1995) for $M_B < -26.7$ quasars is shown to indicate the steepness of quasar luminosity function near the absolute magnitude $M_B \sim -26.0$. The dotted and dashed curves show $g(z)$ (eq. [1]) and $f(z)$ (eq. [6]), respectively.

Note that Figure 5 of Steidel et al. (1999) shows the differential luminosity function of UV-bright LBG galaxies (i.e., star-forming galaxies), calling it $g_d(z)$, while here, $g(z)$ is the cumulative density of formed galaxies. Roughly speaking, if $f(z)$ is constant, then $g(z)/g_d(z) = t_q(z) t_q$, where $t_q(z)$ is the Hubble time at redshift $z$ and $t_q$ is the star (burst) formation duration (i.e., LBG phase) of a galaxy. Since $t_q(z) t_q \approx 10^7 \text{ yr}/10^4 \text{ yr} \approx 10$, the above normalization roughly corresponds to LBGs with $g_d(z) \approx 10^{-3} \text{ h}^3 \text{ Mpc}^{-3}$, which in turn corresponds to LBGs with $M_{AB} = -23$ to $-22$ (Fig. 5 of Steidel et al. 1999).

3. Discussion

On one hand, since $Q(z)$ at $z < 4$ does not depend sensitively on the form of $f(z)$ at $z > 4$, the good agreement between $Q(z)$ and the observed quasar abundance in the redshift range $z = 2–4$ (where both types of objects are observed) suggests that the merger scenario of luminous LBGs provides a quantitatively viable model for bright quasar formation. On the other hand, $Q(z)$ at $z > 4$ does depend sensitively on the adopted form of $f(z)$ at $z > 4$. The fact that the proposed model yields an overall shape at $z = 2–5$ that fits observations implies that the luminous LBG formation rate should drop off at $z > 4$ as indicated by $f(z)$ in equation (1), if the merger scenario holds at $z > 4$. But to have a secure estimate of $f(z)$ at $z > 4$, it is vital to understand the dependences of $Q(z)$ on various other parameters, namely, $Q(z) \propto \beta(z)d(z)\sigma^2(z)r_c^2(t_q(z)(1 + z)^{3/2}(z-4)^{6/5})$. We have set each of the parameters constant (independent of redshift), which is considered to be conservative in the following discussions if a more likely redshift dependence of the quoted parameter (holding all other parameters constant) would require an even steeper decreasing function for $f(z)$ at $z > 4$ than indicated by equation (6). Let us now examine each parameter to assess how each parameter may vary with redshift.

1. It seems that $\sigma(z)$, $r_c(z)$, and $t_q$ are likely to decrease with redshift, making the assumption of their being constant conservative.
2. \( \beta = 0.025 \) is equivalent to the assumption of mergers taking place in galaxy systems corresponding roughly to 2σ peaks and has implications for the correlation function of quasars. The bias factor of halos over mass is \( b = 1 + (\nu - 1)\delta_0 \) (Mo & White 1996), equal to 2.91 for \( \nu = 2 \) and \( \delta_0 = 1.57 \). If the cluster-cluster correlation function has a shape proportional to \( r^{-2} \) (close to the usual slope of \(-1.8\)), then the correlation length of clusters is \( br_n \), where \( r_n \) is the correlation length of the underlying mass and evolves proportionally with \((1+z)^{-1}\) (Kaiser 1986) for \( n = -1 \) and \( \Omega_m = 1 \). Our choice of \( \beta = 0.025 \) consequently implies a correlation length for quasars of approximately 2.91\( r_n(0)/(1+z) \), which is equal to \( \sim 5 \) h\(^{-1}\) comoving Mpc at \( z \approx 2 \) [using \( r_n(0) \approx 5.0 \) h\(^{-1}\) Mpc], in agreement with what is observed for quasars (e.g., Kundic 1997; Boyle et al. 1998). In any case, it is unlikely that \( \beta \) decreases with redshift. Therefore, setting \( \beta(z) \) constant is conservative. An important implication of this model is that the comoving correlation length of luminous quasars should decrease with redshift no faster than \((1+z)^{-1} \) at \( z > 2 \), a potentially testable prediction. Stephens et al. (1997) give a correlation length of \( >2.7 \) quasars of \( 17.5 \pm 7.5 \) h\(^{-1}\) Mpc. It will be very valuable to determine the correlation length of high-redshift quasars with significantly smaller error bars.

3. Observations may have indicated that \( d(z) \) may be an increasing function of redshift at \( z > 4 \) (Djorgovski et al. 1997; Djorgovski 1999). Therefore, assuming \( d(z) \) to be constant is conservative.

4. Finally, for a plausible power spectrum (such as cold dark matter–like), \( n \) is likely to be smaller at smaller scales thus smaller at higher redshift. Thus, assuming \( n \) to be a constant is conservative. Overall, our assumption of constancy for various parameters seems conservative; i.e., \( f(z) \) should decrease at least as rapidly as indicated by equation (6) at \( z > 4 \).

All the analyses so far have been based on the available (optical) observations of quasars, which appear to indicate a sharp drop-off of quasar abundance at \( z > 4 \).

Dust obscuration effects are often invoked to explain the apparent drop-off of quasar abundances at high redshift (e.g., Ostriker & Heiler 1984; Pei 1995). However, recent radio surveys of high-redshift quasars seem to indicate that the drop-off of the number density of bright radio quasars is very similar to that from optical surveys (e.g., Hook, Shaver, & McMahon 1998) with the implication that the effect of dust on the observed drop-off of bright quasars at \( z > 2 \) may be small.

One potential problem with the merger model is that observations show that a large fraction of quasar hosts at low redshift (\( z < 0.5 \)) appear to be quite normal looking, i.e., without disturbed appearances. But one would expect that, if the galaxy-galaxy merger timescale is longer than the proposed quasar lifetime, all quasar hosts should display appearances of some interaction. One possible solution to this problem is that quasar formation is delayed, i.e., a quasar does not start to shine until the galaxy-galaxy merger is nearly complete. In other words, the time it takes to set up the central (black hole) region for quasar activity during galaxy merger may be comparable to the time that it takes for the two galaxies to merge.

4. CONCLUSIONS

In an early classic paper, Efstathiou & Rees (1988) show that quasar abundance at high redshift can be accounted for in the standard cold dark matter model if massive halos are related to the formation of black holes, with an intriguing prediction that the abundance of luminous quasars should decrease rapidly beyond \( z = 5 \) (for a more recent treatment, see Haehnelt & Rees 1993). (The evolution of low-luminosity quasars, of course, does not necessarily have to follow that of their luminous counterparts; e.g., Haiman & Loeb 1998).

In this Letter, a different approach is taken by directly relating the observed evolution of luminous LBGs to the observed evolution of luminous quasars at high redshift (\( z > 2 \)). With a set of seemingly reasonable parameter values, it is shown that consistency between the two classes of objects at \( z = 2−4 \), where both classes are observed, can be achieved if one assumes that (1) Lyman break galaxies merger to trigger quasar activity and (2) the quasar lifetime is \( \sim 10^7–10^8 \) yr. At \( z > 4 \), consistency can be achieved, only if additionally the formation rate of luminous LBGs drops off as \( \exp \left[-(z-4)^{0.75}\right] \) or faster, a prediction that may be tested by future observations. One implication from this model is that LBGs with \( M_{AB} \geq -23 \) to \(-22 \) merge to form quasars with \( M_{AB} < -26.0 \) at \( z > 2 \). Correlation analysis of relevant LBGs and quasars should shed light on this.

At lower redshift additional, more model-dependent assumptions regarding the supply of available gas to fuel black holes would be required to make qualitatively viable predictions. Kauffmann & Haehnelt (1999; see also Haiman & Menou 2000) have presented a detailed model, based also on the merger scenario, to unify the evolution of galaxies and quasars in the cold dark matter model under several plausible assumptions concerning the evolution of fuel gas to the central black holes. The success of the model of Kauffmann & Haehnelt (1999) at low redshift (\( z < 2 \)) and the model presented here at high redshift (\( z > 2 \)) , both based on the galaxy merger scenario, suggests that galaxy merger may play an indispensable role in quasar formation.

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